Australian Acoustical Society

Annual Conference

Acoustics 2001

Noise and Vibration Policy – The Way Forward?

21-23 November 2001

Canberra ACT Australia

Proceedings Edited by Marion Burgess

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The 2001 Conference of the Australian Acoustical Society has been organised by the NSW Division of the Australian Acoustical Society.

A hard copy of the program and abstracts has been produced for the convenience of the delegates of the conference. The papers are provided in full on the CD along with the content of the book of abstracts.

All abstracts were reviewed prior to acceptance for the conference. Full papers, which have been accepted after a peer review process, are indicated as such on the first page of the full paper.

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Each Division of the Australian Acoustical Society has the opportunity to organise an annual national conference. For 2001 the challenge was taken up by the NSW Division, which decided to hold the conference in Canberra, the Capital City of Australia and the seat of Federal Parliament. With such a location, it was considered most appropriate to select a theme for the conference that reflected the influence and role of government. Setting policy is an important part of government business and acoustic professionals need to update themselves on current policy and possibly influence future directions. Therefore the theme was chosen to be:

Noise and Vibration Policy – The way forward?

The program for the conference comprises a range of papers on this theme and they are organised into specific acoustic areas:

Occupational noise	Environmental noise
Noise in buildings	Vibration control
Transportation noise	Airport/Aircraft noise

In addition there are contributed papers on a range of topics which reflect the extensive investigation and research that is being carried out in acoustics both in Australia and overseas. There is also the Display Hall where suppliers of products and services relevant to the many aspects of acoustics provide delegates with an opportunity to see, touch and hear about their latest products.

The organising committee is delighted that there has been such an interest in this conference and we are sure that the event will be most successful. It will also provide the opportunity to forge new collaborations and to renew friendships for those attending from around Australia and around the world.

Of course this event would not have come about without the support of so many of the NSW Divisional Committee members who have willingly taken on extended tasks to help bring you (the delegates) this Annual Conference. Special thanks must be extended to Marion Burgess from the Acoustics and Vibration Unit in Canberra who has unstintingly coordinated all the papers, the technical program, registrations and other local content and Neil Gross from Wilkinson Murray in Sydney who has put together the excellent technical exhibition.

All those involved with the organisation of the conference hope that you find this conference interesting, stimulating and enjoyable.

Ken Mikl
Conference Chairperson

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TECHNICAL EXHIBITION

The following companies have participated in the technical exhibition associated with the conference.

Acoustic Answers

Acoustic Systems

Acoustics Research Laboratories

Bruel&Kjaer Australia

CSR Gyprock

CSR Bradford Insulation

Davidson

Duroid

G P Embleton

Enviro Acoustics

Infobyte

Kingdom

Latimer Acoustics

Marshall Day Acoustics

Matrix Industries

Nutek Australia

Pyrotek

Sound Control

Warshash Scientific

Wilkinson Murray

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PROGRAM OVERVIEW

All sessions and functions held in the Rydges Lakeside Hotel

Wednesday 21 November

14.50	*Screen sound tour*	*Depart from Hotel Reception*
18.00	Registration Desk Open	Burley Griffin Restaurant, top floor
19.00	*Welcome Buffet*	*Burley Griffin Restaurant, top floor*
20.00	Opening of Conference	Prof Peter Cullen, Immediate Past President of FASTS

Thursday 22 November

08.10	*Light Breakfast*	*Display Hall, level 1*
	Registration Desk and Technical Exhibition Open	
08.50	**Sessions A 1 and B 1**	Conference Rooms, level 1
10.30	*Morning Tea*	*Display Hall,* level 1
11.10	**Sessions A 2 and B 2**	Conference Rooms, level 1
12.50	*Buffet Lunch*	*Burley Griffin Restaurant, top floor*
13.50	**Sessions A 3 and B 3**	Conference Rooms, level 1
15.30	*Afternoon Tea*	*Display Hall, level*
16.10	**Sessions A 4 and B 4**	Conference Rooms, level 1
17.30	Close of sessions	
18.00	AAS Annual General Meeting	Conference Rooms, level 1
18.30	*Pre Dinner Drinks*	*Conference Rooms Foyer, level 1*
19.00	*Conference Dinner*	*Conference Rooms, level 1*
	Award of INC Innovation in Acoustics Prize	
	Dinner Speech by Robyn Williams from ABC Science Show	

Friday 23 November

08.10	*Light Breakfast*	*Display Hall, level 1*
08.50	**Sessions A 5 and B 5**	Conference Rooms, level 1
10.30	*Morning Tea*	*Display Hall,* level 1
11.10	**Sessions A 6 and B 6**	Conference Rooms, level 1
12.30	Award of Presidents Prize for best paper at conference	
	Close of conference	Conference Rooms, level 1
12.50	*Buffet Lunch*	*Burley Griffin Restaurant, top floor*
13.50	*Parliament House tour*	*Depart from Hotel Reception*

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Technical Program Thursday 22 November

8:50	A 1.1	*Treagus*	Environmental Noise Policy Making By Government
9:10	A 1.2	*Langgons*	Noise Control Planning For New Industrial Estates
9:30	A 1.3	*Turner*	The New Noise (Environment Protection) Policy In South Australia
9:50	A 1.4	*Renew*	Experiences In Planning For Noise Control In Queensland
10:10	A 1.5	*Macpherson*	Review Of The WA Environmental Noise Regulations
10:30			*Tea*
11:10	A 2.1	*Gunn*	Occupational Noise Policy– Overview Of State, National And International Initiatives
11:30	A 2.2	*Williams*	Noise In The Workplace?
11:50	A 2.3	*Scannell*	The Need For More Than One 8-Hour Noise Level Criterion.
12:10	A 2.4	*Steenkamp*	An Exploratory Study Of Second Defence Noise Control Measures In S African Coal And Platinum Mines
12:30	A 2.5	*Mitchell*	Examination Of Large Audiometric Databases For Enhancing Occupational Noise Management Strategies
12:50			*Lunch*
13:50	A 3.1	*Dickinson*	Surface Transportation Noise – Community Expectations And The Real World
14:10	A 3.2	*Samuels & Parnell*	Some Recent Australian Developments In The Reduction Offroad Pavement Noise
14:30	A 3.3	*Hall*	Queensland Department Of Main Roads Road Traffic Noise Management: Code Of Practice
14:50	A 3.4	*Gowen & Karantonis*	Application Of The NSW EPA's 'Environmental Criteria For Road Traffic Noise' to a Major Arterial Road In Sydney
15:10	A 3.5	*Murray*	Assessment Of Road Traffic Maximum Noise Events At Night Time
15:30			*Tea*
16:10	A 4.1	*Southgate*	The Evolution Of Aircraft Noise Descriptors In Australia over The Past Decade
16:30	A 4.2	*McLeod*	Airservices Australia’s Noise And Flight Path Monitoring System
16:50	A 4.3	*Cohney*	ISIS - A Multimedia Tool For Noise Management Information
17:10	A 4.4	*Rikard-Bell*	Airport Noise Management - Speaking The Community's Language

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Technical Program Thursday 22 November

8:50	B 1.1	*Lew & Nguyen*	Broadband Acoustic Scattering Of Submerged Objects
9:10	B 1.2	*Larsson*	Analysis Of Active Sonar Reverberation Data
9:30	B 1.3	*Tickell*	Noise Reduction Of Steel Pipes & Hollow Tubes
9:50	B 1.4	*Scelo & Fox*	Optimal Transducers Placement For Measurement Of Power Flow And Dynamic Properties Of A Timber Beam
10:10	B 1.5		Vacant
10:30			*Tea*
11:10	B 2.1	*Pan et al*	Acoustics Of Ancient Chinese Music Bells
11:30	B 2.2	*Dickinson & Thwaites*	Bandicoot - A Novel Approach To Using A Pitch-Catch Acoustic Probe For Field Non-Destructive Testing
11:50	B 2.3	*Pan & Dickens*	Multi-Channel Control Of Fluid-Borne And Structural-Borne Noise In A Pipe-Pump System
12:10	B 2.4	*Munn et al*	Real Time Feedforward Control Using Virtual Sensors In A Long Narrow Duct
12:30			Vacant
12:50			*Lunch*
13:50	B 3.1	*Meldrum*	Sound Level Meter Standards For The 21st Century
14:10	B 3.2	*Dodd*	Profiling Listeners
14:30	B 3.3	*Broner*	Low Frequency Annoyance - Why?
14:50	B 3.4	*Guo & Pan*	Low Frequency Noise Control - The Next Step In Noise Control And Management?
15:10			Vacant
15:30			*Tea*
16:10	B 4.1	*Zhao*	Brake Related Noise &Vibration: Review
16:30	B 4.2	*Papinniemi et al*	Vibration Analysis Of A Disc Brake System
16:50	B 4.3	*Zhao*	Subjective & Objective Evaluation Of Brake Related Noise & Vibration
17:10	B 4.4	*Lai et al*	A Double-Pulsed Holographic System For Investigating Brake Squeal

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8:50	A 5.1	*Fitzell & Fricke*	Acoustics Of Multiple Occupancy Dwellings
9:10	A 5.2	*Davy*	Challenges With The Active Sound Insulation Of Windows
9:30	A 5.3	*Mc Minn*	Impact Noise Ratings For Wall Partitions: Building Code Of Australia
9:50	A 5.4	*Gaston & Hooker*	Sound Transmission Through Lightweight Floor Structures
10:10	A 5.5	*Hallows*	Low Frequency Footfall Sounds: Audibility And Performance Of Light Timber Framed Flooring Systems
10:30			*Tea*
11:10	A 6.1	*Gregory*	Impact Isolation Of Hard Floors Surfaces In Concrete Structures
11:30	A 6.2	*Wearne*	Railway Vibration Isolation For Melbourne's Federation Square
11:50	A 6.3	*Law et al*	A New Analytical Model For Sound Absorption Performance Of Micro-Perforated Panel Absorber
12:10	A 6.4	*Choi & Fricke*	The Parameters Contributing To The Acoustic Quality Of Concert Halls
12:30			Award of President's Prize and Close of Conference
12:50			*Lunch*

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Technical Program Friday 23 November

8:50	B 5.1	*Henry*	The Role Of Local Government Planning In The Management Of Community Noise
9:10	B 5.2	*Kamst et al*	Traffic Noise Aspects Of Master Planning
9:30	B 5.3	*Scannell*	Frost Fan Noise Policy The Issues.
9:50	B 5.4	*Heddle*	Pecentile Policy Perils
10:10	B 5.5	*Bullen*	A System For Automatically Detecting The Direction Of Noise Sources
10:30			*Tea*
11:10	B 6.1	*Tickell*	Assessment Of Environmental Noise From Railway Transportation And Sleep Disturbance
11:30	B 6.2	*Gange & Karantonis*	External And Internal Acoustic Tests On A Modern Passenger Train While In Motion
11:50	B 6.3	*Huybregts*	Noise Control Measures For The Proposed Melbourne Airport Rail Link
12:10	B 6.4	*Roberts*	A Proposed Low Frequency Noise Annoyance Guideline
12:30			Award Of President's Prize And Close Of Conference
12:50			*Lunch*

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Environmental Noise Policy Making by Government

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Abstract. *The process of identifying noise impact issues, developing strategies for dealing with them and writing policy documents that are adopted by government is explained. The essence of the process is to develop the right technical solutions to accommodate the needs of both the community, who bear the noise impacts and industry who bear the noise control costs. Fully understanding these needs is the role of consultation. The way these components work together is discussed. There is no short cut to delivering a well accepted policy and the developmental issues are outlined with indications on how they are managed.. Example are given about how detailed policy work can become in relation to background noise determination for the NSW Industrial Noise Policy and how a practical problem relating to application of the Environmental Criteria for Road Traffic Noise was addressed.*

Introduction

It may seem a long time from when the need for public agency guidance on a noise problem is first debated to when a final policy position is published. This is because there are a lot of necessary steps in between that are designed to give the policy a long and successful life. If a policy response to an environmental problem is rushed in the hope that the problem can be addressed earlier, that response could be flawed technically or in the way it is written, it may prove difficult to implement and may not enjoy popular support. If any one of these problems arise then the "quick fix" policy may be rather like a faulty light bulb, burn bright for an instant and then go out. We are back at the beginning and time is wasted.

In framing well considered government policy it takes time to save time. To a busy acoustical consultant who is accounting for his or her time hourly, to think of a person working on the same project for 2 years or longer may appear a little unreal. Assessing the impact for a particular project is characteristically a short term project. But a government policy on environmental noise may be around for years, perhaps decades. It needs staying power. It needs technical competence, attention to detail and be carefully crafted in its expression.

I will set out the broad steps of the government policy process: What the effort is in getting a policy up and running. They follow a logical sequence and are quite transparent to the stakeholders. The sequencing of these steps may be modified to accommodate particular policy development circumstances but overall represent the generic approach.

Step 1 – Defining the problem. This has been made relatively easy by the range of surveys and statistics available as well as extensive anecdotal evidence telling us what the environmental noise impacts are and the extent of the problem. Road traffic noise impacts are examples of these. Other information may tell us of the difficulties industry may be experiencing in implementing old policy, because it is ambiguous, because it lacks detail, because it does not address emerging issues or because the science and practice of acoustics has moved on.

Having a broad idea of the problem is not enough. Identifying the people who work with environmental acoustics and know the problems, and affected groups who live with the impacts, and then engaging all these groups is vital to understanding the range of issues bound up with the overall problem. An example of this was in our discussions with industry regarding industrial noise matters the problem of dealing with noise impacts when temperature inversions were present was highlighted as important and in need of special guidance. Previous policy simply referred to the need to take the effects of inversions into account. What industry wanted now was a detailed procedure that everyone could follow that would quantify the impact attributable to weather conditions.

Step 2 – Researching the subject. This appears to be a straightforward step – examining the literature for the contemporary technical approach, looking at interstate and overseas practice, standards and protocols. A lot of work is usually involved and there are challenges in getting a coherent picture when papers give a wide scatter of results in non-comparable formats using a range of methodologies, descriptors and criteria. As an example of how research directs the technical part of the process, the readings for the NSW Industrial Noise Policy indicated a general move to Leq as a descriptor of choice in measuring impacts. However the previous policy used the L10 for the industrial source. Therefore it was important to determine what effect a change of descriptor would have, on any noise levels set as environmental goals, in terms of impact assessment and in terms of instrumentation requirements.

Step 3 – Developing draft criteria and policy framework. Good environmental policy is much more than the criteria, that is, the noise levels that represent desirable environmental goals. It also includes
How the impact should be assessed – this means detailing the prediction process
How to manage impacts when the criteria cannot be met – a mitigation strategy involving best management practices and best available technology economically achievable
How to manage impacts when the criteria cannot be met even with mitigation – considerations of negotiation with the regulator or the affected community
Procedures for compliance regimes that can practically be applied

One major outcome from good policy framework is to standardise on the way impacts are assessed so that different practitioners assessing the same proposal are likely to arrive at the same answer. This is an ideal that in practice may not occur where there is room for interpretation on any particular policy point. Being meticulous about how policy is expressed in a document to minimise interpretation is vital. Even so difficulties can occur. An example is the amenity criteria of the current NSW Industrial Noise Policy. This section of the policy addresses the need to maintain an acceptable level of amenity in line with resident's expectations for the type of land use that they reside in. Thus residents living in the country would expect a quieter environment than residents living in the inner city. Thus there is an assignment of particular noise levels as amenity criteria for particular land use types. There may well be debate amongst practitioners about which land use type a specific site belongs to especially if it exhibits transitional characteristics.

Another feature of NSW government policy documents on noise is that they are outcome based. In other words, the desired result in terms of environmental impact is what is important and not the means used in achieving it. We describe this approach as being performance based. So a policy document may list the many mitigation measures that are available as a guide but would not prescribe any. The philosophy is that the proponent should know best as to what mitigation strategy should be employed for his or her proposal to meet or come as close as possible to the noise criteria.

The setting of criteria itself is a process directed to satisfying a range of needs:
The need for the criteria to be substantiated by the literature
The need for the levels to represent reasonable protection for the community
The need for the criteria to be equitable – so that the burdens on industry are not unreasonable and uneconomic but are set at a level that is achievable.

The economic costs and benefits of the draft policy need to be assessed. Proper policy formulation should make the community better off for having the policy and it is the role of a costs/benefits paper to indicate this. In the detail such a study may typically identify some additional costs perhaps in monitoring and compliance work but these would be outweighed by advantages in reduced environmental impact and savings attained through the greater certainty in the assessment and approval process offered by the policy.

Finally there is the art of expressing policy in clear unambiguous language without sacrificing policy detail and technical competency.

So all of these considerations go into the framing of a draft policy document.

Step 4 – Consultation with stakeholders.

"Stakeholders" is a well used word these days and describes the group of people and organisations affected by or have interests involving the policy. It is important to identify and engage all of the stakeholder groups with a view to achieving two outcomes:
Inform stakeholders about the policy and encourage debate that would generate focused and valuable feedback that can be applied to improving policy details that would bring a policy document more in line with stakeholder's needs. The better informed stakeholders are about the aims and content of a draft policy the more relevant and detailed is likely to be the comment received back.
Address the issues raised by stakeholders in the policy process so that the policy can attract industry and community support. Such support greatly facilitates its approval by government.

This stage is characterised by publication of a draft policy, mail out to stakeholders that could number in the hundreds, the conduct of seminars, workshops and presentations appropriate to the material being presented, and lastly but most importantly analyse all of the submissions and advice flowing back to the EPA from the consultation process. We need to be transparent about how submissions are taken into account. This means that we need to have established good reasons why any particular advice is or is not included in an amended policy document.

Step 5 – Seeking Government Approval for a "whole of government" policy

Our aim in this process is for the policy to be "whole of government". This means that it is official government policy. In the development of "whole of government policies" relevant government agencies are invited to indicate acceptance and provide comments. Both the Environmental Criteria for Road Traffic Noise and the NSW Industrial Noise Policy have been produced as "whole of government" policies.

For draft policies to be approved on a "whole of government" basis a number of things need to be satisfactorily addressed:

Does the draft policy address community needs
Does it have the support of the community, industry and government agencies
What financial or economic burden on government and the community does it introduce – if there is, can the policy be justified on the basis of its overall net benefit to its stakeholders
How does it fit with other government noise and related policies and government programs generally

All of these matters need to be well documented and clearly indicated. Where concerns of particular government agencies can be anticipated these need to be addressed to that agency's satisfaction prior to the draft policy being submitted to government. The consultation process in fact should have identified such agency issues well before this stage is reached.

The matter of gaining community and industry support is vital. Even good policy initiatives can fail when this support is absent most likely brought about by a lack of proper consultation. The best approach is always to engage the community and industry though each developmental phase of the policy document.

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Step 6 – Implementation and Training

Finally, the efforts described in all the previous stages would be wasted if the policy were not implemented successfully. For any policy involving environmental noise this necessarily involves some technical matters. Many policy users may not be confident in dealing with noise issues.

Therefore a training program for the major groups who will use the policy is offered. For the traffic noise and industrial noise policies this included the RTA, industry and consultants, local government and of course internally within the EPA. In fact we conducted 47 courses across NSW involving 900 participants for these two policies.

Assistance has been ongoing. Although these policies aim to provide guidance for most situations they cannot cover every situation and often guidance is sought in these circumstances. Local government is assuming more responsibilities these days and the Protection of the Environment (Operations) Act has given them more power to address their noise issues. They may decide to be guided by our environmental noise policies which have been designed more for large developments than for small proposals regulated by council. Hence there is ongoing assistance provided for councils to use these policies in a modified way to suit the simpler approach to noise problems that councils necessarily need to take.

Some examples of particular policy work.

Having set out a general scene of the policy process, each type of community noise impact that requires a policy response brings with it some particular problems and specific policy tasks. I would like to briefly cite two examples to illustrate how detailed policy development work needs to be.

Application of the Environmental Criteria for Road Traffic Noise

The main user of this policy is obviously the road developer which in NSW is the Roads and Traffic Authority. The policy provides criteria specific to a range of development categories such as new freeways and arterial roads, redeveloped freeways and arterials, collector roads and local roads. In other words each of these categories has its own criteria. When it came to actually applying these categories to real situations on the ground the problem of transition zones arose which is the interface between two categories. Working with the RTA we developed how these zones should be assessed under the policy. The real life example where this issue arose was a planned by pass road in the region of its intersection with the existing road.

Determining the background noise methodology for the NSW Industrial Noise Policy

Technical papers were developed for all of the major technical features of the policy including the assessment of temperature inversions effects on noise, the employment of modifying factors to take account of additional annoyance when noise has tones, impulses and other characteristics, and the determination of background noise. Finding the level of background noise was a central part of the policy. Therefore it was vital that the best method that determined it be chosen. To do this local, interstate and overseas practices were compared. Then, a number of methods were tested and compared. These included the average background noise level, the lowest repeatable level, the tenth percentile level and the accumulated statistical noise level.

To compare each method required good background noise data from localities with known noise characteristics. So we collected noise data from several locations over a representative period of time that were then used in the analysis. The results were then compared based on two main comparison criteria: (1) that the measure selected be able to protect amenity for 90% of the time, and (2) repeatability, i.e., measures that have low variance when repeatedly applied to the same site on a similar day. Other positions that were developed in this work were the length of monitoring, i.e, the time for each L90 value, and the required number of valid samples.

This work was but one part in a large array of parts that eventually made up the complete policy where the effort required can be measured in person years

Conclusion

These examples indicate both the level of detail that is required in writing good policy material and in ensuring its successful application in the real world. The term ivory tower has long been applied to policy makers who lose contact with the purpose of their work. Working with the people who use the policy ensures that constant reality checks are part of the process. This of course includes how practical checking for compliance is. The best policies in the world are ineffective if there is no practical way of checking that they are being used correctly.

I said at the beginning that it takes time to save time. There are no short cuts to this that are truly sustainable in the light of scrutiny. However the transparency of the policy process as I have outlined means that stakeholders know where we are up to with the work of delivering the product. It is rather like running the marathon in athletics, the result may take time in coming but it is all the more respected when spectators can see what the runners had to do to get to the finish line.

References

NSW Environment Protection Authority., Environmental Criteria for Road Traffic Noise 1999

NSW Environment Protection Authority., NSW Industrial Noise Policy 2000

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NOISE CONTROL PLANNING FOR NEW INDUSTRIAL ESTATES

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Abstract

The NSW Government's Industrial Noise Policy primarily deals with the assessment of noise from individual industrial developments. The policy recognises that, where several developments are proposed in an area, noise impacts from the developments should be assessed as a group. For new industrial estates that are close to residential areas, a strategic approach to planning of noise can result in improved equity and certainty for developers, more efficient assessment for the consent authority and, perhaps most importantly, better outcomes for the community. This paper examines several approaches that have been developed to manage noise for new industrial estates.

Introduction

In early 2000 the New South Wales Government released the Industrial Noise Policy (INP) (NSW EPA, 2000) (www.epa.nsw.gov.au), a guideline for the assessment of noise associated with major industries. This policy aims to provide a comprehensive and effective whole of government approach to managing noise.

The INP primarily deals with noise from individual developments in areas with relatively stable background noise levels. However, Section 2.2.4 of the policy recognises that, where several developments are proposed in a developing area, noise impacts from the developments should be assessed as a group. An example of this situation is the development of a new industrial estate.

This paper presents a discussion on the benefits of a strategic approach to noise control planning for a new industrial estate and examines several approaches that have been used in the past.

NSW Industrial Noise Policy Assessment Criteria

The noise criteria used in the INP to assess noise impacts consists of two components:

- That the contributed intrusive $L_{Aeq(15minute)}$ noise levels emitted by the development not exceed the existing background noise levels for the area (Rated Background Level - RBL) by more than 5dB. This is designed to protect against intrusive noise; and
- The noise contributed by the new proposal not raise the existing level of noise from industry above the recommended noise level from industry for the appropriate land-use. This is designed to preserve the amenity of the area.

The noise criteria are not statutory noise limits but are used as a basis for deriving statutory noise limit conditions on development approvals and licences.

To assess potential noise impacts both components of the criteria are applied and the level of noise control is normally set by whichever component of the noise criteria is the most stringent. The decision on whether the intrusive or amenity criterion is most stringent is dependent upon the existing noise in the surrounding area.

To determine the allowable amenity noise level for a new noise source, the existing $L_{Aeq(period)}$ noise levels from industrial sources needs to be determined. Where the existing levels are greater than 6 dB below the acceptable amenity criteria, then the allowable amenity level from the new source can be set at the acceptable amenity criteria. However, where existing levels approach or exceed the amenity criteria, the allowable amenity level from the new source is reduced.

The INP refers to the most stringent of the criteria from the assessment as the project-specific noise levels (PSNL) for the development. In circumstances where the PSNL cannot be met and the EPA or the consent authority is satisfied that all practicable means to mitigate the noise impacts have been proposed and it is judged that the social and economic benefits out-weight the noise impacts the INP provides for a "negotiated" noise level.

Applying the NSW Industrial Noise Policy criteria for a new industrial estate

In applying the criteria discussed above, for a new industrial estate located in a relatively quiet area, noise criteria for the initial developments would be governed by the intrusiveness criterion. However as background noise levels rise, noise limits for subsequent developments within the industrial estate would be governed by the amenity criterion.

As the background noise levels continue to rise, the amenity noise criteria for each new industrial site could fall to as low as 10 dB(A) below the background noise level. This is designed to ensure that cumulative noise from all industrial developments within the estate meet the relevant amenity criteria in the receiver area.

Where early developments have been allowed to raise noise levels to close to the amenity criteria later developments will face increasingly stringent noise control requirements, which may affect their viability. Alternatively, there may be pressure placed on the consent authority to allow ambient noise levels to increase above the acceptable amenity noise criteria for the area.

The Industrial Noise Policy has been designed to provide the means to manage noise from multiple development with the object of attaining the best possible balance between noise and other relevant socio-economic factors. Applying the principles of the Industrial Noise Policy at the planning stage can avoid future land use conflicts over noise.

A strategic approach

The INP recognises the issues associated with assessing noise in developing areas in Section 2.2.4. The policy states:
"Where several developments are proposed for an area, these are to be assessed as a group. This holistic approach allows project specific noise levels to be set for a proposed industrial development, so that the total impact from all proposed and potential developments does not cause amenity to deteriorate. In addition, this approach provides an equitable distribution in the burden of meeting the noise criteria."(NSW EPA, 2000).

Typically when a new industrial estate is proposed, planning studies are carried out and a planning instrument is released. This could be in the form of a Masterplan, Precinct Plan or Development Control Plan. These documents often specify the new land use zonings for the area, the permitted types of development for the zone and various other requirements.

In developing the noise control requirements for the new industrial estate, a strategic approach can be set out within the planning instrument. Several strategic approaches that have been used in the past are discussed below.

The Ingleburn Noise Management Approach

The State Pollution Control Commission in consultation with Campbelltown City Council, the Department of Environment and Planning and Macarthur Development Corporation developed the Ingleburn Noise Management Approach in 1987.

The Ingleburn Industrial Estate was located on an area of relatively flat topography with residential areas to the south east and north west. The estate provided allotments of various sizes for a full range of industry including many heavy industrial developments. These developments had the potential to generate significant levels of noise.

The Ingleburn Approach to managing noise from new industrial developments was established prior to commencement of development of the estate and aimed to:

- avoid rapid build up of ambient noise,
- reduce confusion about the existing background noise levels; and
- provide a uniform planning strategy.

The Ingleburn Approach essentially sets out equal day and night L_{10} noise limits at the residential receiver for all new industrial sites. The Ingleburn Approach also sets out industrial boundary noise limits for all sites in order to protect the amenity of adjacent sites. The noise limits to be achieved at the receivers were determined based on the following methodology:

1. Background noise levels were assessed at several points within the residential areas.
2. Noise objectives were determined for each sensitive area based on the measured background noise levels and the guidelines presented in the Environmental Noise Control Manual (NSW EPA, 1994).
3. The noise limits were then divided equally by the number of sites proposed for the estate. For example; we can assume a total noise objective of say, 40 dB(A) at the residential area from say, 10 sites. If the allowable noise limit for each of the 10 sites is set at 30 dB(A) at the residential area, the combined level will equal 40 dB(A).

As industrial sites closer to the residential area have the same noise limit as those industrial sites further away from residences, this allows greater noise to be generated by the more distant industrial sites. Therefore, the approach indirectly encourages more noise intensive industries to locate further from the residential areas. The Ingleburn Approach was developed by Campbelltown City Council for use during the assessment of development applications. Proponents for individual developments were required to submit noise impact assessments that determined compliance with the noise limits. The Ingleburn Approach is one way in which the principles of the Industrial Noise Policy (ie: to protect against intrusive noise and maintain amenity) may be achieved.

The Steel River approach

The Steel River industrial estate near Newcastle adopted a different approach to managing noise. Initially, Newcastle City Council developed a Local Environmental Plan for the estate. The LEP established appropriate noise levels at the residential areas surrounding the estate. A noise model of the industrial estate and surrounding receivers was then developed. The noise model was developed and maintained by the Industrial Estate management.

In the initial stages, a noise emission level was attributed to each industrial site in the model. As a development application is lodged for each site, the predicted noise emissions from the site are included in the model to determine whether the receiver noise objectives remain satisfied.

Once each site becomes operational, compliance studies are undertaken to confirm the actual noise emission from the site. The model manager can then update the model with the actual noise emissions from existing developments to supersede the estimated noise levels attributed to each site prior to development of the estate.

This approach has the advantage of facilitating a greater range of noise emissions across the estate. There is a risk however where several noise intensive sites are developed in the initial stages of the estate. The remaining sites will need to meet substantially lower noise limits to compensate. Such a constraint may have an adverse impact on the value of those remaining sites.

After the estate is fully developed, it can be anticipated that the activities on each site will develop and change over time. Each new development application will need to be assessed against the changing noise environment of the estate to ensure ongoing compliance with noise goals. This methodology therefore requires management of a noise model and distribution of the noise limits throughout the life of the estate. This requirement may require significant resources for the consent authority.

The Greystanes approach

Boral currently operates a hard rock quarry at Greystanes. The quarrying activities are nearing completion and therefore Boral proposes to redevelop the land for residential and industrial uses. The Department of Urban Affairs and Planning has recently approved a precinct plan for the site (Boral Resources NSW, 2001), which includes a proactive approach to noise control for the industrial component of the development. This component includes approximately 16 – 20 large industrial sites. The residential component will be located next to the industrial sites, however, there is a significant ridge line that provides acoustic shielding of noise emissions towards the residential area.

The approach that was adopted to deal with noise control for the industrial component at the Greystanes site can be summarised as follows:

1. Appropriate amenity noise levels were determined for the residential area. The Industrial Noise Policy's “suburban” amenity area category noise levels of 55 dB(A), 45 dB(A) and 40 dB(A) levels for day, evening and night respectively were adopted.
2. The industrial land was divided into 5 zones,
3. A noise limit for each zone that applies at the nearest residential area was then determined based on an optimised noise model of the site. The combined limits for all five zones complied with the adopted noise objectives for the residential area,

4. The total number of sites in each zone will be between 2 and 5. Noise assessments included with the development application for each site will need to ensure compliance with the intrusiveness criterion presented in the INP as well as compliance with the noise limit for the particular zone,
5. Council will advise proponents of the existing noise limits for any site's already operating within the zone.

The approach aims to minimise the potential for exceedance of the amenity goals, allow for a more equitable share of the noise "budget" and allow some flexibility to the land developer.

The Greystanes approach combines aspects of the approaches adopted at Ingleburn and Steel River. The planned approach initially adopted for Ingleburn has been undertaken with amenity noise limits specified for several zones. However, noise limits for individual allotments as specified in the Ingleburn approach have not been set for Greystanes. Cumulative assessment of the noise from each development within each zone will be carried out similar to that undertaken for Steel River. However, the number of sites within each zone is limited and therefore, there is no requirement for the consent authority or an estate manager to manage a detailed noise model of the site to control cumulative impacts.

Advantages and disadvantages

The approaches outlined in this paper have advantages and disadvantages. These are summarised in Table 1.

Conclusions

Based on a review of the approaches presented in this paper and the discussion of the advantages and disadvantages of each, no particular approach can be specified for all future industrial estates. The appropriate approach for each new industrial estate will be site specific. It is clear that several factors should be considered in developing a strategic approach. Some of these are:

- Type of development envisaged,
- Separation between the industrial and residential areas,
- Existing background noise levels in the residential area,
- Availability of resources to manage a noise model over the life of the estate,
- The need for flexibility in the development of the estate.

In the future the development of noise modelling and mapping techniques may provide opportunities for improved assessment of noise emissions from industrial estates. As this technology and our understanding of noise prediction improves, the requirement to manage a noise model such as that adopted for Steel River may be less resource intensive.

Setting noise limits for each individual site, such as the approach adopted at Ingleburn, may provide for more straightforward development assessment for the consent authority and the least risk that residential noise limits will be exceeded. However, this method does not provide for the redistribution of allowable noise if "quiet" developments do not use their allowable limit. An approach that provides some flexibility for the redistribution of allowable noise may encourage a greater range of development within the estate.

Whilst this paper does not specify a particular approach to managing noise for new industrial estates, the benefits of adopting a strategic approach in the initial planning for the new estate are considered to outweigh a reactionary approach during the development assessment stage.

References

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2. NSW EPA, "NSW Industrial Noise Policy", Environment Protection Authority, 2000.
3. Boral Resources Ltd, "Greystanes Estate Precinct Plan", Boral Resources Ltd, 2001.

Table 1: Potential advantages and disadvantages of each approach

Approach	Advantages	Disadvantages
Ingleburn (Noise limits for each individual allotment established up front)	• No requirement for background noise analysis for each development application • More straightforward noise impact assessment for developers and Council • Greater certainty for potential developers • Least risk of acceptable residential noise levels being exceeded.	• Where a development does not use all of the allowable noise limit, the remaining noise component of the limit is not redistributed • May limit the development of noise intensive sites • Individual site allotments numbers and sizes must be known
Steel River (Noise model developed and managed with noise emissions from each new development inserted to the model as the development application is lodged)	• Greatest flexibility for the development of the site • All of the acceptable residential noise level can be utilized.	• Estate manager or consent authority required to develop and manage the noise model throughout the life of the estate. • Initial sites may exhaust all of the allowable residential noise level. This may result in restricted development types for future sites or requests to raise the allowable residential noise level.
Greystanes (Industrial area divided into zones. Noise emissions from all sites within each zone must comply with the zone limit)	• Some flexibility for the development of the land. • Some opportunity to share the noise within the zone. • Simplified noise assessment process as the zone limits have been established.	• Some residual risk that initial sites within a zone may use the entire allowable zone limit. However, this risk is significantly reduced.

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THE NEW NOISE (ENVIRONMENT PROTECTION) POLICY IN SOUTH AUSTRALIA

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Abstract
Virtually all processes generate noise - it is an inherent part of most residential, commercial and industrial activity. The response to noise by different individuals can be as wide and varied as the number of activities that produce it. Environmental noise policies attempt to strike the balance between the inherent nature of the production of noise and the need to protect the surrounding community from its potentially adverse effects. A new noise policy is currently being drafted in South Australia that will replace the existing policies that have effectively been in place for over 20 years. The scope of the policy is to address both general and specific sources that generate noise on domestic, commercial and industrial premises, ranging from residential airconditioning units and burglar alarms, wineries, frost fans, bird scaring devices, motor vehicle repair shops and shopping centres through to full scale manufacturing and processing facilities. As well as providing an up to date response to noise issues in consideration of, amongst other things, the World Health Organisation study into community noise effects on health, the new noise policy is intended to provide clarity and transparency for industry, local government, planning authorities, enforcement officers and the community. The following paper presents an overview of the proposed scope, general provisions and specific assessment criteria that have been developed for inclusion into the new policy.

Introduction

The South Australian Environment Protection Authority (EP Authority) is developing a draft Environment Protection (Noise) Policy (EPP) to provide a consistent regulatory framework for the protection of South Australia's environment, according to the principles of ecologically sustainable development outlined in the objects of the (SA) *Environment Protection Act 1993.*

The EPP is currently being drafted by Parliamentary Counsel and, subject to review of the draft by the EP Authority, is due to be released for public consultation in early 2002.

This paper discusses the broad provisions of the proposed policy. It should be noted it is expected that some of these provisions will change due to the ensuing comprehensive review and consultation process.

An EPP is one of a number of legislative tools provided by the (SA) EP Act to address environment protection matters. It can be made for any purpose directed towards securing the objects of that Act. An EPP is laid before both Houses of Parliament.

The proposed noise policy will replace the two current Environment Protection Policies relating to noise in South Australia, the *Environment Protection (Industrial Noise) Policy 1994*, and the *Environment Protection (Machine Noise) Policy 1994.*

The two current policies, based on the repealed *Noise Control Act 1977,* incorporate outmoded technical criteria and deficiencies in applying the principles of ecologically sustainable development. This is particularly evident when considering the increasing interaction between rural living and primary industry activities, and the increasing mix of activities in the central business districts of our cities.

General provisions of the noise policy

The EPP addresses both general and specific noise sources associated with domestic, commercial and industrial premises. The general and specific noise sources range from residential airconditioning units, burglar alarms, wineries, frost fans, bird scaring devices, motor vehicle repair shops and shopping centres through to full scale manufacturing and processing facilities.

The general approach of the policy is to specify goal noise levels that are adjusted according to the amenity of the locality.

The amenity of the locality is provided by the Development Plan/s for that area. The Development Plans are administered by planning authorities, typically being the local council. The plans set the rules for the type of development that can gain approval in that area.

The direct link between enforcement legislation (the *Environment Protection Act 1993*) and development legislation (the *Development Act 1993*) in an EPP is considered an important feature.

An advantage of such an approach is that it promotes assurance for developers that any environmental noise issues that arise post construction are dealt with in a manner that is consistent with the development approval process.

Goal Noise Levels

The goal levels provide protection for the community from the adverse impacts of environmental noise. The levels for residential amenity are based on the recently completed World Health Organisation (WHO) study[1] on, amongst other things, the effects of noise on physical and mental health as a result of long term annoyance and prolonged disturbance to sleep.

The policy adjusts the goal levels, and therefore the level of protection, to suit the range of amenity that results from the mixture of commercial and industrial activities within and adjacent to the residential portion of a community.

It is proposed to specify goal noise levels that correspond to seven categories of varying amenity ranging from rural living to special industry.

Where a Development Plan intends for an area to comprise a mixture of uses corresponding to these broad categories (such as a mixture of commercial and residential uses), the EPP sets the resultant goal level as the average of the levels assigned to the individual uses.

The change in amenity that occurs at the interface of two areas (such as where an industrial area meets a residential area) is also recognised by the EPP. As for an area that is a mixture of uses, the EPP sets the resultant goal levels as the average of those levels assigned to the individual areas.

The result of allowing averaging across the categories is a substantial increase in the range of areas that can be assigned an appropriate goal level by the EPP. The number of categories available under the existing policies is 6, whereas the proposed EPP provides in excess of 20.

The seven broad classifications and the associated goal levels proposed for the EPP are provided in Table 1

Table 1 Goal Noise Levels

Amenity category	Day - dB(A)	Night – dB(A)
Rural living	47	40
Urban residential	52	45
Light Industry	58	50
Intensive Primary Industry	60	50
Commercial	65	55
General industry	65	60
Special industry	70	70

The night time period is taken to be 10pm to 7am.

Factors for assessment

The EPP provides guidance on the factors that the EP Authority must have regard to in assessing and resolving a particular matter where the goal levels have been exceeded.

The factors include, amongst other things:
(a) the practicable noise reduction measures that are available to the noise source;
(b) the financial implications of those measures;
(c) how those measures relate to current technology and industry practice;
(d) the amount by which the goal levels are exceeded;
(e) the duration and frequency of occurrence that the noise exceeds the goal levels;
(f) the duration of existence of the specific activity generating noise; and
(g) the social and economic benefit of the noise source.

Given consideration of the broad range of factors, it is possible for a site to generate noise levels in excess of the goal and be considered to have secured compliance with the *Environment Protection Act 1993*. The goal levels are therefore not used as a mandatory target but as a "trigger" to investigate a noise complaint further.

Where the goal levels are exceeded, identification of the practicable noise measures is fundamental to compliance with the EP Act.

At times where the practicable noise reduction measures available to the noise source are not obvious, the EP Authority will generally require an independent acoustic engineer to determine those measures for a specific site. An independent acoustic engineer is defined by the EP Authority as one who is eligible for membership of both the Institution of Engineers, Australia and the Australian Acoustical Society.

Development Applications

The control of noise issues is most appropriately achieved at the development application stage due to the relative difficulty involved in the assessment and resolution of an existing situation, and the increased capital expenditure in incorporating in situ noise reduction measures.

The EPP will therefore specify the general assessment method for development applications referred to the EP Authority. The existing policies generally only apply to the assessment of existing situations, and the extension of the new EPP to consider development applications is seen as an important feature.

The provisions will be consistent with the assessment procedure for existing situations with the exception that the goal levels will be 5dB(A) lower to account for the increased sensitivity of the receiver in planning situations and the cumulative effect of possible future development on and adjacent the development site.

Specific activities

In addition to a general approach, assessment criteria have been developed for the following activities to more clearly define the specific characteristics for appropriate assessment:

(a) frost fans
(b) bird scaring devices
(c) construction sites
(d) residential premises
(e) local government infrastructure services (such as garbage collection and street sweeping)
(f) building intruder alarms.

Of these, the use of frost fans and bird scaring devices are the most topical in South Australia. The increased use of these devices, particularly in the rapidly expanding wine industry, and an increasing desire to reside in and adjacent to wine regions, has seen a need to develop assessment criteria for their use.

The criteria attempt to strike the balance between primary production methods and their impact on neighbouring properties. In an approach that is consistent with the general section of the EPP, this balance is adjusted according to the amenity of the locality. The frost fan noise criteria are discussed in further detail:

Frost Fans

In developing criteria for the operation of frost fans the following factors were considered:

(a) The intermittent operation of the fans
(b) The restriction of their operation to the early morning hours
(c) The effectiveness of frost fans compared to other forms of frost control
(d) The potential economic benefits for primary producers
(e) The limit of practicable noise reduction measures available
(f) The potential for environmental nuisance over a large area

The recommended goal noise levels developed in consideration of the above are:

Table 2 Frost Fan Goal Noise Levels

Amenity category	**Outside - dB(A)**	**Inside – dB(A)**
Rural living	45	25
Intensive Primary Industry	55	35

The amenity that is to be protected due to the specific characteristics of frost fan operation is that associated with the internal environment (sleep disturbance).

The inside levels are derived from the range of levels delivered by sleep disturbance studies with a 5 dB(A) allowance for the cumulative effect of a number of frost fan installations. Achieving the inside levels are the basis for compliance.

The outside levels are only listed in the EPP given the greater ease for measurement and prediction of noise levels outside of a dwelling. They are based on testing that indicates a minimum reduction of 20 dB(A) can be expected through a typical residential facade exposed to frost fan noise. This means that compliance with the outside levels implies compliance with the inside levels.

It should also be noted that where the inside levels are achieved, the outside levels can be exceeded.

Summary

The new noise EPP in South Australia is intended to provide clarity and transparency for industry, local government, planning authorities, enforcement officers and the community.

The essential feature is the development of a link between the South Australian *Environment Protection Act 1993* and the *Development Act 1993*. This link is provided by the EPP assigning goal noise levels that reflect the amenity of a locality defined by the relevant Development Plan.

References

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EXPERIENCES IN PLANNING FOR NOISE CONTROL IN QUEENSLAND

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Abstract
Since the Noise Abatement Act was introduced in 1978, there have been important changes in environmental noise legislation in Queensland. The paper describes experience gained in working with the legislation over a period of 20 years. It gives examples on the setting of noise conditions on licences and orders and decribes some of the difficulties encountered.

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REVIEW OF THE WA ENVIRONMENTAL NOISE REGULATIONS

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Abstract

The Environmental Protection (Noise) Regulations 1997 *have been in force in Western Australia for almost 4 years. A statutory review of the operation and effectiveness of the regulations, conducted in 1999, concluded that, while the regulations were generally working well, there were areas where possible amendments should be considered. A follow-up report by a series of Working Groups, set up in 2000 to identify possible amendments to improve the regulations, was released early in 2001, and some amendments are now being developed.*

This paper will briefly outline the regulations themselves and the outcomes of the statutory review of 1999, with reference to the results of a survey of officers using the regulations. The progress of the Working Group program in 2000 and the current amendments will be discussed.

Introduction

The *Environmental Protection (Noise) Regulations 1997* were introduced in Western Australia in 1997 under the *Environmental Protection Act 1986,* following a long consultative process. A statutory review of the operation and effectiveness of the regulations was required to be carried out within 2 years of gazettal, and was completed in 1999. The review consisted of a public comment period and requests for the views of Inspectors and local governments (who administer the regulations under delegated powers); acoustical and environmental consultants and the AAS; relevant government agencies; peak industry associations and some known affected individuals. The Inspectors were asked to complete a survey form seeking their reactions to the regulations as a whole and to specific regulations, while local governments were asked to fill in a noise complaints survey form.

The review report prepared by the Department of Environmental Protection (DEP) contained a summary of the regulatory activity which had taken place under the regulations, discussion of the issues raised in public submissions, results of the Inspector and local government surveys and recommendations for possible amendments to the regulations. Following the

1999 review, a series of working groups were established in 2000 to progress these amendments, and these groups reported to the EPA in June 2000.

The regulations

The noise regulations draw their power from section 51 of the *Environmental Protection Act 1986* ("the Act"). The regulations deal with noise passing from one premises to another, including between units in a block of units. Noise from public places is treated in the same way as noise from a premises, with the noise emitter being treated as the occupier. The regulations do not cover the propulsion and braking systems of vehicles travelling on roads, aircraft, trains or emergency warning devices which are required under other laws.

The regulations are structured around two distinct strategies:

- Assigned noise levels -

  Regulations 7 - 10 specify assigned, or permitted, noise levels which apply generally unless specifically overridden by other provisions. These noise levels are designed to provide a good level of noise amenity for occupiers of noise-sensitive premises and commercial and industrial premises. Regulations 19 - 23 and Schedules 1, 3 and 4 provide the supporting provisions relating to measurement procedures and so on.

  The assigned levels for noise-sensitive premises are determined by reference to a table of base $L_{A\,10}$, $L_{A\,1}$ and $L_{A\,max}$ noise levels, to which is added an Influencing Factor (IF). The IF is determined by drawing two circles, 100m and 450m in radius around the receiving point and calculating the percentages of land zoned for Industrial and Commercial use within the circles. The IF increases by 1dB for each 10% that is Industrial, and for each 20% that is Commercial. The IF also includes a Transport Factor of 2, 4 or 6 dB depending on the traffic flow on the major and secondary roads within the circles. The base assigned levels are shown in Table 1.

- Special regulations -

  The special regulations (regulations 11 - 18) recognise a range of economic, cultural and social activities which may occur at levels higher than the assigned levels from time to time without resulting in undue disturbance. These regulations cover blasting, farming vehicles, construction sites, residential premises, bellringing and calls to worship, specified community activities such as crowds at sporting fixtures, and approved non-complying events such as outdoor concerts. Regulation 17 allows a person who considers that they cannot reasonably or practicably comply with the assigned levels to apply to the Minister for approval to vary their noise emissions from the assigned levels.

For the most part, the regulations are enforced by Environmental Health Officers from local governments who are appointed as Inspectors and Authorised Persons under the Act. Noise emissions from premises which are licensed or registered under the Act are dealt with by Department of Environmental Protection (DEP) Inspectors.

Regulatory activity

The local government complaints survey showed that the regulations had been in consistent use. For the period 1 July 1998 to 30 June 1999, the total number of noise complaints handled by all local governments (LGAs) was estimated to be 4100, with 90% of these being in the metropolitan or large country LGAs. This corresponds to 2.7 complaints for each 1000 persons in the metropolitan and large country LGAs and 1.1 complaints per 1000 people in country shires. Reference to the regulations (written or oral) was made in almost 90% of the complaints and sound level measurements were needed in about one quarter of the complaints.

There was a considerable level of other activity under the regulations, including the running of 15 training courses for Inspectors in the first half of 1998; development of a draft EPA Guidance Statement to assist those involved in assessment of proposals to demonstrate that compliance with the regulations could be achieved; and the issuing of a number of approvals for construction sites (7) and outdoor events such as concerts (25). Delegated powers have since been granted to local governments to further their implementation of certain regulations. There was limited enforcement action in the first 2 years of the regulations, including 7 pollution abatement notices and only one prosecution.

A total of 18 applications for Ministerial variations to assigned levels had been received under regulation 17 at the time of the review. Because of legal difficulties with the regulation, only one of these had progressed to gazettal at the time of the review, and since then only one further approval has been gazetted.

Results of Inspectors questionnaire

The survey of Inspectors produced a total of 97 responses from some 258 local government and DEP Inspectors across the State. On a series of 5-point scales, over 90% rated the training course and manual provided by the DEP as Good or Excellent; and two thirds rated their ability to enforce the regulations as Good or Excellent. In comparing the *operation* of the new regulations with the old ones, 40% rated the new regulations Much Better and 37% A Bit Better. In comparing their *effectiveness*, 54% rated the new regulations Much Better, while 33% rated the new regulations A Bit Better.

In comparing the regulations with other regulations which they administer, 56% rated the noise regulations About The Same and 39% A Bit Better or Much Better. In dealing with complaints 69% had used the regulations Often; in setting noise levels for planning 18% had used the regulations Often; and in evaluating proposals 20% had used the regulations Often. About 75% said they had “Rarely or Never” come across a problem which the regulations didn’t cover or which couldn’t be resolved under the regulations.

In relation to the specific regulations, the Inspectors were asked to rate each regulation for Ease of Use; Ease of Explanation to the Public; Time and Resources Needed; Practicality; Control Strategy Provided; Success in Reducing Noise; Fairness of Outcome; and Enforceability, on a 5-point scale from “Excellent” to “Very Poor”. Overall, the most common rating was Very Good, the exceptions being regulations 10 and 16, which had been little used, being rated Neither Good nor Poor. Regulations 13 (construction sites) and 14 (residential premises) received the most comments by Inspectors, mostly in the “Good” category. The results for regulation 14 are shown in Table 2 by way of example.

It was concluded that the Inspectors had given the regulations a high rating overall.

Response to call for public submissions

A total of 40 public submissions were received in response to the call for submissions and letters of request. The general tenor of these submissions was that the body of the regulations is accepted as being operationally workable and effective. A number of noise issues which are not covered well by the regulations were identified as requiring further work to develop special provisions for inclusion in the regulations. These include noise from essential services including garbage collection and emergency services, motor sports, shooting ranges, small community entertainment events, low frequency noise, special noise level zones and audible alarms. The report recommended that these "new work areas" be investigated with a view to the development of special provisions for inclusion in the regulations. A series of 17 amendments to improve the operation and effectiveness of specific regulations were also identified. The review report recommended that any necessary additions or amendments to the regulations be progressed through a series of small expert working groups, to report to the EPA by 30 June 2000.

The area which attracted most criticism in the submissions was the regulation 17 approvals for persons who believe that they cannot reasonably or practicably comply with the assigned noise levels. In all cases, the criticism was that the progress with applications was far too slow, only one having been approved at the time of the review. This was seen in the review report as being in part an issue of process and in part a resourcing issue. The resourcing issue was addressed in the recommendations and it was proposed that the backlog of applications could be cleared by October 2000.

The other recommendations dealt with issues of enforcement, information and guidance.

The way forward?

Since the time of the 1999 review, a working group program has been developed, with 14 representative groups being formed early in 2000 to consider the recommendation of the 1999 review report. The June 2000 report of the working groups to the EPA recommended a two-stage process of amendments, including some 20 short-term amendments to the regulations and 6 longer-term amendments.

A small group of 4 simple amendments was promulgated in late 2000 and, following a State election early in 2001, approval has been given by the new Minister for the Environment to proceed with the drafting of the short-term amendments. The DEP has now committed extra resources to the issue of the ongoing backlog of regulation 17 applications. Further, more detailed, surveys of local noise complaints are being undertaken to enable the sources of complaints to be better identified and proactive strategies to be developed to address them.

Clearly, Western Australia has an effective set of environmental noise regulations which have received wide general acceptance. The review process has been effective in identifying the areas where improvements are needed, and in eliciting the views of stakeholders. The challenge is to resist the temptation to over-complicate the regulations during the amendment process, and to ensure that the amended regulations retain technical soundness while incorporating the various social, economic and political requirements of our community.

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The author acknowledges the assistance of Peter Popoff-Asotoff of the DEP in processing the survey results.

Table 1 Assigned Noise Levels

Type of premises receiving noise	Time of day	Assigned level (dB)		
		L_{A10}	L_{A1}	$L_{A\ max}$
Noise sensitive premises - at locations within 15 metres of a building directly associated with a noise sensitive use	0700 to 1900 hours Monday to Saturday	45 + influencing factor	55 + influencing factor	65 + influencing factor
	0900 to 1900 hours Sunday and public holidays	40 + influencing factor	50 + influencing factor	65 + influencing factor
	1900 to 2200 hours all days	40 + influencing factor	50 + influencing factor	55 + influencing factor
	2200 hours on any day to 0700 hours Monday to Saturday and 0900 hours Sunday and public holidays	35 + influencing factor	45 + influencing factor	55 + influencing factor
Noise sensitive premises - at locations further than 15 metres from a building directly associated with a noise sensitive use	All hours	60	75	80
Commercial premises	All hours	60	75	80
Industrial and utility premises	All hours	65	80	90

Table 2 Responses to Inspector Survey – Regulation 14

Question	Number of responses to question	Distribution of total responses				
		Excellent	Very good	Neither good nor poor	Poor	Very Poor
ease of use	73	16	**45**	9	3	0
ease of explanation to public	73	5	**57**	6	3	2
time and resources needed	73	2	**48**	20	2	1
practicality	69	13	**44**	7	4	1
control strategy provided	61	3	**44**	10	4	0
success in reducing noise	73	2	**36**	29	5	1
fairness of outcome	73	15	**31**	7	20	0
enforceability	71	12	21	**28**	8	2

Note: Regulation 14 permits noise emissions from the use of "specified equipment" (any equipment which requires the constant presence of an operator for normal use) on residential premises to exceed the assigned levels provided it is used in a reasonable manner; between certain hours; for less than a specified time; and its use does not unreasonably interfere with the neighbours.

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OCCUPATIONAL NOISE POLICY – OVERVIEW OF STATE, NATIONAL AND INTERNATIONAL INITIATIVES

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Abstract
The National Standard for Occupational Noise was amended in 2000 to update it technically by referring to the 1998 edition of AS/NZS 1269 and changing the weighting of the peak noise level from linear to C-weighting. This paper summarizes the extent to which the Australian States and Territories have adopted the National Standard into legislation. The work of the National Occupational Health and Safety Commission Noise Standard Network is explained along with its recent recommendations for expanding the scope of the National Standard. Initiatives in occupational noise control in various states and overseas are also discussed.

Introduction

In the 1990s a major revision of the Australian Standard dealing with hearing conservation was undertaken, culminating in the publishing in 1998 of the 5-part AS/NZS 1269[1]. This comprehensive series of documents shifted the emphasis from hearing protection and audiometric programmes to controlling workplace noise in a managed way, reflected in the series title 'Occupational noise management'. It also updated technical aspects of noise assessments, importantly introducing new requirements for daily noise exposure level calculations for people working 10 or more hours per day. It also gave the option of measuring peak noise levels with C-weighting.

The National Standard for Occupational Noise[2], originally declared by the National Occupational Safety and Health Commission (NOHSC) in 1993, referenced the earlier version of AS 1269 in the definition of $L_{Aeq,8h}$. Other references to AS 1269 were made in the accompanying Code of Practice for Noise Management and Protection of Hearing at Work[3].

In November 2000, after a period of public comment, the National Standard and National Code[4] were amended to refer to the 1998 AS/NZS 1269 and also to make the technical change to a C-weighted peak noise level. This latter change was deemed necessary to obtain greater consistency in results when measuring impulsive noise with different meters and aligns with similar moves in Europe and USA and in International Standards for sound level meters.

Regulation for Noise Exposure

The National Standard exposure to noise in the occupational environment is an eight-hour equivalent continuous A-weighted sound pressure level, $L_{Aeq,8h}$, of 85dB(A). For peak noise the national standard is a C-weighted peak sound pressure level, $L_{C,peak}$, of 140 dB(C).

The National Standard in itself does not have any legislative force. In Australia each State, Territory and the Commonwealth jurisdiction has its own legislation for occupation health and safety. National Standards and Codes are declared as guidance and encouragement for a uniform approach across the Nation. However there is no compulsion on jurisdictions to take up the National Standards. Some jurisdictions have automatic update to the latest version of any Australian Standard referenced in their legislation, while others require an amendment.

Table 1 summarizes the take-up of the National Standard for Occupational Noise.

Table 1 Australian Jurisdiction Take-up of National Standard
(as at 30 September 2001)

Jurisdiction		Take-up of National Standard
ACT		Has no regulations on occupational noise. Approved the National Standard and National Code as a code of practice on 1 March 2001. Recommendations to create regulations based on the National Standard are expected in 2002.
Cmth		Occupational Health and Safety (Commonwealth Employment)(National Standards) Regulations 1994 (Part 3 – Occupational Noise).
		Changed to a C-weighted peak exposure standard on 1 November 2000. Commission has agreed to update reference to AS/NZS 1269:1998 and amendment is presently being drafted.
NSW	(i)	Occupational Health and Safety Regulation 2001 (Part 4.3, Div 4 : Noise management)
		Changed to C-weighted peak and reference to AS/NZS 1269:1998 on 1 September 2001. AS/NZS 1269:1998 is also listed as a Guidance Note.
	(ii)	Mines Inspection General Rule 2000 (Clause 43)
		Changed to C-weighted peak and reference to AS/NZS 1269:1998 in August 2000.
	(iii)	There are no regulations on occupational noise for coal and shale mines. The government is presently reviewing the Coal Mines Regulation Act and it is likely that regulations similar to those in the minerals sector will be developed in 2002/03.
NT	(i)	Work Health (Occupational Health and Safety) Regulations 1992 (Reg 56 : Noise)
		Will be reviewed in early 2002 with regard to the National Standard.

NT	(ii)	The Mine Management Regulations (including Reg 16 : Noise) are soon to be repealed. The soon to be gazetted Mining Management Act 2001 will not have regulations for occupational health and safety issues, but rely on duty of care, Australian Standards and NSW guidelines.
	(iii)	Petroleum (Occupational Health and Safety) Regulations (Reg 39 : Noise) No discussions for changes to C-weighting at the moment, but will probably change when the Work Health regulations do, if the Commonwealth hasn't taken back responsibility by then.
QLD	(i)	Workplace Health and Safety Regulation 1997 (Part 10 : Noise). Presently assessing the impact of a change to C-weighted peaks and AS/NZS 1269:1998.
	(ii)	Mining and Quarrying Safety and Health Regulation 2001 (Schedule 4) Refers directly to the National Standard for Occupational Noise. As no year is quoted the latest version is assumed to apply (Covers coal and minerals).
SA		Occupational Health, Safety and Welfare Regulations 1995, (Div 2.10 – Noise) Still has a 90 dB(A) $L_{Aeq,8h}$ exposure standard for existing workplaces. There are presently no plans to change this. Changes to a C-weighted peak and reference to AS/NZS 1269:1998 will be considered with changes to other regulations at a later date (These regulations also cover mines).
TAS		Workplace Health and Safety Regulations 1998 (Part 4, Div 4 : Noise). Will consider an update to the C-weighted peak when amendments to other regulations are needed (not this year). The most recent version of any Australian Standard called up in regulations applies (These regulations also cover mines). The revised National Code is a document that must be considered in assessing and controlling noise risks (Reg 17(2)(b)).
VIC	(i)	Occupational Health and Safety (Noise) Regulations 1992. The use of the revised National Standard and Code is being considered during the process for developing new regulations for noise, which are due by February 2003.
	(ii)	Mineral Resources (Health and Safety) Regulations 1991 (Reg 2.45 : Noise Control). No plans to update these regulations as they are due to "sunset" soon and mines will then come under the OHS legislation.

WA	(i)	Occupational Safety and Health Regulations 1996 (Part 3, Div 4 : Noise control and hearing protection). Amended to refer to AS/NZS 1269:1998 in December 1999. The change to C-weighted peak has been agreed to by the Commission and Minister and an amendment is currently being drafted. A revised Code of Practice adapted from the National Code is currently being finalized.
	(ii)	Mines Safety Inspection Regulations 1995 (Part 7, Div 1 : Noise Control) (covers coal and minerals) The most recent version of any Australian Standard called up in regulations applies. There are presently no plans to change to a C-weighted peak.
	(iii)	Petroleum Act 1967 and Petroleum (Submerged Lands)Act 1982 Have no specific regulations on noise – rely on general duty of care.

Workers' Compensation for Noise Induced Hearing Loss

During the last ten years the various jurisdictions have curbed the number of noise-induced hearing loss claims by introducing thresholds for percentage loss of hearing which have to be attained before a claim is valid (Table 2) and more closely controlling audiometric testing and analysis procedures.

Table 2 Thresholds for Percentage Loss of Hearing Used in each Jurisdiction

Jurisdiction	Threshold PLH
Cmth (+ Act Gov workers)	20% [New legislation with 5% threshold has been passed, awaiting proclamation]
NSW	6%
NT	Uses American Medical Association Guide to the Evaluation of Permanent Impairment.
QLD	5%
SA	5%
TAS	5%
VIC	7%
WA	10% (note: 10% more than at baseline test)

National Occupational Health and Safety Commission (NOHSC) Initiatives

The NOHSC recognizes noise as one of its priority hazard areas. Last year it set up a Noise Standard Network comprising members from Queensland, New South Wales, Victoria, Western Australia, Australian Capital Territory and Commonwealth OSH government departments and the ACTU and ACCI.

Its task was to review the National Standard and Code for Occupational Noise[4] and make recommendations on areas where work could be undertaken to improve them. The resulting Draft Annual Situation Report for noise is to be presented to the NOHSC in October 2001.

It recommends that the following issues be considered:

- the combined effects of exposures to noise and certain physical or chemical agents;
- the non-auditory effects of noise;
- noise standards for designers and suppliers of machines;
- the effects of infrasound and ultrasound;
- updating the Code in the personal hearing protector, audiometric testing and reference sections; and
- monitoring changes to exposure standards elsewhere in the world, in particular any lowering of the $L_{Aeq,8h}$ level to 80 dB(A) and in the means of assessing impulsive noise.

If NOHSC and the Labour Ministers agree to these priorities a workplan will be drawn up to address them.

The NOHSC also has a series of Noise Control Solutions on its website at:
www.nohsc.gov.au/OHSInformaiton/Databases/OHSSolutions/ohssolutions.htm

Other Recent or Planned State Initiatives in Occupational Noise

WorkCover NSW is starting a project in October 2001 focusing on securing effective management of workplace noise by employers and contractors in the construction industry. An industry seminar will be held on 13 November. This follows on from a research project conducted in 1999/2000 that assessed the main noise activities and extent of compliance with the code of practice in the NSW building industry. (See www.workcover.nsw.gov.au).

WorkSafe Western Australia (DOCEP) is presently carrying out a similar noise inspection project on Western Australian construction sites. It has placed a guidance document 'Noise Management in the Construction Industry : A Practical Approach' and several practical noise control case studies on its website (www.safetyline.wa.gov.au/sub30.htm).
Also available on the website are an extensive 'Directory of Noise and Vibration Control Services', an illustrated lecture on the hierarchy of noise control, a 'Code of Practice for Control of noise in the Music Entertainment Industry' and a report on an inspection project in that industry carried out in 2000.

Queensland's Division of Workplace Health and Safety has also developed an industry guide and carried out inspection projects in the entertainment industry, resulting in two successful prosecutions. A survey of patrons' attitudes to sound levels in entertainment venues is planned, as are studies of noise levels inside and outside abrasive blasting helmets and on high-rise construction sites.

The Victorian WorkCover Authority has noise components in its target industry interventions in the textile, meat, forestry, construction and food industries.

In South Australia grants from the Mining and Quarrying OHS Committee have funded research by the University of South Australia to identify prime noise and vibration sources and control options for quarry machinery. Another grant has funded training on noise and its management to workers at 100 quarries.

Overseas Initiatives

In Europe, political agreement was reached in June 2001 for a new EC Physical Agents (Noise) Directive. This sets a daily noise exposure level limit of 87 dB(A) and peak level limit of 200 Pa (140 dB(C)) which must not be exceeded, but can be achieved with hearing protection; an upper exposure action level of 85 dB(A) and peak action level of 200 Pa (not taking account of hearing protection) which requires a program of technical and organizational measures to reduce exposure, delimiting areas, use of hearing protectors and hearing checks by a doctor; and a lower exposure action level of 80 dB(A) and peak action level of 112 Pa (135 dB(C)) (not taking account of hearing protection) which requires hearing protection to be made available and information and training to be provided.
The Directive is to go to the European Parliament and is expected to be adopted by the end of 2001. Member states will then have 3 years to implement the Directive in legislation.

In the USA it has been found that thousands of construction workers have impaired hearing. In response the Laborers' Health and Safety Fund of North America has started the Construction Noise Control Partnership. It is comprised of trade unions, contractors, public health organisations, government agencies, equipment manufacturers and academics. The Partnership is developing a best practice guide standardized methods for measuring noise and means of communicating results. More information can be found on www.lhsfna.org/html/_noise_partnership.html.

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IF IT'S LOUD, IT'S A PROBLEM;
the effective use of education as a tool in the prevention of noise injury.

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Abstract
We all 'know' that noise in the workplace is an occupational health hazard. We also 'know' that occupational health and safety must be an integral part of any workplace practice or process. Why is it then that workers appear to resist our best efforts to tell them about the problem and to give them obvious solutions for reducing noise exposure levels?

Are we making the correct assumptions and presenting the information in a way that can be accepted by our audience? Initial indicators suggest that some assumptions are inappropriate and that to have an influence on workplace noise exposure we need to adopt a different approach from the conventional education program.

Introduction

In late 1998 National Acoustic Laboratories commenced the *'Local Government Occupational Noise Management Implementation Strategy'* project. This project involved Warringah Council and was funded under the *WorkCover NSW Injury Prevention, Education and Research Grants Scheme*. The aim of the project was "*by the year 2004* [to] *substantially reduce the number and average cost of hearing loss claims submitted by local government workers"*.

In the true spirit of the aim of the project, plans were commenced to produce a 'really good training program' of the typical 'chalk-and-talk' genre. Not long into the project it was realised that most of the local government (council) workers '*sort of knew'* that loud noise was a problem and that '*something should be done by some body'*. But who should do it? Certainly they did not realise that they could take some responsibility or that they needed to or could take any direct action.

On deeper examination it was revealed that very few, if any, individuals, including managers and supervisors, really understood what Occupational Health and Safety was all about, who had what responsibilities and how an OHS system should operate. Hence, before any *noise program* could be developed an even more basic issue required attention, that of the role of OHS and the workplace.

Background

Any perusal of workers' compensation statistics (WorkCover NSW (1997), National Occupational Health and Safety Commission (1998)) will quickly reveal that claims for hearing loss compensation absorb a significant amount of the compensation dollar and represent both a social and financial burden on the workforce. For example in NSW 1995/96 the total gross incurred cost of compensation for hearing loss paid by WorkCover NSW was almost $101m[1]. This figure only includes the direct costs, in the form of a "compensation payout". It does not include any of the incidental costs borne by the worker or by the employer, such as inconvenience and lost time, or any of the social or dislocation costs suffered by the workers, their families or social acquaintances.

Hearing loss compensation is a problem for local government authorities where the incidence of claims is 7.6 per thousand workers compared to the figures of the overall workforce of 2.6 per wage and salary earners[2]. While this is not as high as some sections of the workforce, for example basic metal products manufacturing where in 1994/95 the incidence was 25.9 (WorkCover NSW 1996), it is never-the-less significant and represents a definite financial, social and physical cost to those experiencing the loss.

Current OHS "training"

At some stage individuals working in the area of OHS will have been in the position of "explaining" to a group why it is important to be aware of noise exposure and what the results of excessive noise exposure are likely to be. While it is not always assumed that everyone understands that prolonged exposure to loud noise will cause noise injury, it is usually assumed that everyone understands occupational health and safety in the workplace.

Many courses have been developed for instructing workers as to how they should "conserve their hearing" (for example Worksafe Australia:1991; Work Cover:1997). Unfortunately these training courses do not seem to have the desired impact and compensation expenditure on hearing loss has been steadily growing (WorkCover: 1996).

The original direction of the *'Local Government Occupational Noise Management Implementation Strategy'* project was to develop a "better"

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[1] Note more recent statistics appear to show this figure in decline at around $54k

[2] Statistics Bulletin 1996/97, NSW – personal communication

training course to more closely meet the needs of the target audience. Several focus groups were held with the aim of establishing a starting point and determining the amount of common knowledge that could be assumed for a ‘typical’ group of local government employees (or any employees).

It was soon established that there was a reasonable amount of knowledge concerning noise and its effects on hearing. In fact, collectively almost any group could develop some very practical methods of reducing noise and noise exposure at work. However, there was a lack of understanding of occupational health and safety issues. For example, there was no understanding of the different levels of responsibility that fall on various levels of the workforce, from government, management, supervisors or individuals. The most common conception of OHS was that *“I need to be careful while I’m at work, but if something does go wrong there’ll be a ‘compo’ payout”*.

Thus, what is required in many work places is an introduction to the basics of occupational health and safety with a particular emphasis placed on developing the individual’s understanding of the fundamental concept, responsibilities and outcomes of OHS.

Purdy and Williams (2001) noted that when individuals participated in a work based hearing test programme they had “*enhanced perceptions about the benefits of reducing noise* [exposure]” and that “*these findings indicate that individual worker characteristics need to be considered when designing hearing loss prevention programmes*”.

Why not a workshop?

The results of focus group discussions and the realisation that there was a need for a more basic understanding, led to the development of a workshop style format for training as opposed to the traditional ‘*chalk-and-talk*’ format.

To quote Kroehnert(1991):

> *“**Workshops** may be groups of any size, but … the group would have a common interest or a common background. A workshop is generally conducted so that the participants can improve their ability or understanding by combining study and discussion. Workshops tend to be user driven, that is the participants may influence the direction of the programme at its very beginning.” (p 83)*

For OHS training this is an important point to consider. More often than not the trainer will have some form of tertiary qualifications while the participants may range from basic skill levels to tertiary level. More often than not, however, OHS skill levels will be very basic. For this reason it is important to encourage peer group learning and understanding at the level with which the group is most comfortable. This needs skillful facilitation on the part of the trainer.

Through the use of a workshop we are trying to change an individuals perceptions of their behavioural control of their actions. Not behavioural control in the sense of *behavioural modification* (see Skinner: 1974) but behavioural control in the sense of *self-efficacy* (Bandura: 1997).

Prochaska, diClemente and Norcross (1992) "*determined that efficient self-change depends on doing the right things (processes) at the right time (stages)"* and that *"insight alone does not necessarily bring about behavior change"* (p 1110). However, they also found that "*overt action without insight is likely to lead to temporary change* (p 1111). Basically this means that people need know what action to take when they wish to take it and this must be when they are in a receptive frame of mind. The easiest method of carrying this out is through pier group learning in a workshop environment where individuals can discuss issues with peers under the guidance of a facilitator.

Workshops

In the final format of the developed workshop was divided into two principle sections. The first section is a general discussion concerning OHS in the work place, with the second section taking noise as a specific example of a particular work place hazard.

Section one focuses on a group discussion of what is to be expected in terms of work place health from the point of view of a 'reasonable' person. The concepts discussed and developed are:-

- the role of government regulation;
- the responsibility of employers for providing a safe place of work and safe systems of work;
- the responsibility of managers and supervisors to ensure that safe systems and procedures are in place, complied with and operate satisfactorily;
- the responsibility of employees to implement and follow required safe work procedures and practices; and
- the concept that all of those involved with the work place have a responsibility to report any unsafe procedures, practices or occurrences that could possibly result in injury or risk of injury.

These discussions will typically lead to the form OHS legislation. (For example, in the new New South Wales "*Occupational health and Safety Act 2000", "Part 2 Duties relating to health, safety and welfare at work"* clearly demonstrates the salient points). The outcome of the discussions should be that individuals clearly understand that they can have influence over work place OHS issues and that their input is important.

Section two considers noise in the work place as a specific example of a work place hazard. The discussion encourages participants to think about and develop ways that they can either reduce the noise levels or at least reduce their own noise exposure level. Often individuals with no 'scientific' knowledge develop very effective strategies for reducing noise exposure. They do not require noise metrics or sophisticated measuring equipment, all the knowledge required is that if the noise is loud then there is a potential problem.

Upon completion of the workshop participants should clearly realise that they can have an effect on the outcome of OHS strategies and that their actions can affect individual outcomes. This falls into the area of developing self-efficacy (Bandura: 1997) where individuals have belief in their own "*capabilities to organise and execute the courses of action required to produce given attainments"* (Bandura: 1997, p 3).

Positive outcomes

Examples of noise solutions that come out of these workshops are simple solutions. It is not 'rocket science' or 'brain surgery'.

Suggestions included such actions as:

- moving away from areas of loud noise if there is no reason to be there;
- when given a choice of noisy machines that can do the same task, choose the quietest one;
- if you need to purchase a new machine then specify a quiet one.

Perhaps the best co-operative example came from a group of painters who had the mechanical staff from the repair workshop present. (The best groups include all those individuals who have something to do with the work of the group including line managers, supervisors, repair and maintenance staff)

These painters are frequently required to clean and repaint the internals of public toilet blocks. The wall surface is stripped using a very noisy "water laser". This is powered by a portable pump normally located adjacent to the operator(s). The repair staff suggested lengthening the operating hose such that the pump would be located outside the toilet block. This significantly reduced the noise exposure of the operator(s) and created a safer work place.

Obvious! Yes. Simple! Yes, but it was a solution arrived at by the group after they understood the problem. Was it critical to know by how many dB the exposure level was reduced? By any estimation the reduction would have been significant. The point is that the group solved their problem in a manner that was appropriate for them.

Conclusion

An understanding of the research to date indicates that an effective way of increasing OHS awareness is by the conduction of training through a workshop presentation format. It is not safe to assume that workers have an understanding of OHS and its role in the work place. Before effective training is viable a common starting point must be established and from that basis an OHS frame work can be constructed.

If individuals understand what the problem is and they can have an input to the solution, they are more likely to participate in that solution. So the take home message seems to be, keep it simple. *If its loud, its a problem*.

Projects are currently under way to see how this concept can be further developed and used to enhance workplace OHS and individuals' self-efficacy.

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THE NEED FOR MORE THAN ONE 8-HOUR NOISE LEVEL CRITERION

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Abstract

In NSW the Occupational Health and Safety Regulation 2001 states that "an employer must ensure that appropriate control measures are taken if a person is exposed to noise levels that exceed an 8-hour noise level equivalent to 85 dBA.....". Similar criteria are given in other States of Australia. Although some States have a criterion of 90 dBA, NOHSC National Standard for Occupational Noise [NOHSC: 1007 (2000] gives an exposure limit in the occupational environment for an 8-hour equivalent continuous A-Weighted sound pressure level ($L_{Aeq,\ 8hr}$) of 85 dBA. The criteria give the incorrect impression that an 8-hour noise level equivalent 84.9 dBA is 'safe' (hence no action needs to be taken) and an 8-hour noise level equivalent 85.1 dBA is 'damaging' (hence full action needs to be taken). In Europe the 'Noise Directive 1986' gives 'action levels' where different responsibilities are placed on an employer depending upon the level of risk of hearing damage. This paper examines the Australian and European regulations and suggests a range of action levels based on Australian research into hearing damage risks. Although the range of levels makes the implementation slightly more complex for employers, the author argues that the outcome will result in a greater understanding of the risks involved and ultimately in a reduction of industrial hearing damage.

Introduction

Noise induced hearing loss is an irreversible deafness, which can develop from exposure to high levels of noise. Between 1991 and 1998 the number of NSW workers claiming compensation for deafness has varied between just under 5,000 to over 10,000 per year [1]. In 1995/96 the costs for NSW exceeded $100 million [2]. Although there has been a decline in costs between 1998/99 the cost still exceeds $50 million and deafness accounts for approximately 50% of all occupational diseases [1].

There is an obvious need to reduce the hearing damage to workers and the high costs to industry. This can be achieved in many ways, for example increasing the quality of noise awareness training [3], acknowledging the real performance of hearing protection [4] and a much greater emphasis on noise control at source (see for example references [5] and [6]). In this paper it is considered whether the criteria for noise laid down in official publications sends the right signals to industry to assist in the reduction of occupational hearing loss.

Occupational Noise Policy

In NSW the Occupational Health and Safety (Noise) Regulation 1996 [7] stated that "a place of work is unsafe and a risk to health if any person is exposed there to noise levels that exceed an 8-hour noise level equivalent of 85 dBA….". This has now been replaced with a new NSW Occupational Health and Safety Regulation 2001 [8]. Division 4 states that an employer must ensure that no person is exposed to noise levels that exceed an 8-hour noise level equivalent of 85 dBA. Similar criteria are given in other States of Australia. Although some States have not yet reduced the criterion from 90 dBA, The National Occupational Health & Safety Commission (NOHSC) have issued a National Standard for Occupational Noise [9] which gives an exposure limit in the occupational environment for an 8-hour equivalent continuous A-Weighted sound pressure level ($L_{Aeq,\ 8hr}$) of 85 dBA.

All of the criteria give the incorrect impression that an 8-hour noise level equivalent of less than 85 dBA (say 84.9 dBA!) is *'safe'* (hence no action needs to be taken) and an 8-hour noise level equivalent of more than 85 dBA (say 85.1 dBA!) is *'damaging'* (hence full action needs to be taken).

Background

The USA has a similar Noise Policy [10] but Europe has applied 'action levels' in their Noise Policy since the European Commission (EC) Noise Directive of 1986 [11]. The first action level is at a daily personal noise exposure (8 hour) of 85 dBA and the second action level is at a daily personal noise exposure of 90 dBA (there is also at peak action level at 200 Pa or 140 dB re 20 μPa). Different demands are placed on the employer depending upon the action level.

The 1993 EC proposal for a Physical Agents Directive sought to establish a new framework for the regulation of physical agents at work applying initially to noise, vibration, optical radiation and non-optical electromagnetic fields.

In 1999 the German Presidency put forward a revised proposal limiting the scope of the Directive to vibration (hand-arm and whole body) with the intention of developing further Directives on other physical agents in later, sequential Directives. Following on from the political agreement on the Vibration Directive in November 2000, the Swedish Presidency introduced a proposal for a Noise Directive. This would repeal the existing 1986 Noise Directive implemented, for example, in the UK by the Noise at Work Regulations 1989.

The Swedish Proposal

The main changes in the Swedish proposal to the 1986 Directive were:

- the action values of 90 dB(A) and 85 dB(A) were reduced to a limit value of 85 dB(A) and an action value of 80 dB(A);
- there was a lower action value of 112 Pa for impulse noise instead of 200 Pa;
- health surveillance by or under the responsibility of a doctor was required at 80 dB(A) and 112 Pa;
- hearing protection, which must be worn above 85 dB(A) and 200 Pa, must reduce the risk to below 80 dB(A) and 112 Pa;
- there was no derogation provision from the hearing protection requirements;
- there were no exceptions for sea and air transport.

The UK Proposal

In line with the agreed negotiating strategy, UK negotiators pressed for a more detailed evaluation of the existing 1986 Noise Directive, an updated *'fiche d'impact'* of the proposal and more detailed consultation with the social partners. The European Commission's view was that this had already been undertaken with regard to the Commission's original proposal in 1993 and the UK received no support from other member states. The UK's negotiating strategy was then to reduce the burden of the proposal on industry, in particular by seeking to raise the proposed action values towards those in the 1986 Directive.

The Swedish Presidency pressed ahead rapidly with negotiations in the Council Working Group, which often met at weekly intervals. The Presidency succeeded in reaching political agreement on a common position at the Employment and Social Policy Council on 11 June 2001

Several Member States already operate at the values proposed in the draft Directive, and it was not possible to persuade these and others that the values should be raised. Nevertheless, UK negotiators achieved considerable success, as they saw it, in reducing the burdens on industry implicit in the draft without detracting from the benefits to workers' health. In particular in the UK negotiators view:

- *the limitation on personal noise exposure now allows hearing protection to be taken into account – in the original proposal it appeared to refer to exposure without the use of hearing protection. This means that industry is not restrained in its activities providing it has done its best to reduce noise and that workers wear appropriate hearing protection;*
- *the limitation on personal noise exposure has been agreed at 87 dB(A) rather than 85 dB(A) – a more appropriate level for a prohibition;*
- *hearing protectors are no longer required to reduce the risk to below 80 dB(A). This would have been unnecessary in terms of health benefit and technically difficult to achieve where there were high ambient noise levels;*
- *where noise exposure varies from day to day, it can be averaged over a week rather than over 8 hours. This will concentrate noise control on the areas of risk from continuous exposure and will release many occasionally exposed workers from many of the provisions of the Directive;*
- *the requirement for health surveillance at 80 dB(A) is now a right to hearing checks at 85 dB(A) (as in the existing Directive). This will avoid considerable unnecessary and costly medical intervention;*
- *the limitation of 60 dB(A) on noise in sleeping quarters has been deleted. This would have proved unworkable in certain industries.*
- *derogation powers from wearing hearing protection have been introduced where it conflicts with health and safety.*
- *an extra transposition period of five years from the limit on exposure has been agreed for shipping to enable technical advances in noise exposure to be incorporated in ship design.*

Suggestion for an Australian Policy

The views of the author and suggestion for an Australian Policy are more in line with the Swedish proposal to the 1986 Directive than the UK proposal. A comparison of the proposals is in Appendix A and the suggestion for an Australian Policy is summarised below:

- action values of 80 dB(A), 85 dB(A) and 95 dB(A) are introduced;
- action values of 112 Pa and 200 Pa for impulse noise are introduced;
- health surveillance by or under the responsibility of a doctor is required at 85 dB(A) and 112 Pa;
- hearing protection, which must be worn above 85 dB(A) and 200 Pa, must reduce the risk to below 80 dB(A) and 112 Pa;
- there are no derogation provision from the hearing protection requirements;
- there are no exceptions for sea and air transport after 5 years.

The action level at 95 dBA is a totally new suggestion, not included in any of the overseas Policies. This has developed from research carried out by the author [4] who found that, although theoretically, hearing protectors can give a 30 dB to 35 dB noise reduction in the ear, in practice this is decreased to a maximum of circa 15 dB noise reduction when long-term daily exposure is experienced. This is partly because of the poorer performance of hearing protectors in low frequency noise but mainly due to the time people actually wear earmuffs when in the noise area and the way earplugs are actually fitted. A software program has been developed [14] which allows all of these critical factors to be used to calculate a much more realistic 'in-ear' noise level.

For long-term daily noise exposure (i.e over 6 hours) levels ($L_{Aeq,\ 8hr}$) of 95 dBA or over, hearing protection programs alone cannot be relied upon if hearing impairment is to be kept to not greater than 2 dB for 95 percent of the population at any frequency. This is based on the 80 dBA in-ear exposure level given in the Australian Standard AS/NZS AS/ANZ 1269.4:1998 [13].

Hence an 'action level' at 95 dBA, which requires employers to provide certification for any equipment that has been reduced to the lowest reasonably practicable level. The certification would have to be supplied by a recognized acoustical organization (i.e members of the Australian Acoustical Society or equivalent overseas organization). This action level together with the action levels at 80 dBA and 85 dBA are recommended. This is summarized in the Table below:-

Action Level	Noise Exposure ($L_{Aeq,\ 8hr}$)	Action
1	80 dBA to 85 dBA	Carry out an Assessment; Provide information and training; Make hearing protection available; Place advisory signs in the areas or on equipment where risk occurs;
2	Greater than 85 dBA to 95 dBA	Carry out an Assessment; Provide information and training;; Place mandatory signs and make hearing protection compulsory in the areas or on equipment where risk occurs;
3	Greater than 95 dBA	Carry out an Assessment; Provide information and training; Place mandatory signs and make hearing protection compulsory in the areas or on equipment where risk occurs; Provide certification that equipment has been reduced to the lowest reasonably practicable level. Carry out audiology checks every two years

Conclusions

It is concluded that the single number 8-hour noise level criterion for occupational noise exposure does not send the correct signal to industry to prevent industrial deafness. It is suggested that this is replaced with three action levels, 8-hour equivalent levels of 80 dBA, 85 dBA and 95 dBA. Action levels are used in Europe. An additional action level at 95 dBA, which also requires employers to provide certification for any equipment confirming that it has been reduced to the lowest reasonably practicable level is suggested. Although it is accepted that this range of actions levels makes the implementation slightly more complex for employers, the outcome sends more realistic signals to industry about hearing damage. This should result in a greater understanding of the risks involved and ultimately in a reduction of industrial hearing damage.

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APPENDIX- A -Comparison of main provisions of 1986 EEC Noise Directive, Swedish Proposal January 2001, EEC political agreement June 2001 and Suggestion for Australia.

Provision	1986 Directive	Swedish proposal	Council political agreement	Suggestion for Australian Policy
Reduce risk	*to lowest level reasonably practicable*	*eliminated at source or reduced to a minimum*	*eliminated at source or reduced to a minimum*	*eliminated at source or reduced to a minimum*
Assess and where necessary measure exposure	*where noise experienced*	80 dB(A) & 112 Pa	*where these is a likelihood of exposed to risk*	80 dB(A) & 112 Pa
Assessment period	*8 hours*	*8 hours*	*8 hours or 1 week*	*8 hours or 1 week*
Provide information and training	85 dB(A) & 200 Pa	80 dB(A) & 112 Pa	80 dB(A) & 112 Pa	80 dB(A) & 112 Pa
Workers' right to hearing checks	85 dB(A) *by or under responsibility of a doctor*	-	85 dB(A) *by or under responsibility of a doctor*	85 dB(A) *by or under responsibility of a doctor*
Health surveillance	-	80 dB(A) & 112 Pa *by or under responsibility of a doctor*	*appropriate health surveillance where assessment indicates risk to health*	*appropriate health surveillance where assessment indicates risk to health*
Make ear protection available	85 dB(A) & 200 Pa	80 dB(A) & 112 Pa	80 dB(A) & 112 Pa	80 dB(A) & 112 Pa
Ear protection to be worn	90 dB(A) & 200 Pa	85 dB(A) & 200 Pa *but must reduce risk below 80 dB(A) & 112 Pa*	85 dB(A) & 200 Pa	*selected to eliminate risk or reduce to a minimum*
Ear protection Accepted as Ineffective	-	-	-	95 dB(A) exposure over more than 6 hours per day
Limit on exposure	-	85 dB(A) & 200 Pa *ambient noise*	87 dB(A) & 200 Pa *at the ear*	85 dB(A) & 200 Pa *at the ear*
Programme of control measures	90 dB(A) & 200 Pa	85 dB(A) & 200 Pa	85 dB(A) & 200 Pa	85 dB(A) & 200 Pa
Delimit areas, put up signs and control access	*where reasonably practicable* 90 dB(A) & 200 Pa	85 dB(A) & 200 Pa	85 dB(A) & 200 Pa	85 dB(A) & 200 Pa

Provision	1986 Directive	Swedish proposal	Council political agreement	Suggestion for Australian Criteria
Workers' reps to receive information on: **- assessments** **- programme of measures**	85 dB(A) & 200 Pa 90 dB(A) & 200 Pa	- -	-	-
Restrict noise in sleeping quarters	-	60 dB(A)		-
Derogations	*- weekly exposure averaging* *- from hearing protection where health and safety risk*	*- weekly exposure averaging*	*- from hearing protection where health and safety risk*	-
Transitional periods	-	-	*5 years from exposure limitation for shipping*	*5 years from exposure limitation for shipping*
Non-application	*sea and air transport*	*conflict with public service activities*	*conflict with public service activities*	*conflict with public service activities*

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AN EXPLORATORY STUDY OF SECOND DEFENCE NOISE CONTROL MEASURES IN SOUTH AFRICAN COAL AND PLATINUM MINES

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(Based on presentation at 7th Science and Technology Coalindaba, August 2001)

Abstract
The first defence against noise (noise control engineering) is a high priority in mines. Second defences should be a last resort when the engineering control of noise is inadequate. Innovation in noise elimination is an enormous challenge and success in this operations management function brings much relief in second defence interventions (hearing conservation. It is believed that conventional hearing protection devices (HPDs) will be phased out worldwide and that various types of custom-made HPDs (CHPDs) will be introduced. The best HPD may be seen as the minimum standard for second defense noise control. CHPDs may prove to be the catalyst for quality hearing conservation and will be regarded as an investment (this hypothesis needs to be verified). The findings from an exploratory study will be outlined in this paper.

1. BACKGROUND TO THE NOISE CONTROL PROBLEM

1.1 Overview

The first defence against noise (noise control engineering) is a high priority in mines. Second defences should be a last resort when the engineering control of noise is inadequate (Davis, 2001). Innovation in noise elimination is an enormous challenge and success in this operations management function brings much relief in second defence interventions (hearing conservation). The following underlines the complexity of noise control engineering:

- Ongoing research on the noticeability of environmental sounds to noise annoyance
- Experimental modelling approaches for automotive noise control problems
- Re-engineering projects to eliminate hazardous noise in mines

- The need for methods to study human response to type of sounds since the character of the sound is a key ingredient to noticeability
- Wind-induced noise causes problems for unattended noise monitoring
- Continuous quest for quiet residential sound insulation (eg, aircraft noise; impact of diversity in aircraft noise ratings)
- The need for evaluation of human exposure to building vibration
- Sound quality considerations in rating noise from heating, ventilating, and air-conditioning systems in buildings
- Physical laws: even quiet bore machines create noise when the surface is connected

Noise (above ±80 dB) is not only a physical hazard, but also a psychological hazard that may create or exacerbate ergonomic or mechanical hazards. Noise is a multifaceted problem and the effects of noise are also multidimensional. The focus should therefore not only be to eliminate long term NIHL (noise-induced hearing loss) but also to control noise for other occupational, medical, QWL (quality of work life) and productivity related reasons. Occupational health addresses several groups of hazards that cause occupational diseases. Noise (and heat) can be categorised as physical hazards while annoyance due to noise also causes other injuries, absences, mistakes, stress, high blood pressure (other medical problems), social isolation, lack of concentration, lower productivity, annoyance due to noise and others. Noise generally has detrimental effects on speech discrimination, sleeping patterns, job achievement (accuracy), hearing loss (PTS and TTS), irritation, ability to reason and ability to solve problems.

Hearing loss due to industrial noise exposure has been estimated to be the most prevalent industrial disease and the world may have a hearing impaired society of up to 20%. Noise engineering would not be so high on the agenda if noise was under control. If the first defence is not in place, more pressure is on HCPs (hearing conservation programmes). NIHL would not be so high on the agenda if HCPs were up to standard. This is why noise-induced hearing loss (NIHL) is prevalent and on the priority list of the WHO. NIHL is the most common work related disorder in the United States and other parts of the world. The irony is that overprotection (by means of powerful hearing protectors) may cause fatalities. Cases exist where workers did not hear alarm signals such as trains, with fatal results. NIHL (temporary or permanent) risks the physical ability of workers because NIHL is irreversible and hearing impairment negatively affects other human capabilities.

1.2 The NIHL reality

NIHL is a type of deafness. A sufferer can hear well, but certain sound such as speech is distorted. A typical symptom is that the sufferer always thinks the problem lies with the other party in that they seem not to communicate clearly. Most occupational illnesses and injuries have been successfully controlled except NIHL. Since hearing damage cannot be felt it is easily quietly managed. The irony is that management "whisper to noise" (and the silent disease) if one considers a few statistics (eg, a $16 million claim for NIHL which were equal to the total amount paid out for general disabilities). White (1997) in EAR Cat (1999) reported a dark picture in "Occupational noise: how is industry shaping up?" The sombre picture of compensation payments says it all. Ever since 1982 (and much earlier) publications such as Sutton's (1982) in EAR Cat (1999) report "More than 1000 000 ears need protection now", underlines the problem. More workers in the USA are exposed to potentially dangerous noise levels than to similar levels of any other noxious agent (Rink, 1996).

The report "The human and economic benefits of hearing protection" the economic burden of inadequate hearing conservation was indicated by Lofgreen (1982) in EAR Cat (1999). Today notifiable hearing damage is even more prevalent and indicators show that the hearing-impaired sector of society is growing. Vaught (2000) recently provided the disturbing fact that 90% of coal miners have a hearing impairment by age 51 compared with only 10% of the general population. This fact followed a study of 17 260 audiograms of 2871 coal miners. The hearing impaired society is on the increase. In Sweden, for instance, 70 percent of construction workers do not have normal hearing (Kuhar, 1996) and 70 percent of Germany's population are noise disturbed. In the Netherlands one million of its people's proximity to Schiphol Airport causes suffering from excessive noise.

1.3 Hearing conservation priority

The facts regarding NIHL clearly indicates the overwhelming reality of inadequate first defence noise control engineering. The need for second defence measures forces management to high standards since the second defence mode can not tolerate second best measures. In a study by Kahan and Ross (1994) the knowledge and attitudes of a group of South African mine workers towards NIHL and the use of HPDs indicated that workers did not perceive noise as a health hazard. Factors such as these, complicate hearing conservation. This fact may lead to an emphasis on awareness and education as the core of a HCP (hearing conservation program). Many research are being done to find a HCP model that is simple and effective. Many models (conventional and unconventional) exist. Models may focus on HPD ownership. One example is the Anglo Platinum model that is primarily based on high quality hearing protection as the catalyst for their HCP. This approach solves the problem of HPD ownership. It is also believed that quality hearing conservation leads to fewer injuries, absences, defects on the job and medical problems. Schmidt, Royster and Pearson (1980:59) also observed a significant drop in other injuries after the implementation of a quality hearing conservation programme. Effective hearing conservation, therefore, adds value in terms of the elimination of NIHL and the promotion of general health (safe working conditions/QWL) and productivity. In his report on 588 692 industrial audiometric tests, Rink (1996) confirmed these benefits of a quality HCP.

Inadequate HCPs may therefore harm the human capital of an operation in terms of quality, productivity, safety, general health and hearing. Healthy hearing is directly related to good quality of life and QWL. Williams (1992) in EAR Cat (1999) wrote “Enjoy, protect the best ears of your life”. Suter (1992) reported on the importance of communication and job performance under noisy conditions (EAR Cat 1999).

One major problem with conventional HCPs is overprotection. The challenge is to find the balance between attenuation and speech discrimination. Most HPDs (if properly worn) cause isolation due to overprotection. “Overprotection” by implication refers to overreaction that may cause more hazards than advantages. The ideal HPD should therefore be able to provide maximum protection (attenuation) and maximum speech discrimination (communication ability and the ability to hear warning signals). These products (usually custom-fitted HPDs with filtering devices) operates on a resonant cavity principle for sound control. Noise control through hearing conservation is thus not for ears only, it can even save lives.

2 THE PROBLEM: SECOND BEST SECOND DEFENCE

The research question is: if noise control primarily depends on HCPs, why is it compromised? If noise cannot be eliminated, then good effective hearing protection should be the logical solution and core of hearing conservation. Unfortunately, this is not the norm since hearing protectors falls far short to its intended purpose. HPDs needs to be investigated.

2.1 HPD analysis

The literature survey indicates the different HPD schools of thought seem to be here to stay. Swanson and Miller’s (1976) study in EAR Cat (1999) of seven different HPDs confirms this. Sortine and Weeks (1977) in EAR Cat (1999) on “comparing hearing protectors” and Zohar’s (1980) report in EAR Cat (1999) on promoting the use of PPE with the aid of behaviour modification techniques also emphasises the problem. Wilson’s (1989) in EAR Cat (1999) hard look at hearing protectors and Watkins’s (1989) report in EAR Cat (1999) on the “wearability of hearing protectors” also shows the same symptoms. The list goes on as Webster (1995) in EAR Cat (1999) reports on “Ear defenders: measurement methods and comparative results” and York (1980) describes the properties of hearing protectors in EAR Cat (1999).

Thousands of publications indicates the large performance gap between laboratory tested HPDs (plugs and ear-muffs) and HPD application in industry. Regardless of whatever test report and conformed standard, if the HPD is not comfortable, its application will be compromised. Even if workers wear them, the HPD will not be effective since they will be adjusted to meet the need for comfort. Therefore, the first quality dimension should be comfort (defined in terms of physical comfort, ventilation, sound control, orientation, speech discrimination, localisation and less isolation). This is only possible by products with filtering mechanisms. Besides this, conventional HPDs should be under fire because its overall ownership is questioned, its cost-effectiveness is questioned and its hygiene features (especially in Coal mines) are also questioned.

2.2 Real world performance of HPDs

> Hearing protectors are often misused and in general their real-world performance falls far short of the protection that properly-worn and maintained HPDs can provide (Berger, 1996).

Berger (1996) lists all the problems with conventional HPDs such as utilisation problems, fitment problems, inadequate compatibility, need for readjustment and deterioration. Laboratory tested HPDs are simply not the “same” in practice. The best HPD is the one that is worn. Conventional HPDs only seals properly by means of pressure. This causes discomfort which leads to the compromise of proper HPD application because the device will be adjusted or taken out for comfort. Berger (1996) also refers to a disadvantage of the conventional ear-muff in that it confuses the user about the direction of the source of the sound. In some cases ear-muffs can even aggravate noise. The "bigger is better" school of thought forms the misconception that an ear-muff is more effective than other products. This also relates to “doubling-up” (where two HPDs are worn simultaneously) which raise several question such as mistrust in noise-reduction rate (NRR) figures and overprotection. Real world performance of conventional HPDs is basically affected by the two categories discussed next.

2.2.1 HPD design failure

Ear canals are not round, yet HPDs are designed that way. Most conventional HPDs is based on a pressure fit and the better the pressure and seal, the more uncomfortable the muffler. Effectiveness of mufflers is diminished by wear and tear and products cannot be adapted to suit the ear canal or user. Other limitations are deterioration and wear-out caused by the disposable nature of the product which force regular inspections, reordering and reissues of HPDs. Lastly, limited sizes cause air and sound leaks that compromise NRR values.

2.2.2 Human error due to HPD design

HPDs are modified to improve comfort (springing earmuff headbands to reduce the tension, cutting flanges off, drilling holes through plugs and so forth). HPDs are abused due to HPD design, lack of pride and respect and HPDs are regarded as a hassle rather than a self-sustaining, respectable affair. Ear defenders is shifted under rough working conditions and ear infections (*otitis externa*) are caused by dirty noise mufflers or muffler pressure (which leads to operations/production downtime and medical costs) and so forth.

2.3 PPE implies user choice

To complete this section on the research problem, it is necessary to underline the selection process as part of the problem. Conventional HPDs are still the norm due to a perception that hearing protection is limited to a few types of traditional ear defenders. Knowledge of WAP technology (such as cellular phones) had a significant effect on the demand for cell phones. The same can happen to HPD selection if management gain the knowledge that better more "personal" protective equipment is available. It seems quite clear that the products described under section 2.2 will not be the first choice if mine workers knew better and if they had a choice. Berger (1996) recommends that comfortable HPDs must be selected and employees must be encouraged to make the final decision as to which he/she will use. It seems quit obvious that the average miners will not choose a HPD that is "laboratory-designed for animals".

The complexity of the problem demands a vigorous and total approach that rules out a single-factor solution. Even the best quality HPD will not provide a quick fix, but it may be a catalyst or core of a quality hearing conservation programme. As management is obliged to make the second defence work, it is difficult to imagine how conventional devices will be used for much longer.

PPE choice lies primarily with management because preservation is to keep safe from injury or destruction and to keep alive and free from decay. Noise control through conservation refers to the careful (not forceful) protection of human hearing by means of a unique management approach and a well-designed model for quality hearing conservation to prevent exploitation, destruction and physical disability. This implies a quality approach of innovation, change and improvement. Part of this is HPD excellence.

4 RESEARCH PURPOSE AND METHODS

4.1 Research purpose

The primary purpose of the empirical investigation is to explore the multifaceted nature of "quality HPDs" referred to as custom-made HPDs (CHPDs) and its application in mining. The secondary purpose of this survey is to identify further research areas and hypotheses.

4.2 Research methods

Qualitative methods were introduced to explore and describe CHPD application and related issues. One goal of qualitative research is the development of concepts that help us to understand social phenomena in natural settings. What is “x” and how and why does “x” vary in different circumstances rather than “how many x’s are there?” is the value of qualitative research. The major strength therefore is validity. The research framework is given in Table 1.

Table 1: Research framework

RESEARCH DESIGN DIMENSION	SUBJECT
1. Domain	Occupational hygiene; noise control
2. Population	South African mines
3. Sample	Platinum and Coal mine cases
4. Research problem	Second defence noise impact control
5. Research purpose	Explore, understand and describe the multi-faceted nature of the problem
6. Research approach	Personal qualitative research. Its value lies in the presence of the researcher to reach parts other methods cannot reach. Coertze (1994:162) refers to the phenomenological approach, which explains qualitative techniques of data collection and the researcher as the principal instrument. A personal survey consequently presents the opportunity to use visual material and to explain (clarify) for effective control, and the benefits of physical presence and appearance.
7. Type of research	Exploratory, case studies and descriptive
8. Measuring instruments	Observation and interviews
9. Specific focus	Hearing protection through HPDs
10. Secondary focus	HCPs
11. Research status	The exploratory phase is completed and certain other more comprehensive variables are studied over the long run. A comprehensive survey is currently being done at Impala Platinum Limited.

4.3 Secondary (literature based) research results on CHPDs

4.3.1 Universal fit HPDs is CHPDs

Scott (1998) reports in EAR Cat (1999) on what is believed to be the core success factor of CHPDs, namely, customized comfort. Ear canals are not round, yet conventional earplugs are manufactured and marketed in that form. Ear canals cannot sustain physical pressure, yet conventional earplugs are designed to pressurise the ear. This cause HPD abuse and the only way to assure that real world HPD performance equals laboratory performance is to get out of the lab and fit workers personally at the job. The history of conventional HPD performance indicates that pre-moulded universal fit designed HPDs has not been effective.

4.3.2 CHPDs do not require workers to snugly fit or adjust it

Any HPD that is not properly sized, custom-fit and permanently adjusted is basically worthless. A CHPD is fitted either correctly or incorrectly. If the earplug is properly sized, personally and carefully fitted it will be worn. One cannot expect from the thousands of mine workers (as in Africa) to choose different HPD sizes, to be well trained and be able to adapt and adjust the HPD. This will not happen and it did not happen in the past. Although some employees may adapt, many will not. To train the thousands of miners in all of these steps is practically very difficult and even costly. Proper fitting of a foam insert type protector requires a complicated procedure. The following steps are examples provided by Michaels (1998:182): 1. roll the plug down into a tight cylinder; 2. insert the plug as deep as possible into the canal while pulling on the pin with the opposite hand, and 3. hold the plug in place while it expands. If any of these steps are omitted, the purpose of the device will be compromised.

4.3.3 The use of CHPDs increases among workers with identified noise-induced hearing loss (NIHL)

The report "use and non-use of custom-molded and conventional hearing protectors among workers occupationally exposed to hazardous noise" by Bennet (1998) from the United States Air Force confirms an interesting trend. She confirmed that CHPD use increase among workers with identified noise-induced permanent threshold shifts (PTS). If this study indicates a significant increase of custom-molded hearing protector use among workers with identified NIHL or permanent threshold shifts (PTS), then it may have an even more positive result among workers without PTS, if they have a choice to be well informed, educated and fitted with CHPDs.

4.3.4 Basic characteristics of CHPDs

The quality dimensions which these products have to meet are: filtering harmful amplitudes (high frequencies) and retaining speech discrimination; physical comfort; psychological comfort; cost-effectiveness; durability; effective attenuation according to custom circumstances; user friendliness (easy maintainability); seal testing; high user ownership. All these features foster worker pride. Some products also contain the worker's *name* and the user can also *exercise a choice* in the custom-made process in terms of personal colour choice. The basic differences of CHPD products are given in table 2.

Table 2: Basic differences of CHPD products

CHPD products A	CHPD products B
Hard acrylic material, neatly packed with cleaning tools	Soft moulded material
Sound control through a pure flow system	Sound control through a resonant cavity filter
Calibrated for specific noise zones: types with movable components needs re-calibration (servicing)	Calibrated for specific noise zones: types without movable components are permanent fixed calibrated (no re-calibration costs)
Number ID tracing system	Personal name ID tracing system
Single transparent colour	Different colour choices to increase ownership
No ventilation or seal test possibilities	With ventilation and seal test features

4.3.5 Cost-effectiveness of CHPDs

Sara Bloom (1997:24) cites Smith, that employees make a mistake if they supply workers with cheap sponges (foam plugs). CHPD are made of quality materials and does not shrink or crack. Its durable acrylic material and the way it is presented and packed support the way it is received and perceived. Durability of CHPDs also refers to its features, appearance, effectiveness, the way it is packed and its maintainability. Miners do not want to lose them due to its features, and may maintain them for at least four years. It is true that the initial investment of ±R350 could be perceived to be expensive - but the break-even cost point (compared to a cost of R2,70 per day for “cheap” HPDs) is reached after only six months. WorkSafe Western Australia published a "Safetyline solution" to be "Insta-mold custom fitted protectors" that saves $365 per person over a period of three years.

Quality management teaches that cheap things are actually expensive over the long run. HPDs are a good example. If noise pollution and the NIHL problem is on the priority list of the ILO and the WHO, then its unthinkable how cheap uncomfortable earplugs can be a solution.

4.3.6 CHPDs with filtering devices enhance communication and productivity

Most CHPDs have a kind of a filter mechanism that controls sound for speech discrimination. In their publication titled "In search of meaningful measures of hearing protector effectiveness", Berger and Royster (1996:5) states that communication needs and hearing ability are neglected or overlooked in favour of choosing the HPD with the highest NRR. One dimension of comfort is the ability to communicate and HPD selection criterion certainly includes communication. Recently, however, suppliers that issue HPDs have been held responsible for accidents related to communication difficulties due to overprotection while wearing "powerful protectors". Calibrated CHPDs can provide reduced attenuated for improved warning signal detection and speech discrimination. Workers will therefore not remove the protector because certain sounds can be heard. Communication ability has a positive effect on QWL and several studies have been done on the positive effects of HCPs on motivation, quality, safety and productivity. Most of these studies were done on conventional HPDs and predicts that CHPDs could be a much bigger improvement.

4.3.7 CHPDs are fitted outside the laboratory for better NRR performance

CHPDs are calibrated for specific noise zone attenuation and is seal tested after fitment. The NRR (noise reduction ratings) debate is primarily for products other than CHPDs. Berger and Royster (1996:6) state that NNR can be very misleading and greater than 90% of the noise-exposed population needs only 10dB of actual delivered real-world attenuation. Berger (2001) also states that CHPDs must have a precise fit to assure a proper acoustic seal. Although this is true, it is a contradicting statement because foam or any other HPDs should be seal tested in the first place and yet is not seal tested. CHPDs are tested for a leak tight fit and conventional plugs have such a large problem with sealing, it may even fall out or is adjusted for comfort. CHPDs is fitted either correctly or incorrectly.

4.3.8 CHPDs require a delicate medical fitment process

This is an important fact that CHPDs requires a more intricate and delicate medical procedure. The operational teams receive special one-to-one training from a skilled audiologist. Suppliers only use audiologists or trained medical personnel to do impressions and fitments. These processes demand certain procedures where the miner/client is the central point of attention. This high contact service system has several advantages. The primary advantage is its personal touch since custom-fit earplugs imply personal protection. Conventional PPEs are impersonal and should not be referred to as PPE.

4.3.9 CHPDs are hypo-allergenic and hygienical

Hygiene is an important factor since any degree of infection can eliminate a worker from work. According to Bloom (1997:24) is workers' hands not always clean when they roll up and insert the sponges and infection is prevalent. This is not the case with acrylic type hypo-allergenic CHPDs.

4.4 Primary/empirical research results of CHPDs user cases

4.4.1 Results

A summary of case study observations is provided in Table 3. The following point scale is used: U = unknown; Wip = work-in-process; ID = information disclosure (WIP); 0 = very negative; 1 = negative; 2 = positive and 3 = very positive. The variables applies to the following six cases:

1. Case 1 = Coal mines in general;
2. Case 2 = Impala Platinum Limited (Rustenburg);
3. Case 3 = RPM Anglo Platinum group (Rustenburg);
4. Case 4 = RPM Anglo Platinum group (Rustenburg, Rasimone Bafokeng);
5. Case 5 = RPM Anglo Platinum group Swartklip union section
6. Case 6 = RPM Anglo Platinum group Amandelbult section

Table 3: Summary of case study observations

VARIABLES OBSERVED	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Top management driven	2	3	3	3	3	3
Large scale implementation	2	3	3	3	3	3
Supplier lead time effectiveness	2	3	1	3	ID	3
CHPD general user ownership	3	3	U	3	3	3
CHPD detailed long term effect (eg base line audiogram evaluations)	U	U	U	U	ID	U
CHPD effects on quality of work life	U	Wip	U	U	ID	U
CHPD effects on HCP	U	Wip	U	U	ID	Wip

4.4.2 Discussion of case study results

- **General feedback**

The upgrading of second defence noise control through CHPDs seems to be the new norm. The exploratory investigation shows a strong management drive towards CHPD application and large scale implementation (see table 3). The signs are there that the users (wearers) are satisfied with the new types of HPDs. Observations such as workers becoming impatient to wait for their CHPD to be fitted is a good indication, but more empirical information is needed. Certain measurements can only be made after a year or two and other projects are current, as indicated in table 3. There is a need for hard measurable facts such as before-after baseline audiogram (BA) information and other QWL (quality of work life) before-after information.

- **CHPDs can be issued on large scale**

The biggest challenge lies at the customer-supplier interface in the value chain. This relationship is vital since the custom-made process demands careful planning and accurate scheduling. If the client provide their support in terms of facilities and scheduling, the rest of the challenge lies with the supplier. It boils down to operations management functions such as layout of stations, line balancing, capacity planning, short lead times, quality control and administration accuracy. Suppliers must be geared with medical teams to serve the masses without unnecessary delays. Their operations systems need to be upgraded from a service shop (job shop type) to a batch or mass service system. In one instance at Impala Platinum almost 1000 workers were serviced (by taking impressions) over a period of three days and in only nine hours. This is a good example where the operation is less intermittent and more repetitive.

- **Incremental CHPD implementation at Coal mines**

Although such a high percentage of coal miners have a hearing impairment (see section 1.2) is there no indication that a corporate decision drives CHPD implementation in the Coal mines. Sasol and other coal mines does seem to move to CHPDs on a larger scale. Currently they introduce CHPDs incrementally (smaller batches being phased in) as part of their upgraded HCPs. Examples of these Caol Mines are Koornfontein, Optimum, Kriel, Blinkpan, Bank, Duiker and several others. Vaught (2000) evaluates the role of positive and negative emotion in promoting hearing conservation behaviours among Coal miners. The big challenge to get workers to wear HPDs underlies this investigation. This fact followed a study of 17 260 audiograms of 2871 coal miners and that 90% of coal miners have a hearing impairment by age 51. Byrne (1998) from the Pittsburgh Research Laboratory is currently in the third year of five, designing a model HCP for Coal miners.

- **The Impala Platinum Limited case**

This major role player in the platinum industry recently commenced with large scale CHPD implementation. The mine is known for its effective health and safety measures and strict environmental policy. Their active support of quality hearing conservation and continuous research and participation in the Mine Ventilation Society's mission to contribute to the elimination of NIHL led to the support of CHPDs. Although their feedback is very positive (Schophaus, 2001), their concern is the long-term actual measurement of real world hearing protection performance. The mine is currently supporting a research HCP project from members of the University of Pretoria (Department Audiology), Unisa TQM (Certificate Programme: Total Quality Management) and Sociale Geneeskunde (Netherlands). A comprehensive empirical survey of 500 CHPD wearers will be done in September 2001. The core of the survey will focus on six features of CHPDs and six variables related to QWL effects of CHPDs.

- **Anglo Platinum cases**

Anglo Platinum mines work according to their "Blueprint for the implementation of CHPDs to eliminate noise induced hearing loss". This standard was designed and introduced following a comprehensive pilot project in 1999. This project was a huge success and it proved that CHPDs can be implemented on a large scale (Erasmus, 2000). Workers valued the personal approach to PPEs much more and sensed ownership was very high. The blueprint elaborates on the fact that it should not stipulate the requirements for a HCP as per the Chamber of Mines guidelines. It should be included as an addition to a HCP. The statement that CHPDs should form the catalyst to quality HCP is widely supported. The objective of the blueprint reads: "to lay down guidelines for effectively issuing each employee exposed to noise >85dB(A) in the workplace with custom manufactured hearing protection devices". The Anglo Platinum CHPD blueprint suggests specific standards and quality dimensions as baseline product, service and supplier requirements. One major improvement is their requirement for a BA (baseline audiogram) to be specifically recorded during the issue date of fitment to support the hearing conservation program. The blueprint states "for the purpose of supporting the hearing conservation programme it is important to build up sufficient information that will indicate the condition before, during and after implementation of a custom-made hearing protector".

- **Rasimone Bafokeng Anglo Platinum case**

This is a relatively new mine and has taken the decision to issue all workers with CHPDs as they are employed. Workers are issued as they are assigned at an average rate of about 300 units per month. The general feedback is very positive (Baker, 2000) and workers are impatient to wait for their CHPD to be fitted.

- **The Amandelbult Anglo Platinum case**

This mine is known for its high standards and is currently implementing CHPDs according to Anglo Platinum CHPD blueprint. The project is well under way and the general feedback is positive (Pienaar, 2001). A total of ±3000 CHPDs is already issued and the first 1000 workers (250 workers per day) were paraded in a week where three workstations were necessary for the operation. Workers are prepared before the procedure commences and a full-time medical workstation is currently in operation for the project. Initially a bottleneck was experienced with the fitting procedure that is now something of the past.

5 CONCLUDING REMARKS

Conventional approaches to hearing protection did not offer a solution. It is believed that conventional HPDs will be phased out worldwide and that various types of CHPDs will be introduced. The best HPD may be seen as the minimum standard for second defense noise control. CHPDs may prove to be the catalyst for quality hearing conservation and will be regarded as an investment (this hypothesis needs to be verified). This exploratory study however, indicates that CHPDs are associated with (A) quality (HCP upgrading, new HCPs, a wholesale solution) and (B) the PHD concept.

(A) "Third world" hearing protection demands simplicity through quality

The perception that "third world" people must have "third world" HPDs is correct, if "third world" is associated with quality, durability and simplicity. Many assume third world HPDs to be cheap foam products. These HPDs are in fact very expensive over the long run and actually needs well-trained mine workers or experts to snugly fit them into the ear canal (a few steps need to be taken to fit them correct). The cases discussed indicate that the only complicated aspect of CHPDs lies with the supplier (to manufacture custom-made products). The rest of the scenario relates to simplicity. It either fits 100% or does not fit.

(B) The PHD concept of hearing conservation

A narrow viewpoint (as apposed to a total quality view) of hearing conservation is only on the protection of hearing. A holistic viewpoint however, will also acknowledge the other benefits of quality hearing conservation. These basically refer to QWL and economy. The clear message of the World Hearing Conference (in Brussels 1999) was that the hearing impaired population will increase by 42% over the next 5 years. A wide audience was sensitised to the effects of hearing loss regarding QWL and quality of life. Quality HCPs have value beyond hearing protection and an effective HCP may not only prevent industrial NIHL, but adds value in terms of QWL, general health, safe working conditions, and productivity.

The new concept associated with CHPDs is PHD (protection hearing device) and to change from "HPD to PHD". Due to the new awareness of the fact that hearing protection is "more than meets the ear" and not for ears and hearing only, officials support the idea of moving from the conventional HPD-idea to the PHD way of thinking. The focus is more holistic based on the TQM philosophy. The underlying philosophy of the "protection-hearing-device" concept is the fact that quality HPD interventions (such as CHPDs with several features such as filtering mechanisms) has a quality of life value further than hearing protection alone. CHPDs protects more than hearing and promotes more than safety.

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EXAMINATION OF LARGE AUDIOMETRIC DATABASES FOR ENHANCING OCCUPATIONAL NOISE EXPOSURE MANAGEMENT STRATEGIES

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Abstract

Noise Induced Hearing Loss (NIHL) is probably the most prevalent occupational injury in the industrial world. Pure tone audiometry is the primary tool for verifying NIHL or "industrial deafness" as it is commonly termed. Audiometry can establish the severity, and to some degree of reliability to the nature and origin of the hearing loss. However it cannot prevent hearing loss. This paper examines the use of large audiometric databases and methods of analysis to provide meaningful information to evaluate and improve industrial hearing conservation interventions. Within the greater Australian mineral industry sector during 1993/94, disease occurrences accounted for 32% of all compensation claims. For this period, noise induced hearing loss accounted for 80% of all claims classified by nature of disease with significant compensation payments in major Australian coal producing areas of New South Wales and Queensland.

These highlight the significance of occupational noise induced hearing loss within the Australian coal industry. However investigations have generally focused attention on quantifying the size of the problem rather than studying the nature of circumstances that have not been able to prevent so many employees to be injured by excessive exposure to noise within the coal industry. This paper reports on the use of large audiometric datasets to assist with the development of future strategies for preventing noise induced hearing loss in the Australian coal mining industry.

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SURFACE TRANSPORTATION NOISE – COMMUNITY EXPECTATIONS AND THE REAL WORLD

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Abstract:
Noise from surface transportation is one of the major pollutants of our time, adversely affecting the lives and health of countless millions of people. In a democratic and knowledgeable society this is unacceptable.

Twenty years or more ago, we may well have had the excuse that the technology was not far enough advanced to counter the rising levels of sound exposure experienced by the community at large. But such is not true today. There is more than sufficient knowledge to make a judgement on how much noise is too much, and we have the technology to correct matters if need be.

We also have instrumentation far in advance of anything even contemplated that time ago - instrumentation capable of capturing the true sound exposure in very short intervals of time and storing vast quantities of data - but we should remain aware of the limitations that still exist. We should also realise that mathematical modelling may not be anywhere near as accurate as imagined (or as one has been led to believe).

A basic tenet is that all people have the right to live in peace and tranquillity. However, it must not be assumed that government has the obligation to ensure this, nor that the people themselves are aware of this and will cooperate, unless it is firmly established in the law.

At times, It is well to step back and consider how we arrived at the position we are in, and what we may have forgotten in the process. Perhaps now is such a time, for surface transportation has burgeoned and the noise generated is one of the major pollutants of our time, adversely affecting the lives and health of countless millions of people. In a democratic and knowledgeable society this is not acceptable and one must wonder how it has been allowed to happen. From the earliest times, a basic human right has been to live in peace and tranquillity. This is incorporate in British Law dating back to the Magna Carta of 1215, and buttressed by the Petition of Right in 1628 and the Declaration of Rights in 1689. There is a similarity in French Law from the "Declaration of the Rights of Man and of the Citizen" adopted in 1789, and in the preamble to the text of the Constitution of the United States, in the same year. The Weimar Constitution of 1919 follows in like vein, and similar worthy aims are incorporated in the basic laws of many other democratic countries, including New

Zealand. In all cases the laws may be interpreted as including the right to live in health, free from noise disturbance.

In modern times, the various noise control acts throughout the world exemplify the nations' attempts to fulfil this obligation or at least to appear to be fulfilling this obligation. The major role of any democratic government is to preserve the health and welfare of the community at large. Unfortunately, welfare often is interpreted as simply monetary well-being, and there has been a general reluctance to bring public health into equal consideration. To make matters worse, many people do not consider excessive noise exposure as adverse to health and, in practice, noise control more often than not takes a back seat to other more visible problems.

It is regrettable that from the earliest development of machinery and propulsion, loud sound has been considered an indication of power and in no way a health problem. This reasoning still prevails amongst the majority of people. It is also a common concept that loud sound that is enjoyed does no harm. Only in recent times has the insidious nature of the effects of noise exposure on the health and well-being of the community been realized, and, only in recent years, have we had the technology and the instrumentation to quantify harmful levels of noise exposure with enough conviction to satisfy the formulation of plans and legislation to protect community health. We must realise, however, that even the most accurate of sound measurement instrumentation has severe limitations [1]: We can measure the light received from the farthest visible star, we can measure the heat received from a candle one kilometre away, we can measure the time that light takes to travel 3 millimetres, but although we have instrumentation far in advance of anything contemplated some twenty years ago, instrumentation capable of capturing the true sound exposure in very short intervals of time, and storing vast quantities of data, we cannot measure sound any better than with a possible ±26% error – and that is in strictly controlled laboratory conditions. Outdoors even the very best measurements have a measurement uncertainty of ± 4.8 dB with class 1 instrumentation [2]. That's a possible error in excess of ±200%. Yet we have some members of the acoustical fraternity almost always publishing environmental measurements to a tenth of a decibel (±2%), and one or two that have been known to give results to one thousandth of a decibel on occasion (±0.02%). No doubt this is meant to give an impression of high accuracy, but to those well versed in acoustics it merely suggests quackery. For measurement of surface transportation noise only integer values should ever be used, and by rights the uncertainty in measurement should be given. This author has yet to see anyone brave enough to do so.

And then we have mathematical models. This author designed and produced one of the very first computer models – one to compare the effects of different aircraft noise reduction strategies on the soundscape around an airport [3]. For such a task – that of comparing the noise resulting from one strategy to that resulting from another, all other variables remaining constant - models are very useful. In absolute terms, however, at the very best such models can only predict the sound propagation as well as we can predict the exact microclimate concurrently at every point between the sound source and the receiver at some finite time in the future [4], and the acoustic impedance of every surface along every sound path. The accuracy of computer models leaves very much to be desired. Using the most popular of such models in New Zealand to predict absolute values, errors of 12 dB or more (± 1500%) have been experienced. On the other hand, the output of some of the models is very attractive giving the impression that the work has been done very professionally. If the contours are given in 10 dB steps, we can take the spaces in between the lines as being the real contours and then we will at least be within the bounds of possibility. If the contours lines are in 5 dB steps, then we can take each line as really spreading out across the spaces either side. If the contours lines are given in steps of less than 5 dB then this author suggests the model is not to be trusted and the person giving the report should be asked to do it again.

Collating research results into working criteria for the protection of health, has been quite difficult, and those working with the World Health Organization (WHO) towards such a goal have taken many years to produce a working document [5]. We now have the technology to control transportation noise and the criteria to achieve, but are faced with an even greater difficulty – that of getting people to agree on implementing noise control based on that criteria. In building up the criteria, there was a reluctance of many scientists to commit themselves to suggesting control criteria - which is understandable when one considers the economic power of many of the companies producing the major part of our environmental pollution, and the need for the scientists to get support for their work - indeed to retain their jobs in some cases. Now in trying to implement noise control to achieve the WHO criteria, there are those involved in the transportation, service and construction industries who must look on the practical side and consider not only the costs of implementing even the most simple of measures to reduce noise - costs which may be thought totally out of the question – but also the effectiveness of the measure, and how it can be policed. Getting the planning, roading and transport authorities to accept the WHO criteria, is proving to be extremely difficult. There is an unwillingness the accept that road traffic noise can affect health to any significant degree. If we are ever to succeed in producing a National Standard for Road Traffic Noise, some of the deleterious effects of not containing the noise emission to within certain limits have to be shown.

After some years of searching for such evidence, this author in the mid 1980s put together Table 1 which relates the average daily sound exposure in a residential area to the possible adverse health effects to be found in that area. Such a table should be taken only in the context of it being a baseline resource for the formulation of strategies to protect community health. Rather than stating what one should expect to find, the table portrays "What we should not be surprised to find" at those exposures. It is emphasised that it relates to expected long term effects on community health and not necessarily to individual health concerns. People have a wide range of tolerances to individual noise events. There are always some people that are supersensitive and more likely to develop an illness condition, and others that seem imperturbable - but that does not mean that their health is unaffected by the noise in the long term. Some may consider that the table errs on the side of exaggerating the effects of noise. The author does not believe that to be the case, but does admit to being biased more towards the protection of community health than towards the aims of commercial interests.

That noise can be the origin of an illness condition is usually totally disregarded, even though there is clear and undisputable evidence that it can. The work of Dr Karagodina and his medical colleagues in the 1970s [6] provided ample evidence of the very severe effects of noise on the population, and in the last 25 years or so many more investigations have come up with similar findings [7]. More recent medical evidence brings to light noise problems and resulting illness experience where none would have been thought to exist - for example among the families of the elephant handlers in the jungles of Northeast Thailand [8]. During 15 months of field work among the people of the Kui, an indigenous people residing in the southern part of Northeast Thailand, Dr Komatra Chuengsatiansup found prevalent in the community illness characterized by a variety of symptoms: sleeplessness, shortness of breath, loss of appetite and chronic fatigue. This was closely associated with the audio-sensory perception of specific village sounds - of which motorised transportation dominated where once was relative quiet. A direct link between the sounds and the illness experience was found. Transportation noise can and does cause illness, and one must not lose sight of that fact.

Of continuing concern are the 10% or so of people that are highly susceptible to any stimulus and to whom the least disturbance may result in extreme agitation. To them any noise is too much and complaints arise. Strategies for the protection of community health from noise often are costly and usually cannot include special consideration for these people. One can really only plan to be successful in covering the needs of about 90% of the population. Ethically, this may be wrong. It can be argued this 10% of the population has the right to live in peace and quiet however this may be defined. A counter argument, or another way of looking at this, is that for everything there is a price. Just as an outsize person may find getting clothing to fit difficult and expensive, so those that are extra sensitive to noise may have to pay more to live in areas where the noise exposure meets their expectation.

If people come to live in an area that is already noisy then one must assume that the environment has been judged acceptable to them. If, on the other hand, a new noise source, such as a new road, is introduced to their environment, or a sound source increases over time, we have a totally different situation, and often a difficult judgement to make if they complain of the new noise source, but no one else does. If the noise source were some private commercial venture of little benefit to the population or the government, the authorities may have little hesitation in demanding the problem be rectified or the process closed down. But if the extra noise source is a new road, the benefit to the exposed population may be somewhat blurred, particularly so when the people themselves use the road and contribute to the noise. Then should the needs of this 10% prevail, and should these people be compensated or relocated? Such questions to any level of government are extremely difficult to answer - if an answer can be found at all. Of course, one might question the government's having any obligations in this matter, or indeed having any obligations at all.

A new concern is the large increase in heavy vehicles, both in size and numbers, that are now using roads to transport goods rather than the traditional way by rail. Along New Zealand's State Highway 1 throughout the night on average there is one heavy vehicle every 2 minutes [9], and the highway passes through the middle of several small (sleepy) communities. No sooner does the sound die away from one vehicle than the sound from the next starts to be heard. The increase in sound over the background sound may be more than 60 dB and even though the daily day/night sound exposure does not exceed 100 Pa^2s (about 65 Ldn) the local people report [9] severe disturbance to their sleep patterns and illness experience very similar to that found in the Thai report (above). Finding that they could make no headway with the authorities to lessen the noise, some of the community have erected noise barriers outside their homes - only to find that where they have left a small area for entry from the highway to their property, the sound penetrates to the same extent but now with a much faster onset and decay, which is more disturbing - even with good double glazing. The use of engine braking too has raised so many complaints from people, that many town councils now prohibit engine braking while the vehicles are in town limits [10] - except in a real emergency of course.

But all is not gloom and doom. Whereas central government may well prefer to opt out of responsibility for protecting public health, local territorial authorities are becoming more aware of the needs of the people and introducing their own rules to protect public health from

the growing incursion of road traffic noise. In New Zealand, some are building their own bypasses to take the heavy traffic well away from residential areas [11], others are setting specific routes for heavy traffic through their area, it being prohibited elsewhere [12], and many are beginning to spend more on quiet road surfaces, rather than trying to cut costs by using cheap (and noisy) chip-seal.
Things are also improving on the waterfront. A new international standard has been gazetted [13], specific areas are being set aside for power boats and jet skis, their use being prohibited in other areas, and many jet boat owner operators are taking pains to make their vessels as quiet as possible so as to provide as little disruption as possible when taking tourists into wilderness areas, or travelling along inland waterways close to residential areas. Of still great concern is the effect of the increasing road, and off-road, traffic on the soundscape of our national parks. The national parks were set up to preserve a natural environment for people to enjoy. It needs the people to provide the financial support necessary, but as the growth of tourism develops, so the natural environment is degraded, and the park service in many places is at its wits' end trying to balance the one with the other. The U.S. National Parks Service is experiencing such difficulties that one researcher [14] is trying to find one square inch of quiet in each National Park. I believe he is having little success.

Herodotus in "The Histories" [15] provides an interesting discourse in ancient Persia on the roles of government. True, he has been called the "Father of Lies" (as well as the "Father of History") and the discourse may well have been fabricated. But the aims of government as he saw it have not changed. If the government is democratic and drawn from the people, "then those in the government are held responsible for their conduct in office, and all questions are put up for open debate." But, in drawing the members of government from the people there is a problem. "The masses are a feckless lot - nowhere will you find more ignorance or irresponsibility …..." So even if the government is chosen to look after the needs of the people, one cannot assume that the health of the people is the prime requisite unless it is firmly established in law. In countries with Bills of Right and/or Acts of Parliament relating to health, then the government does have an obligation to protect community health from the adverse effects of noise, but may not necessarily carry it out unless it feels it is a necessity. Similarly the people themselves have at least a moral obligation to keep noise emissions from their activities off or on the road down to reasonable levels. The main trouble is that unless this too is laid down in law, and the people know about it, there may be little incentive to make them do so - particularly if some people, without redress, seemingly take no notice whatsoever of the law, or of how they may inconvenience others by their actions.

Table 1
Noise and Health

Day/Night Average Sound Exposure E_A Pa^2s	One should not be surprised to find:	Day/Night Average Level Ldn dB
5	No adverse health effects. (This is the usual limit in NZ for general environmental noise at residential boundary)	52
10	No adverse health effects. (This is the level suggested by the US EPA and WHO as requisite for the protection of public health with an adequate margin of safety.)	55
10-35	Complaints starting to arise about the noise	55-60
35	Complaints, about the noise, becoming widespread and people starting to suggest their health is being compromised.	60
35-100	Substantial annoyance and likely concerted community action to stop the noise (Below this level of exposure there have been no medically substantiated adverse health effects in)	60-65
100	Severe annoyance and a noticeable increase in sleeplessness, morbidity and stress. (This the internationally accepted limit of tolerance for transient noise events)	65
100-350	Stress related illness & increased absenteeism from work An increased rate of mortality over 60 years Strong legal action by the community	65-70
350-1000	An unacceptable increase in mental instability An increase in cardio-vascular disease An increase in proneness to accidents An increase in gastro-enteric problems In some people, damage to vocal cords by gastric-eruption (At this level full recovery from TTS is unlikely)	70-75
1000	No recovery from TTS following industrial exposure, Endemic severe illness experience prevalent. (Human habitation is strongly proscribed)	75
1000-3500	Not only severe illness prevalent, but some hearing damage as well	75-80

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9 New Zealand Environment Court Hearings: Appeal Mobil v Taupo District Council September 1999

10 For example: In New Zealand: Cambridge, Hamilton, Hunterville, Levin, Mangaweka, Matamata, Motuoapa, Otaki, Paekakariki, Paraparaumu, Porirua City, Pukurua Bay, Putaruru, Taupo, Tokoroa, Turangi, Tirau, Waikanae, and many more.

11 For example: Taupo District Council, New Zealand

12 For example: Hamilton City Council, New Zealand

13 ISO 2922:2000 *Acoustics – Noise from vessels on inland waterways and harbours*

14 Gordon Hempton *One square inch of quiet.* Details may be found on http://www.gorp.com/gorp/interact/guests/gordon_audio/a1.htm

15 Herodotus *The Histories.* A translation is available in the Penguin Classics series.

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SOME RECENT AUSTRALIAN DEVELOPMENTS IN THE REDUCTION OF ROAD PAVEMENT NOISE

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Abstract

The importance of pavement type in the generation of road traffic noise is both well known and has been long established. For this reason there have been considerable efforts made over some years in the technology, the design and the development of quieter pavements, both in Australia and internationally. Some recent Australian work on these issues is presented in the current paper, with particular emphasis on so called rigid pavements which are constructed of Portland Cement Concrete. The paper is based on recent empirically based studies of various rigid pavement types and of conventional asphalt pavements, which are also known as flexible pavements. In this context the acoustic attributes of a range of pavements are presented, compared and discussed. Also included is the relatively new rigid pavement surface type, known as Exposed Aggregate, which is reputed to have low noise characteristics. A novel approach for comparing these acoustic attributes has been adopted which involves using the Statistical Passby Index. This particular index, which was developed a few years ago by the International Standards Organisation, has not hitherto been applied in Australia. By means of this index an indication of the overall effects of pavement type on road traffic noise levels has been obtained.

INTRODUCTION

The level of road traffic noise produced along any particular road depends on many factors. These include traffic factors such as volume, composition and speed along with a variety of other factors such as the noise propagation conditions between the road and roadside receivers (UK DoT 1988). From a technical perspective, traffic noise may be regarded as the sum of the noise generated by individual vehicles in the traffic stream. The noise from any given vehicle is produced from several sources, the predominant ones of which include the engine and transmission system, the exhaust system and the interaction of the tyres with the road pavement wearing course. With the general exception of motorcycles, for all vehicles in a reasonable state of maintenance, tyre/road interaction represents the main source of noise at constant speeds in excess of around 40 km/hr (Samuels 1982). For this reason there is much to be gained in terms of traffic noise control by focusing on the tyre/road noise source. Both tyre and vehicle manufacturers are aware of this and consequently over the last 15 to 20 years there have been gradual reductions in the tyre component of tyre/road noise as a result of the development of quieter tyre tread designs. Within the road sector both in Australia and internationally considerable technological developments have also occurred which have led to quieter pavements (Samuels and Dash 1996, Sandberg and Ejsmont 1998).

The general area of tyre/road interaction noise is one that has in fact been the subject of considerable research and development effort for more than 25 years. As far as pavements are concerned, it would be fair to say that over this period, the vast majority of published work from Australia, Europe and Scandinavia has focused on the design, the construction and the acoustic performance of new flexible and rigid pavements. However in the USA the primary attention has been on rigid pavements. One key consensus of all this work for the flexible pavements is that the so called porous surfaces, also known as Open Graded Asphalt (OGA), produce considerably lower traffic noise levels than conventional surfaces such as Dense Graded Asphalt (DGA). In turn, the Portland Cement Concrete (PCC) rigid pavements are louder than the DGAs (Samuels and Dash 1996). These pavements are common throughout Australia and, according to Sandberg and Ejsmont (1998) they have been widely used on motorways and expressways throughout Europe. All these pavement types are also used in the USA, although the incidence of rigid pavements is greater there than in either Australia or Europe. Indeed factors for the effects of all these pavements have been incorporated into the new American Traffic Noise Model (Fleming et al. 1995).

The present paper brings together the conduct and outcomes of recently conducted Australian studies of the noise attributes of various pavement types such as those mentioned above. The pavements included various PCCs along with DGA’s and OGA’s. Of some interest was the inclusion of an Exposed Aggregate Cement Concrete (EACC), a relatively new pavement that is reputed to have low noise properties.
The pavement noise attributes were determined empirically by a technique known as the statistical passby test method (ISO 1997). Particular emphasis was placed on quantifying the noise attributes of the pavements involved and from there comparing these with the noise attributes of other rigid and flexible pavements (Samuels and Dash 1996, Samuels and Parnell 2000).

DATA COLLECTION AND ANALYSIS PROCESSES

Experimental Designs

Considerable local expertise and experience in undertaking investigations such as those reported herein have been gained in recent years (Samuels 1982, Samuels and Glazier 1990, Samuels and Roper 1991, Samuels and Nichols 1994, Samuels and Dash 1996, Samuels and Parnell 2000). In simple terms, the experimental designs adopted involved collecting samples of passby data from selected vehicle types on a range of pavements of interest. A wide variety of pavements has been investigated and this has been outlined above. The vehicle types included cars, medium trucks and heavy trucks.

Site Selection

In studies such as these, site selection is usually one of the most important and difficult tasks involved. This is because there are many factors that must be considered and allowed for in the selection process. For instance the sites must provide the range of pavement types required and at the same time be acoustically suitable for the noise data collection process. Furthermore there must be a reasonable sample of the designated vehicle types operating in the traffic at each site. When taken all together these compounding factors usually serve to place considerable limitations on the nature and type of sites finally included in the studies. Suffice it to say here that all of the sites represented in the present paper complied with all these stringent requirements. They tended to be located along high speed road facilities such as rural freeways or highways.

Data Collection

As mentioned previously, collection of the pavement noise data was undertaken according to the statistical passby technique. This involves the simultaneous measurement of the noise and the speed of individual vehicles in the traffic stream as they pass by a measurement location (ISO 1997). All of the noise data were collected with precision (Type 1) Sound Level Meters which were at the specified calibration throughout, as required by ISO (1997). Speed data were collected utilising a radar speed meter situated adjacent to the noise measurement station. During the measurements, this speed meter was concealed as far as possible so as not to influence driver behaviour at or near to the measurement station. All data were collected under weather conditions that were fine and mild to hot throughout, with occasional very light breezes.

Moreover, data were collected for cars, medium trucks and heavy trucks that were apparently in a reasonable state of maintenance. This meant that those vehicles producing an abnormally high level of engine or exhaust noise, most commonly due to a faulty exhaust system or the like, were not measured. Again this was in accord with ISO (1997). Here, cars included just about all two-axled, four-wheeled vehicles. Excluded were some four wheel drive vehicles that were equipped with off-road tyres that produced a pronounced whine. Typical vehicles in the medium truck category were rigid body trucks and buses, while the heavy vehicle category included articulated trucks and the like.

Data Analysis

All data were collated and analysed in accord with the established, scientifically based procedures adopted in previous studies such as Samuels and Dash (1996) and Samuels and Parnell (2000). Parameters involved in the analysis included the following.

- Pavement type
- Vehicle type
- Vehicle speed
- Vehicle trajectory to microphone distance

A two-component analytical process was initially involved. Firstly, each of the measured noise levels was adjusted to a reference distance of 7.5 m and a reference speed of 80 km/h. These adjusted levels were then aggregated by vehicle type for each of the pavement types involved to produce a set of data sub-populations. From there the second component involved determining the means and standard deviations of these sub-populations and applying them in quantifying and comparing the noise outputs of the various pavements included in the experimental program. It was at this stage that the Statistical Passby Index (SPBI) was subsequently determined for the various pavements according to ISO (1997). .

RESULTS

Overall data trends

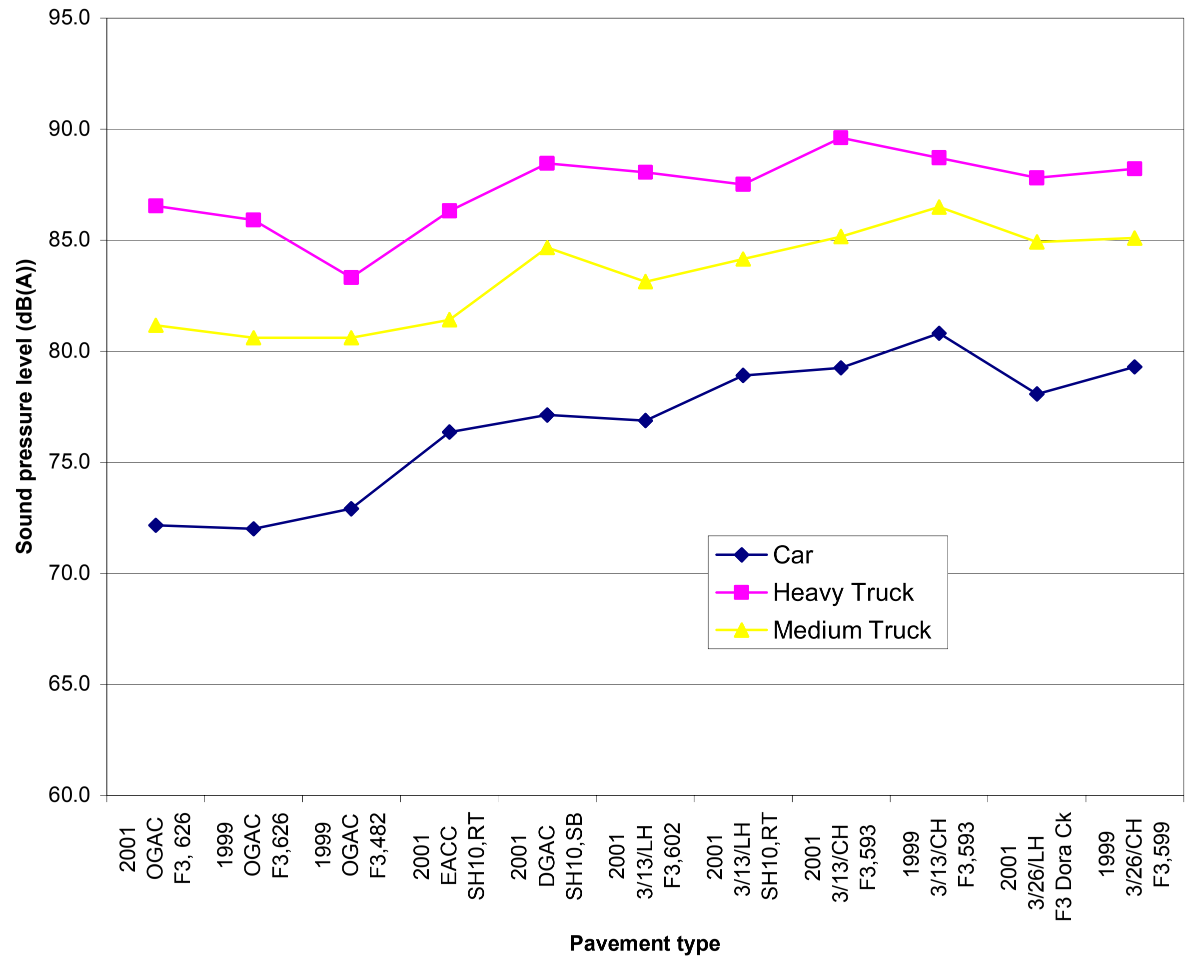
The complete set of statistical passby noise data is very large and is documented in publications such as Samuels and Parnell (2000). Consequently just a summary is presented in Figure 1, where the mean noise levels from 11 independent sets of data are plotted against pavement type. It may be reported here that good sample sizes were obtained as required for all vehicle types at each Site. Generally 50 to 100 cars were measured at each Site along with about 20 to 50 medium trucks and a similar number of heavy trucks. Further more, over all Sites the standard deviations of noise levels of the 33 sub-populations (3 per site) were in the range 0.7 to 3.5 dBA and were typically around 2.0 dBA. Statistical passby results such as these are acceptable scientifically and therefore satisfied the requirements of the studies for which they were collected. The abbreviations on the X-axis of Figure 1 are explained in Table I. Note that the four tyned pavements are Cement Concretes.

The data represented in Figure 1 were collected in a series of exercises that extended over a period of about 18 months from 1999 to 2001. Two of the Sites along the F3 Freeway, namely the OGA at Phone #626 and the PCC at Phone #593, were included in exercises that took place at the beginning and the end of this period. In both cases the two sets of data are within 1 dB(A) of each other, for all three vehicle types. This particular observation may be interpreted as indicating that the long term experimental reproducability achieved was indeed very good. On this basis the data may be confidently applied to what now follows.

Table I. Abbreviations on X-axis of Figure 1.

Line	Abbreviation	Explanation
1 (Date)	1999	Data collected during mid1999
	2001	Data collected from Nov 2000 to Feb 2001
2 (Pavement type)	OGA	Open Graded Asphalt
	EACC	Exposed Aggregate Concrete
	DGA	Dense Graded Asphalt
	3/13/LH	Tyned 3mm deep 13mm apart plus light hessian drag
	3/13/CH	Tyned 3mm deep 13mm apart plus coarse hessian drag
	3/26/LH	Tyned 3mm deep 26mm apart plus light hessian drag
	3/26/CH	Tyned 3mm deep 26mm apart plus coarse hessian drag
3 (Site location)	F3	F3 Freeway North of Sydney
	SH10	NSW State Highway 10
	626 etc	Emergency phone numbers along F3
	RT	Raymond Terrace
	SB	Swansea Bends

Figure 1. Passby noise data at 80 km/h and 7.5m



Exploring further what appears in Figure 1, it is apparent that over all pavement types there is a consistent trend for the noise emissions of heavy trucks to be the greatest, followed by medium trucks and cars in descending order. Typically the heavy truck levels exceed the medium truck levels by about 4 to 5 dB(A), with the medium truck levels exceeding those of the cars by around 5 to 6 dB(A). Again these observations are consistent with those from the previous studies such as Samuels and Dash (1996) and of the experiences in the USA (Fleming et al 1995). The OGA pavements produced the lowest noise levels with the PCCs producing the highest. In addition the EACC and DGA pavements appeared to generate comparable noise levels that were about mid way between the OGA and the PCCs. However it may also be noted that this observation was slightly more pronounced for cars than for trucks.

Summary

The data were aggregated to produce the summaries that appear in Table II, from which the following observations have been made.

- There was a clear gradation in vehicle noise level at all sites from heavy trucks to medium trucks to cars.
- The between pavement noise differences were generally most pronounced for cars, less so for medium trucks and less so again for heavy trucks.
- The PCC pavements tested produced comparable noise levels, for all three vehicle types. These pavements produced the loudest noise levels, particularly for cars.
- The OGA pavements produced the lowest noise levels.
- The above results are consistent with those from similar studies conducted previously.
- The EACC pavement produced comparable noise levels to the DGA. Together these two pavements were louder than the OGA and quieter than the PCCs. Again this trend was more apparent for cars than for trucks.

Table II. Overall summary

Pavement type	SPL (dB(A))		
	Car	Medium truck	Heavy tuck
OGA	72.1	80.9	86.2
DGA	77.1	84.7	88.4
EACC	76.3	81.4	86.3
PCC	78.9	84.8	88.3

The statistical passby index

Originating from European work on pavement noise conducted during the 1990s, the Statistical Passby Index (SPBI) was developed as an index that could be used to quantify the overall effects of pavement type on traffic noise (ISO 1997). The concept here was that the contributions of various vehicle types to the traffic noise generated on a given pavement could be incorporated in an index which is a function of their noise emissions, their proportions in the total traffic volume and their speeds. It should be noted that the SPBI was not devised as a road traffic noise index, such as the Leq(24 hour) or the L10(18 hour). The SPBI is defined in Equation 1.

$$SPBI = 10Log\,(W_1 \times 10^{L_1/10} + W_{2a}(V_1/V_{2a}) \times 10^{L_{2a}/10} + W_{2b}(V_1/V_{2b}) \times 10^{L_{2b}/10}) \qquad (1)$$

Where

SPBI = The Statistical Passby Index (dB)

Lx = The passby noise level of vehicle type x at reference speed Vx (dB(A)).

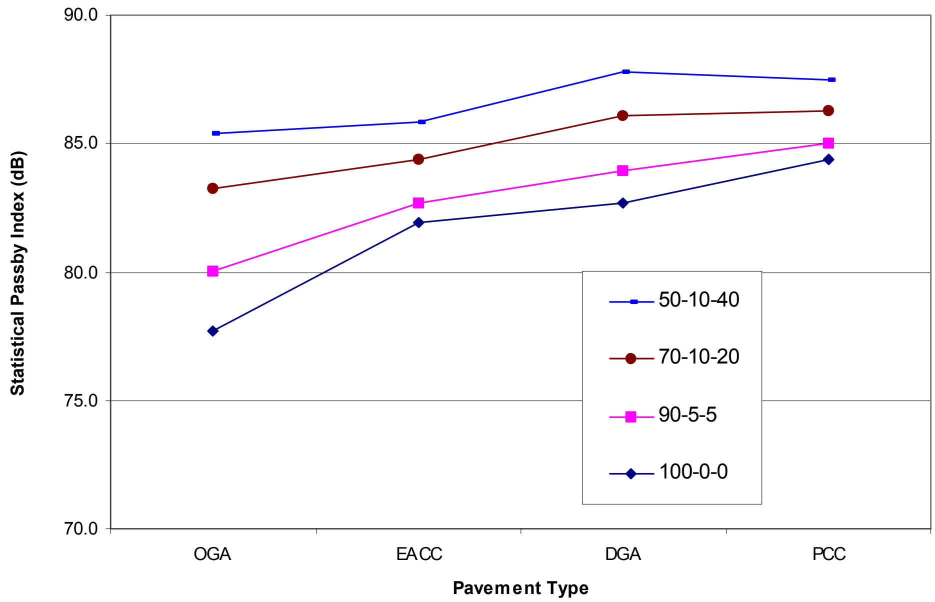
Wx = The proportion of vehicle type x in the traffic (-).

Vx = The reference speed of vehicle type x (km/h).

By way of explanation, three vehicle types are involved and these are Cars (1), Medium Trucks (2a) and Heavy Trucks (2b). The reference speeds are specified by ISO(1997) as being “high”, “medium” or “low”, but for the purposes of the present paper, just the “high” condition was adopted. Under this condition, cars, medium trucks and heavy trucks were, in accord with ISO (1997), assigned reference speeds of 110, 85 and 85 km/h respectively. Then, values of Lx were determined from an analysis of the statistical passby noise data upon which Figure 1 is based, again as set out in ISO (1997). Values of SPBI were thus calculated for four pavement types along with four traffic compositions and the results are presented in Figure 2. The traffic compositions range from a situation of cars only (100-0-0) to an extreme scenario of 50% cars with 10% medium trucks and 40% heavy trucks (50-10-40). They were selected to represent the range of traffic compositions that regularly occur in practice across the major road network in and around Sydney.

Firstly it is apparent in Fig 2 that the plots of the four scenarios exhibit generally similar trends of between-pavement noise variability. Moreover, it is also apparent that the SPBI seems to present a good representation of the between-pavement variability that was presented and discussed earlier in the present paper. This observation is supported by the similarities between the plot of car noise levels in Fig 1 and the cars only scenario plot of Fig 2. Turning now to the effects of traffic composition on what appears in Fig 2, it would seem that this factor might have a rather complex effect on SPBI over the pavement types included in the present paper. On the OGA pavement the SPBI spans a range of 7.7 dB over the four traffic scenarios. This range seems to vary with pavement type and is a minimum of 3.0 dB on the PCC pavement. Similar observations were made on several other plots such as Fig 2 that have been made for a wide variety of traffic scenarios but which have not been reported in the present paper.

Figure 2. Statistical Passby Index v pavement types for various traffic compositions at high speed



The reasons for these observations are not yet clear but it has been speculated that they might ensue from some interactions between the pavement type, traffic composition and speed factors that have not hitherto been recognised or identified. Resolving this matter is an area of future research that is currently being explored by the authors of the present paper. Potential outcomes of this work may lead to more precise specification of pavement type as a noise control technique which is specifically tailored for the traffic conditions at a given site.

CONCLUSIONS

As reported herein, high quality noise level data were successfully collected for a range of pavement types with the statistical passby technique. Subsequently these data were analysed according to well-tried and scientifically robust techniques. Generally clear, consistent trends were evident and the following conclusions have been drawn.

- The PCC pavements produced the loudest noise levels, followed by the EACC and the DGA which were, in turn, followed by the OGA.
- The EACC and the DGA produced comparable noise levels.
- The EACC pavement tested was clearly quieter than the PCC pavements by around 1 to 3 dB(A).
- The results of the present paper are consistent with those from similar studies conducted previously.
- Application of the SPBI to the data revealed trends that suggested that there might be some as yet unidentified, complex interactions between pavement type and traffic conditions that affect the generation of road traffic noise.

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QUEENSLAND DEPARTMENT OF MAIN ROADS (QDMR) ROAD TRAFFIC NOISE MANAGEMENT: CODE OF PRACTICE

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ABSTRACT

The departmental districts with high proportions of noise sensitive land use are continually being approached by the public with respect to complaints about the annoyance of road traffic noise. The purpose of this presentation is to provide an overview of the Code of Practice which aims to guide and instruct the user in the assessment, design and management of the impact of road traffic noise.

There is a need for the Department to move towards achieving both the acoustic environmental objective and long term planning levels as specified in the Environmental Protection (Noise) Policy which is subordinate legislation to the Environmental Protection Act 1994. Through this Code of Practice, the Department can demonstrate its "General Environmental Duty" by establishing and implementing best practice environmental management.

1.0 INTRODUCTION

The purpose of the Code of Practice is to provide guidance and instruction for the assessment design and management of the impact of road traffic noise.

The specific objectives of the Code of Practice are as follows:

- to provide advice on the appropriate criteria to be used for the assessment of road traffic noise;
- to establish consistent methodologies for the assessment of the impact of road traffic noise including establishing priorities for noise attenuation measures; and
- to provide guidance on an integrated design process for the inclusion of noise attenuation measures into the road environment so that the social, economic, visual, safety, community and environmental factors are not compromised.

2.0 TERMINOLOGY

Many Main Roads Districts have been concerned, and rightly so, about the implications of road traffic noise related Queensland legislation, policies and responsibilities on their works programs and funding commitments.

2.1 General Environmental Duty

The Environmental Protection Act refers to "General Environmental Duty" - a person must not carry out any activity that causes, or is likely to cause environmental harm unless the person takes all reasonable and practicable measures to prevent or minimise the harm.

While the department is required to embrace the concept of "General Environmental Duty" from a road traffic noise perspective, there have been instances where the implementation of noise attenuation measures may not have been technically feasible in order to meet the departmental criteria, and in particular, would not have been cost effective.

Therefore it is considered reasonable that the department may not implement any noise attenuation measures under these circumstances.

2.2 Acoustic Quality Objective

The Environmental Protection (Noise) Policy (EP(Noise)P) applies to the whole of Queensland's acoustic environment. The "acoustic quality objective" is a long term goal of attaining a good standard of amenity with respect to environmental noise. The objective is an ambient level of 55 dB(A) L_{eq} (24h) or less for most of Queensland's population living in residential areas.

It should also be realised that while the Department should be party to achieving this "acoustic quality objective", it is only one of the many stakeholders responsible for the management of the impact of road traffic noise.

2.3 Beneficial Asset

The EP(Noise)P introduces the concept of "beneficial asset" within the environment. The policy names an airport, approved industrial estate, navigable waterway and a public road or railway as a "beneficial asset".

Beneficial assets are necessary for the community's environmental, social and economic well being although their operation or use can have adverse effects on the environmental values. However, it is intended that, as far as practicable, any significant adverse effects from their use or operation be progressively reduced.

2.4 Planning Levels

An acoustic environment for a beneficial asset can be identified in terms of "planning levels" criteria under an environmental management program. The criteria do not presume to protect the environmental values of the human environment. This means that people living within an environment exposed to noise from a beneficial asset will be affected by that noise.

The planning levels as stated in EP(Noise)P are as follows:

> The planning levels for a public road are the following noise levels, assessed 1m in front of the most exposed part of an affected noise sensitive place –
>
> a) the following levels assessed as the L_{10} (18 hour) level
>   - i) for a State-controlled road - 68 dB(A)
>   - ii) for another public road – 63 dB(A)
>
> b) 60 dB(A), assessed as the highest 1 hour equivalent continuous A-weighted sound pressure level between 10.00 p.m. and 6.00 a.m [(L_{eq} (1 hour)];
>
> c) 80 dB(A), assessed as a single event maximum sound pressure level (L_{Amax}).

It should be noted that the criteria stated in the Code of Practice generally are in accordance with, or are less than the planning levels stated in the EP(Noise)P except for the L_{eq} night time noise level and the L_{Amax} criteria.

It is also considered that "planning levels" are the levels to be progressively implemented during the life of the EP(Noise)P i.e. 7 years. These planning levels are not design goals.

3.0 BACKGROUND TO CODE OF PRACTICE

From a road traffic noise perspective, the Department had operated in the past under the "Interim Guidelines and Technical Notes for Road Traffic Noise Amelioration. 1992".

However, due to the following issues there was a need to produce a new road traffic noise guideline:

- experience with the use of the Interim Guidelines;
- review of past practices;
- enactment of the EP(Noise)P; and
- emerging issues facing the Department and industry. e.g. Integrated Planning Act.

CONTENTS OF THE CODE OF PRACTICE

The contents of the Code of Practice include the following Sections:

- **Overview -** Framework Behind the Code of Practice and Guide to the use of the Code of Practice.

- **Description of Road Traffic Noise -** Definition of Noise, Factors Influencing Road Traffic Noise, Generation and Propagation and Environmental Indicators for Road Traffic Noise;

- **Priorities and Criteria -** Limitations, Existing Residences, Education and Health Buildings, Parks, Outdoor Educational and Recreational Areas, and Proposed Developments;

- **Assessments -** District Road Traffic Noise Management Strategy, Road Traffic Noise Study and Selection of Noise Barrier Type;

- **Integrated Design -** Safety Requirements, Maintenance Requirements, Public Amenity, Horizontal and Vertical Alignment, Fauna Movement, Visual Considerations and Community Art.

- **Glossary**

- **Bibliography**

4.0 DISTINCTIVE ISSUES IN THE CODE OF PRACTICE

The main contents of the Code of Practice, are stated below:

5.1 Priorities and Criteria

5.1.1 Traffic Planning Horizon

A traffic planning horizon of 10 years following construction, upgrading or assessment is to be considered for all criteria and priorities.

5.1.2 Urban and Rural Environments

To some extent the criteria for urban and rural environments are defined especially for new access controlled roads and proposed residential developments.

5.1.3 Criterion Levels – Existing Residences (Facade Corrected)

(a.) New Access Controlled Roads – Priority 1
$\geq$ 60 or $\geq$ 63dB(A) L_{10} (18h) depending on the increase above the preconstruction noise level [55dB(A) L_{10} (18h)].

(b.) Upgrading Existing Roads
Priority 2 $\geq$ 68 dB(A) L_{10} (18h) and an increase $\geq$ 3 dB(A)
Priority 3 $\geq$ 68 dB(A) L_{10} (18h) and an increase < 3 dB(A)

(c.) Existing Roads – No Roadworks.
Priority 4 $\geq$ 68 dB(A) L_{10} (18h) and an increase $\geq$ 3 dB(A)
Priority 5 $\geq$ 68 dB(A) L_{10} (18h) and an increase < 3 dB(A)

5.1.4 Criterion Levels – Education and Health Buildings (Indoor Levels)

(a.) New Access Controlled Roads
Priority 1 $\geq$ 48 dB(A) L_{10} (1h) and an increase $\geq$ 3 dB(A)

(b.) Upgrading Existing Roads
Priority 2 $\geq$ 55 dB(A) L_{10} (1h) and an increase $\geq$ 3 dB(A)
Priority 3 $\geq$ 55 dB(A) L_{10} (1h) and an increase < 3 dB(A)

(c.) Existing Roads – No Roadworks
Priority 4 $\geq$ 55 dB(A) L_{10} (1h) and an increase $\geq$ 3 dB(A)
Priority 5 $\geq$ 55 dB(A) L_{10} (1h) and an increase < 3 dB(A)

(d.) Proposed Residential Development

- Residential Habitable Floors
63dB(A) L_{10} (18h) where existing levels > 40dB(A) L_{90} (8h) (10 pm – 6 am)
60dB(A) L_{10} (18h) where existing levels $\leq$ 40dB(A) L_{90} (8h) (10 pm – 6 am)

-Balconies and Formal External Open Space
63dB(A) L_{10} (18h) where existing levels > 45dB(A) L_{90} (8h) (10 pm – 6 am)
60dB(A) L_{10} (18h) where existing levels $\leq$ 45dB(A) L_{90} (8h) (10 pm – 6 am)

-Where these criterion levels cannot be met, internal maximum design criterion levels specified in AS2107 may be considered provided the Department can be certain that this criteria will be implemented at building application stage of the development process.

5.2 Noise Management Methods

(a) Control at the Source.

The use of various pavement surface types can have a noticeable effect on road traffic noise levels. The latest information search has indicated that for the life of a pavement surface, the following correction factors can be used:

Road Surface Type	Change in Noise Level dB(A)
Dense Graded Asphalt	0
Open Graded Asphalt	-4
Stone Mastic Asphalt	-2
Portland Cement Concrete	+4

It should be noted that these correction factors can be used for all speeds from 60km/h and above.

(b) Control between the Source and Reception Point.

The design and construction of noise barriers shall be undertaken in accordance with the following requirements:

- design and construction in accordance with departmental Standard Specification, MRS 11.15 (12/99);
- undertake a landscape assessment process to consider the existing and intended landscape vision for the road to ensure that the design of any attenuation measures are fully integrated into the road landscape; and
- undertake an integrated design process to ensure that social, economic and technical factors are considered equally.

(c) Control at the Reception Point

The intent of the Code of Practice is that noise attenuation works will only be undertaken within the road reserve.

Where noise sensitive development is proposed beside a state-controlled road, the developer shall be responsible for the assessment of the impact of the road traffic noise. In this instance, the mitigation of the impact of road traffic noise maybe achieved by the use of the following options:

- provision of buffers within the development;
- restriction of building to single storey;
- building layout/design;
- architectural design measures (AS2107, AS3671) (thickened glass, double glazing, brick construction, ceiling insulation, airconditioning or mechanical ventilation);
- courtyard noise barriers; and/or
- covenants (Based on Natural Resources and Other Legislation Amendment Act 2000, March 2000. The purpose of covenants capable of registration under the Land Act 1994 and Land Title Act 1994 have been expanded to allow the State, statutory body representing the State or a local government to enter into registerable covenants that are about the use of land, a building or a proposed building.)

5.3 Integrated Design

As an integral part of the design of noise attenuation measures eg. noise barriers, there are a number of other issues to consider that will influence the design of the barriers. Hence the importance of the integrated design process whereby social, economic and technical factors are considered equally.

5.3.1 Safety Requirements

- Clear Zones
- Sight Distance
- Lighting

5.3.2 Maintenance Requirements

- Maintenance Access

5.3.3 Public Amenity

- Privacy and Security
- Shade Effects
- Air Circulation
- Views
- Public Consultation

5.3.4 Horizontal and Vertical Alignment

- Avoidance of small gaps
- Rationalisation of barrier heights.

5.3.5. Fauna Movements

- Wildlife fencing

5.3.6 Visual Considerations

- Staggered alignments
- Vegetation
- Shadow lines

5.3.7 Community Art

- Artistic Impression

5.0 USE OF DEPARTMENTAL STANDARD SPECIFICATION, MRS 11.15

6.1 Design

- Registered Professional Engineer of Queensland.
- Wind loading Code.

6.2 Vandalism

- Impact Test

6.3 Timber Barriers

- Grading Specification
- For sawn timber and plywood noise barrier material, the sampling requirements for preservative penetration and retention are provided. The required testing can add up to $20,000.00 to the cost of the material for a $1,000,000.00 project.

6.4 Absorptive Panels

Only two steel absorptive panels have been approved for use in QDMR projects. These include the Fenco Absorptive Noise Barrier System and the BHP/Ingal Civil Products Sentinel System.

6.5 Transparent Noise Barriers

A supplement to departmental Standard Specification MRS 11.15 has been prepared for transparent noise barriers.

7. CURRENT RESEARCH

The EP(Noise)P introduces the concept of night time noise criteria with respect to the planning levels. The "Calculation of Road Traffic Noise" model (CORTN) has been successfully used to calculate/predict the L_{10} (18 hour) parameter but is not able to calculate the night time L_{eq} parameter.

In order to progressively address community concerns about night time road traffic noise, it has become necessary to investigate the availability of a suitable model to calculate the L_{eq} parameter. A significant degree of confidence is required in the calculation accuracy of an adopted model.

A study is presently being undertaken to determine the calculation accuracy of the US FHWA, Traffic Noise Model (TNM) as well as to understand how the model operates.

From a statistical view point, the results indicate that TNM is a reasonably good calculation model that generally appears to be suited to Queensland conditions.

8. CONCLUSION

The Road Traffic Noise Management: Code of Practice develops a framework for the assessment and management of road traffic noise. It aims to provide a "best practice" approach considering social and environmental impacts associated with State-controlled roads. It also establishes priorities and departmental criterion levels as well as design criteria which can be used to reduce the impact of road traffic noise.

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APPLICATION OF THE NSW EPA'S 'ENVIRONMENTAL CRITERIA FOR ROAD TRAFFIC NOISE' POLICY TO THE PROPOSED WESTERN SYDNEY ORBITAL MOTORWAY IN SYDNEY

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Abstract
The NSW EPAs new policy for assessing road traffic noise, the 'Environmental Criteria for Road Traffic Noise' *(ECRTN) was released in May 1999 in response to the need to provide an efficient road transport network, whilst maintaining environmental amenity. The policy provides a framework for assessing and managing noise impact for a range of developments, including new residential and noise sensitive developments affected by existing roads, developments with the potential to increase traffic on existing roads, redevelopment of existing roads and, as discussed in this paper, proposed new roads.*

The Western Sydney Orbital (WSO) is a proposed motorway approximately 39km long, that will connect the M5 Motorway (Hume Highway) at Prestons in the south with the M2 motorway at West Baulkham Hills in the north, forming part of a 'ring road' around the Sydney Metropolitan Area. The proposed arterial road was assessed in terms of the ECRTN and as such provides a good opportunity to present the methodology behind assessing impact of a major road corridor in terms of the EPA's new policy.

This paper presents a summary of the noise impact assessment process for the PROPOSED WSO, along with key issues found in assessing a major road corridor to the ECRTN.

Introduction

The Western Sydney Orbital (WSO) is a proposed motorway approximately 39km long, linking the Hume Highway/ M5 Motorway at Prestons with the M2 Motorway at West Baulkham Hills. Part of the NSW Government's integrated transport plan for Sydney, *Action for Transport 2010* is that the proposed WSO would promote growth in existing industrial areas, provide good connections to the developable employment land in Western Sydney and complete the Sydney Orbital Road network. The proposed WSO would replace the Cumberland Highway as the National Highway Route, potentially reducing travel time through Sydney by up to 67 minutes[1].

As a large, linear project the noise impact assessment of the proposed WSO was complex. The 39km long route passes through vastly different environments, including industrial and commercial areas; long established residential areas; new and proposed residential areas and agricultural lands. The area is rapidly changing as Western Sydney opens up to new development of commercial, industrial and residential areas.

The Environmental Impact Statement (EIS) and consequently the Noise Impact Assessment for the proposed WSO was carried out in two sections:

- the southern section, from the Hume Highway/ M5 Motorway at Prestons to Elizabeth Drive, Cecil Hills (approximately 11km); and
- the northern section, from Elizabeth Drive, Cecil Hills to the M2 Motorway at West Baulkham Hills (approximately 28km).

The project assessment process was lengthy. The EIS was commenced in 1995, finalised in late 2000 and exhibited in January to March 2001. During this period the method of assessing noise impact from road projects experienced several changes, particularly the introduction of the NSW Environment Protection Authority's (EPA) *Environmental Criteria for Road Traffic Noise* (ECRTN) in May 1999.

A review and update noise impact assessment was then commissioned to form part of the Representations Report prepared by the Roads & Traffic Authority for submission to DUAP.

Renzo Tonin & Associates Pty Ltd was commissioned to carry out a noise impact assessment of the proposed WSO. The overall study assessed a four-lane, divided carriageway road, proposed to run from the M5 Motorway at the Camden Valley Way interchange to the M2 Motorway, as depicted in **Figure 1** below.

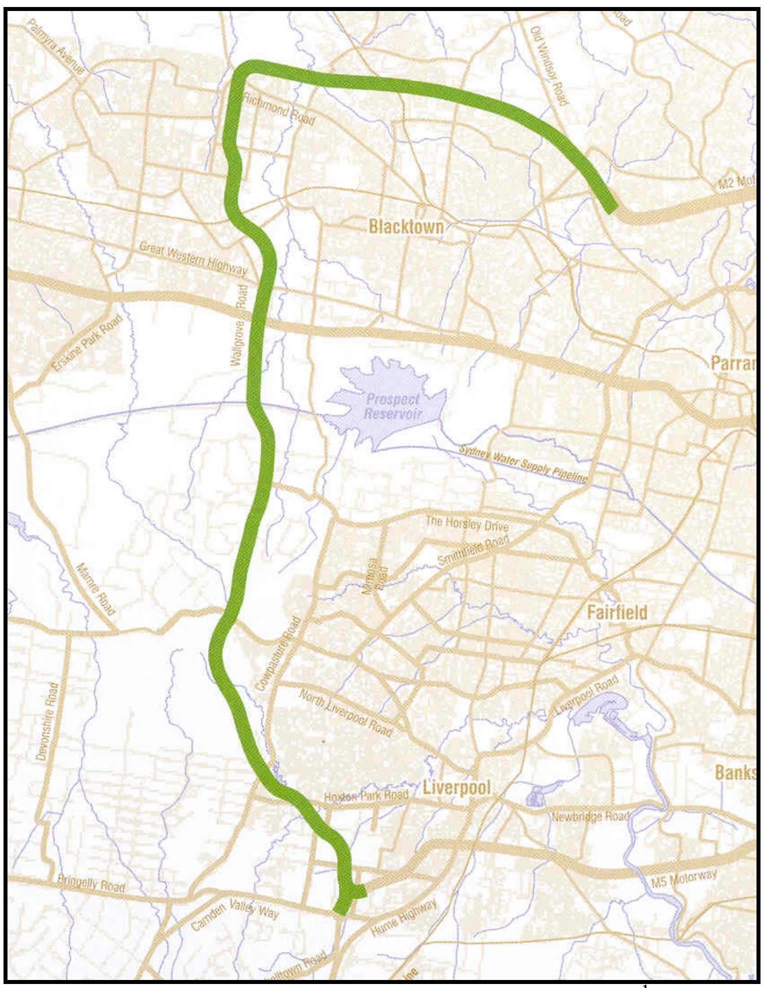

Figure 1 Proposed Western Sydney Orbital[1]

Noise from the proposed road was calculated for its ultimate development in the year 2016, which could have up to approximately 54,000 vehicles per day using the road. Predicted operational noise levels were assessed in terms of the noise goals set in the EPA's ECRTN.

This paper discusses the noise impact assessment process for the WSO route, highlighting points of interest with regard to assessing road projects in accordance with the ECRTN.

Measurement of Existing Noise Levels

Existing ambient noise levels were monitored using mostly long-term noise monitoring techniques, backed by short-term measurements. There were a total of 40 long-term noise monitoring locations spread out along the 39km route.

As the existing noise environment varied along the length of the route, it was divided into sections and the existing noise environment was established for each section. Traffic noise was generally found to be the dominant noise source.

Establishing Noise Criteria

Road traffic noise from the proposed WSO was assessed to the NSW EPA's ECRTN. Noise criteria for residential areas along the route were taken from Table 1 of the ECRTN[2], which establishes noise criteria for a new freeway or arterial road corridor applicable to residential-, rural- and urban-zoned lands occupied by dwellings. Noise criteria for sensitive land uses, including existing and proposed schools, places of worship and recreation areas, were taken from Table 2 of the ECRTN[2]. These became the 'base criteria' for the project.

The noise criteria specified in Tables 1 and 2 of the ECRTN refer to total traffic noise rather than only noise due to the project under consideration. [2]

Where the 'base criteria' cannot be achieved, then traffic noise mitigation measures implemented shall approach these criteria as far as is reasonable and feasible while taking into account cost effectiveness. That is, a +0.5dB(A) allowance over existing traffic noise levels is permitted for new roads only where all feasible and reasonable mitigation measures have been exhausted.

Sleep arousal from traffic noise was assessed with reference to the EPA's 'Environmental Noise Control Manual' (ENCM)[3] and Appendix B of the ECRTN, although this is not further discussed in this paper.

Traffic Noise Prediction Methodology

Noise levels along the proposed WSO were modelled and noise predictions were calculated for daytime ($L_{eq,15\ hour}$) and night time ($L_{eq,9\ hour}$) at the first year of opening of the road (2006), and ten years after opening (2016) in accordance with the ECRTN.

Noise predictions for the southern section of the route were based on the method developed by the United Kingdom Department of Environment entitled 'Calculation of Road Traffic Noise (1988)' known as the CORTN88 method, which was modified for Australian conditions and to include three noise source heights in its calculations. Total traffic noise generated by the proposed WSO and existing surrounding roads was modelled as part of the assessment.

In the initial phase of the project, noise predictions for the northern section of the route were undertaken by others. In that study, traffic noise generated by the proposed WSO was modelled, however existing adjoining roads were not included. The situation was rectified in our review if the entire route.

Validation of the CORTN88 model was accomplished by comparing measured existing noise levels at several locations with modelled existing noise levels. The results showed the model accuracy was within 63dB(A) of measured traffic noise levels, confirming the suitability of the model for the project.

Traffic Noise Assessment (Residential Areas)

To determine the degree of impact upon residences along the proposed road during its operational phase, the route was sub-divided into a number of sections or receptor areas, identified as Noise Catchment Areas (NCAs). Each NCA was selected on the basis of having similar topographical features and similar noise contour patterns. A total of 33 NCAs were defined for the southern section and 24 NCAs for the northern section. In the review and update of the noise impact assessment some northern section NCAs were split into sub-catchments where it was considered necessary, bringing the total to 29 NCAs.

For each NCA, predicted traffic noise levels, number of dwellings exceeding the 'base criteria' and noise mitigation options were determined. Dwellings affected by road traffic noise exceeding the ECRTN were counted if those dwellings fell within the non-compliant noise contour and within the boundaries of the nominated NCA. It was found that defining NCAs is critical to any assessment of noise impact, as is selecting the representative location for noise predictions and noise barrier height calculations for each NCA.

Western Sydney is an area experiencing rapid change in land use. Recently developed residential areas and areas zoned 'Future Residential' were included in the assessment based on a *Review and Update of Zoning and Land Use*[4] report. The number of potentially affected residences in areas not yet developed was based on an estimated maximum number of dwellings within each land parcel.

The results of the assessment are summarised in **Table 1**.

Traffic Noise Assessment (Sensitive Land Uses)

39 existing and proposed schools, 5 places of worship and 36 recreation areas were identified over the entire WSO route and assessed to the ECRTN criteria.

All schools, with the exception of 11, potentially affected by the proposed WSO were found to achieve compliance with the ECRTN's $L_{Aeq(1hr)}$ 55dB(A) external playground noise criterion and $L_{Aeq(1hr)}$ 40-45dB(A) internal noise criterion, between 8.30am and 3.30pm. Of the 11 schools where these criteria were not achieved, 5 schools would not comply with the criteria when windows and doors were closed. Upgraded glazing was therefore recommended for these 5 schools, with mechanical ventilation or air conditioning required for all 11 schools.

Three of the five places of worship were found to not comply with the ECRTN. However, noise monitoring and modelling conducted for these places of worship indicated that ambient noise levels were controlled by traffic noise from existing roads. Noise barriers along the proposed WSO were found not to provide a net improvement to overall traffic noise levels at these locations.

The assessment of recreation areas found that the use of recreation areas as buffer zones on a site-by-site basis was justified by considering the type and frequency of use of the public areas and the likelihood that predicted noise levels would have an impact on the recreational activities. Proposed parks and proposed changes to parks were also considered in the study. The RTA and the community could then use this information in determining the appropriate acoustic treatment to apply to such recreational areas.

Project Design Modifications

Project design modifications considered to potentially change noise impact from the proposed WSO were modeled and assessed in the review and update report. They consisted of existing road and interchange upgrades, and vertical and horizontal realignment of the route.

Nominal Barrier Heights

Nominal barrier heights were also determined for each NCA where traffic noise levels were found to exceed the 'base criteria'. Noise barrier heights were determined based on the assumption that barriers were the only viable option in all cases. Although this is not the case in every NCA, the information was provided as input for future cost-effectiveness and feasibility analysis. A summary of nominal barrier heights is provided in **Table 1**.

Noise barrier requirements may change should the 'allowance' criteria be used in the final road design analysis, as permitted in the ECRTN. Use of the 'allowance' criteria may provide a reduction of noise barrier design heights, and possibly an elimination of noise barriers in some locations. This would be apparent along sections of the route already affected by traffic noise, where provisions of noise barriers along the proposed WSO may not reduce the total noise due to contributions from other surrounding roads.

The process of reviewing barrier heights is currently 'in-progress' for a selected number of NCAs as part of the cost effectiveness study for noise barriers along the proposed WSO route. Noise monitoring originally conducted for the EIS is considered dated and unreliable for use in cost effectiveness study. Thus, existing noise levels in critical areas are being re-monitored so that a suitable 'allowance criteria' may be set.

Table 1 Results of the Noise Impact Assessment of the proposed WSO on Residential Areas

NCAs	Predicted Traffic Noise Levels at Residences (2016), dB(A)		No. of Affected Dwellings Exceeding: Daytime $L_{eq, 15hr}$ = 55dB(A)		Night $L_{eq, 9hr}$ = 50dB(A)		Proposed Noise Mitigation Options	Nominal Barrier Height, m	
	$L_{eq,15hr}$	$L_{eq,9hr}$	Exceedance, dB(A) 1–5	6–10	Exceedance, dB(A) 1–5	6–10		WSO	Other
Southern Section - Prestons to Cecil Hills									
E1-E4	52-62	47-57	83 (~345)	36 (~235)	83 (~345)	36 (~235)	Noise Barriers	0-2	6+
E5-E7	49-65	45-60	2	3	2	3	Building treatment	1-7	0-4
E8-E9	49-53	<45-48	0	0	0	0	No treatment	0-2.5	-
E10-E11	46-65	<45-60	67	36	67	36	Noise Barriers	-	1-3
E12-E16	<50-65	<45-60	0 (~200)	0 (~80)	0 (~200)	0 (~80)	No treatment	-	-
E17 – E18	<55-60	<45-55	30	3	27	15	Noise Barriers	1-3	1-1.5
W1-W2	46-54	<45-49	0 (~120)	0	0 (~120)	0	No treatment	-	-
W3-W5	48-61	<45-56	6	5	6	5	Building treatment	1.5-4	2-3
W6-W8	45-53	<45-48	0 (~30)	0	0 (~30)	0	No treatment	0-1	-
W9-W10	47-65	<45-60	52 (~46)	13	52 (~46)	13	Noise Barriers	0-4	2-3
W11-W13	48-63	<45-58	5 (~150)	2	5 (~150)	2	Building treatment	1-3	1.5-3
W14	50-65	<45-60	0 (~220)	0 (~200)	0 (~220)	0 (~200)	No treatment	-	-
Northern Section - Cecil Hills to West Baulkham Hills									
1E - 5	<45-65	<45-60	49	32	46	29	Building treatment	1-7	1-3
6 - 7E	<45-65	<45-60	0	0	0	0	No treatment	0-3	-
7W	<50-65	<45-60	17	3	15	2	Building treatment	0-3.5	-
8-9	<45-65	<45-60	66	104	58	94	Noise Barriers	3-5	-
10E	<45-65		1	0	1	0	Building treatment	3	-
10W-14	<45-65	<45-60	177	176	187	175	Noise Barriers	2-5	-
15N	<50-65	<45-60	1	1	1	1	Building treatment	1	-
15S-24	<45-65	<45-60	1735	1056	1674	1054	Noise Barriers	2-6	0-2

Notes: 1. *Summarised from Table 6.1.1 & Table 8.1 of the WSO Assessment Update Report*[7]

2. *Numbers appearing in brackets (x) represent estimated number of houses potentially affected by the WSO in areas zoned for residential development.*

Key Issues Found

It is worthwhile highlighting some interesting issues that were identified during the application of the ECRTN to the assessment of the proposed WSO project.

The definition of NCAs is critical to the assessment process. This can be difficult for larger road projects (a total of 62 NCAs were defined for the WSO). However this is necessary to properly identify residences affected by a proposed road, subsequent noise mitigation cost-effectiveness studies and eventual detail design of the selected noise mitigation measures. NCAs must be selected to represent a similar noise environment across the entire catchment. Where this is not achieved, the catchment should be subdivided into smaller catchments.

The application of the ECRTN is found to require more extensive modelling than previously required as both the proposed road and surrounding roads must be modelled to predict total traffic noise levels. Further, more detailed noise monitoring is now required to characterise the existing traffic noise environment when assessing the reasonableness and feasibility of noise mitigation options and the possible adoption of the 'allowance criteria'. Thus the cost of assessing the noise impact of a road project is potentially increased. Note however, that apart from establishing background noise levels for the assessment of construction noise impact and obtaining traffic noise levels for model validation, additional noise monitoring would not necessarily be required should the project be assessed simply to the ECRTN 'base criteria', as these are absolute levels.

Selecting the appropriate road traffic noise criteria for a road project may also be difficult where more than one 'Type of Development' applies to the road project. This difficulty was experienced on the WSO project, where the proposed WSO would run adjacent to Wallgrove Road. Traffic using Wallgrove Road would essentially be transferred to the WSO, which posed the question of whether the proposed road should be assessed as a 'New freeway or arterial road corridor' or as a 'Redevelopment of an existing freeway/ arterial road'. The latter type of development allows an additional 5dB(A) to the traffic noise criteria. For the assessment of this project the adoption of the more conservative approach was appropriate, as the WSO would generally be perceived as a new road traffic noise source.

The ECRTN relies on the use of reasonableness and feasibility to determine whether or not traffic noise from the project and existing roads can be reduced and whether the 'allowance criteria' can be used. It does not however explain how to determine what is reasonable and feasible. To assist with future road projects, the RTA is in the process of preparing a '*Noise Management Manual'* which will provide a process for selecting and designing reasonable and feasible noise treatment options.[6]

Finally, in future projects where there is a multiplicity of consultants involved in assessing a major route, the necessary mechanisms should be put in place to allow a consistent approach to be followed by all consultants involved in the project. For example, the difference in policy interpretation between the consultants involved in the WSO noise impact assessment could have been avoided by better communication at the outset of the project. The RTA's proposed '*Noise Management Manual'* might also provide a solution to this by providing suitable guidelines and procedures to be followed when assessing road projects.

Conclusion

A Noise Impact Assessment was carried out as part of the EIS for the proposed WSO, a proposed motorway standard road linking from the Hume Highway/ M5 Motorway in the south, to the M2 Motorway in the north. The assessment was carried out in two sections, the southern section (Prestons to Cecil Hills) and the northern section (Cecil Hills to West Baulkham Hills). A review and update report was provided as part of the RTA's Representations Report, providing a holistic approach to the EIS noise impact assessment.

The ECRTN requires that total traffic noise from a road project must be considered. This means that noise from the proposed road and from surrounding roads must be included in the noise modelling and assessment process. Adequate noise monitoring of existing road traffic noise levels is required so that an 'allowance criteria' may be set, where applicable. In defining NCAs it is important to ensure a similar noise environment across each NCA.

This methodology results in a more comprehensive approach to assessing noise impact serving to protect the noise amenity of communities surrounding a proposed road project.

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1. Roads & Traffic Authority, Proposed Western Sydney Orbital – Summary of the EIS, p4, 2000.
2. NSW Environment Protection Authority, Environmental Criteria for Road Traffic Noise, p6, 10, 11, 1999.
3. NSW Environment Protection Authority, Environmental Noise Control Manual, 1994.
4. Sinclair Knight Mertz, Review and Update of Zoning and Land Use, 2001.
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ASSESSMENT OF ROAD TRAFFIC MAXIMUM NOISE EVENTS AT NIGHT TIME

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Abstract
The RTA in NSW has prepared procedures for the assessment of maximum noise level events associated with heavy vehicles at night time. Existing maximum noise levels have been measured at night time, requiring the development of a specialised measurement system. Measurements were made on an arterial road and a number of collector roads and local streets. The results revealed apparent anomalies between locations regarding the number of heavy vehicle movements and associated noise levels at night time. A diagnosis has shown that many light vehicles, particularly 4WD vehicles, generate maximum noise levels which would be ordinarily defined as night time maximum noise events.

Introduction

It is well recorded that maximum noise level events at night time can cause sleep disturbance and that the most common cause of these events is the passage of heavy vehicles along nearby roads. Research to date indicates that the degree of sleep disturbance is related not only to the noise levels generated by these events and the number of events, but also the noise levels relative to the general ambient noise level, commonly expressed as an L_{Aeq}.

The Roads and Traffic Authority in NSW (RTA) has prepared a Practice Note for the assessment of maximum noise level events associated with new roads at night time. The procedure requires the measurement of existing maximum noise levels and the prediction and assessment of future maximum noise levels associated with the proposed new road development.

In the assessment of the noise impact of a road proposal in the Wollongong Region, measurements of existing maximum noise level events have been undertaken and the results are here analysed and discussed.

RTA Maximum Noise Level Event Practice Note

The RTA Practice Note [1] defines a maximum noise level event as follows:

- Occurring during the night time period (10.00pm – 7.00am)
- Having a maximum noise level greater than or equal to 65dBA
- Having a maximum noise level greater than or equal to the $L_{Aeq,1hr}$ (for the hour in which the event occurs) plus 15dBA.

The 65dBA level is the outdoor equivalent of the indoor 50 - 55dBA referred to in the *NSW Traffic Noise Guidelines* [2] as being the level below which awakening reactions are unlikely to be caused. The L_{Aeq} plus 15dBA level is similar to the background level plus 15dBA set as an $L_{A1,1min}$ sleep disturbance criterion by the NSW Environmental Protection Authority (EPA) [3].

In any event, this definition of a maximum noise level event appears to be reasonable in the light of the research into sleep disturbance already carried out.

Given this definition, it is clear that the number of maximum noise level events at night time will depend upon the number of loud vehicles using the road, the maximum noise levels generated by these vehicles and also the general road traffic noise level expressed as L_{Aeq}.

The Practice Note recommends measurement of the number of existing maximum noise level events occurring, and also prediction and assessment of the number that would occur in the future as a result of a proposed road development.

Measurement Technique

The existing number of maximum noise level events was measured on the existing roads as part of the Wollongong Project. The measurements were carried out at residential facade locations in accordance with normal road traffic noise measurement procedures.

Since currently available noise measurement instrumentation which can be left unattended does not lend itself directly to the recording of the number of maximum noise level events at night time, a noise measurement system was developed to allow the measurements to be carried out. This involved the use of a standard environmental noise logger whose output was fed to a laptop computer. It was then necessary to write and use software that could analyse the data being fed to the laptop and record the maximum noise level of an event and the time that the event occurred. In this case, the maximum noise level event was defined as follows:

- Having a maximum noise level greater than or equal to 65dBA.
- Being separated from any other maximum noise level event by at least three seconds.
- Being separated from any other maximum noise level event by a drop in levels of at least 5dBA.

Post analysis of the results (after the $L_{Aeq,1hr}$ level had been determined) allowed those events where the maximum noise level was less than L_{Aeq} plus 15dBA to be excluded.

From this information the number of defined maximum noise level events during each 1hr period at night time was determined.

Measurements and Results

The measurements of existing maximum noise level events were made as part of an assessment of the proposed road development in the Wollongong Region. Measurements were made on streets along the route of the proposed development and also along the Princes Highway where much of the traffic ultimately to use the new route is currently travelling.

The Princes Highway currently carries relatively heavy traffic with significant numbers of heavy vehicles. This is in contrast to the existing streets along the proposed route where fewer vehicle movements currently occur with a very limited number of heavy vehicle movements. The existing number of movements for the two measurement areas are shown in Table 1.

Table 1 Existing Traffic Flows

Area	Night Time Vehicles Movements (10.00pm - 7.00am)	
	Light Vehicles	**Heavy Vehicles**
Proposed Route	896	19
Princes Highway	2,542	242

Measurements were made at two residential locations adjacent to the Princes Highway and two residential locations along the proposed route, Mitchell Street and Thompson Street. All four measurement locations were similar distances from the road, although the measurements along the proposed route were slightly closer to the traffic than those on the Princes Highway.

The number of maximum noise level events measured during each hour of the night time period are shown in the histograms in Figures 1-4.

Figure 1 Night Time Noise Events At Mitchell Street

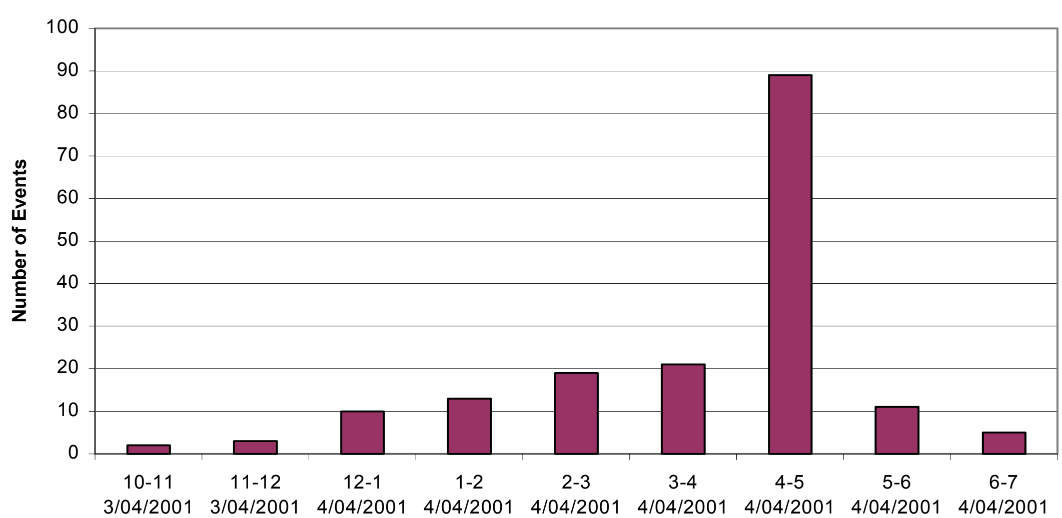


Figure 2 Night Time Noise Events At Thompson Street

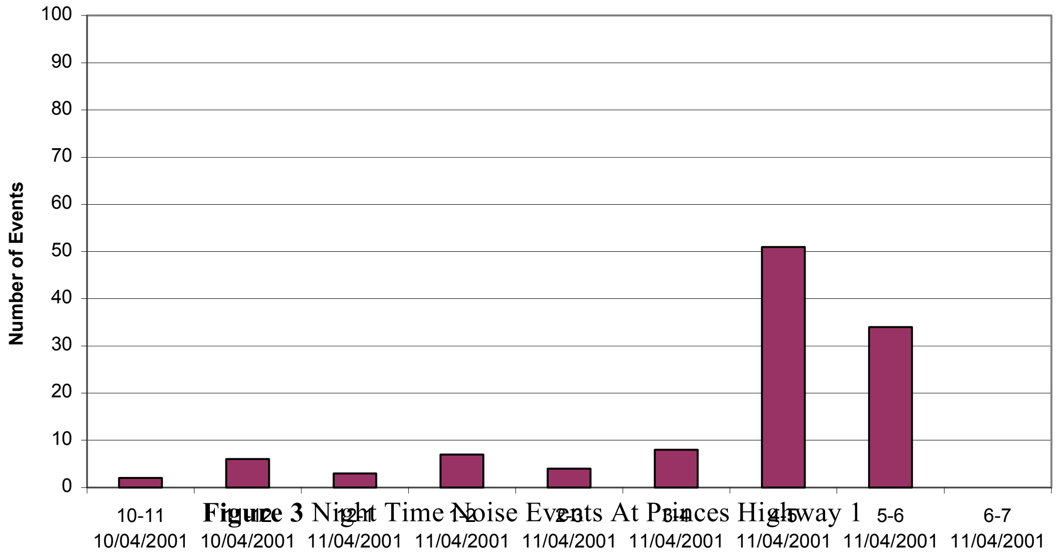


Figure 3 Night Time Noise Events At Princes Highway 1

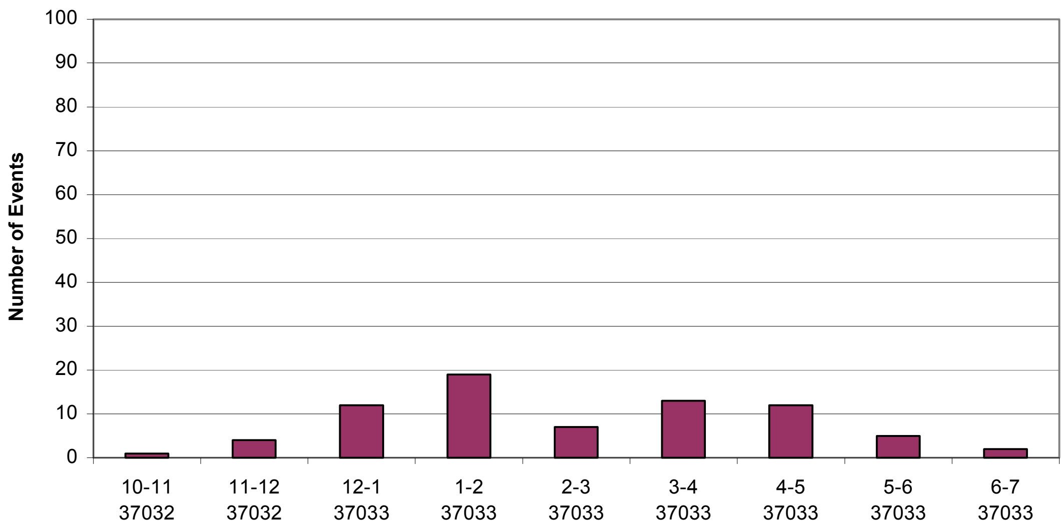
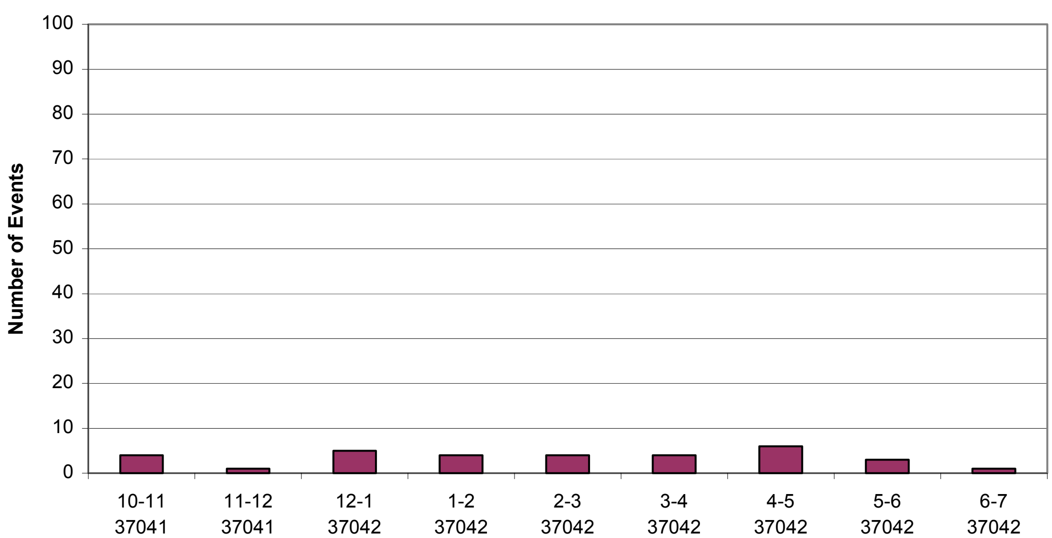


Figure 4 Night Time Noise Events At Princes Highway 2



Analysis of Results

The results obtained (Figures 1-4) were not as initially expected.

Despite the relatively heavy flow of heavy vehicles on the Princes Highway at night time, only a small number of maximum noise level events was recorded. Up to twenty events in any hour was recorded at Princes Highway 1 and up to five events in any hour at Princes Highway 2.

These findings were in contrast to the findings on the proposed route. At Mitchell Street, up to ninety movements per hour were recorded and on Thompson Street, up to fifty movements per hour.

Despite the greater number of heavy vehicles movements on the Princes Highway, fewer events were recorded at this road.

It was initially understood that the lower traffic flow on the proposed route would result in lower L_{Aeq} levels on this route. This was confirmed by observation of the measured results.

Whilst this would tend to increase the number of defined events on the proposed route, it did not appear to explain totally the significantly greater number of events on this route. In fact, with only nineteen heavy vehicle movements on this route over the full night time period (approximately), it is hard to understand why up to 50 and up to 90 events per hour were recorded at the two measurement locations.

Further observations were carried out at the measurement locations on the proposed route and these observations revealed that many light vehicles were generating noise levels at the residential facade measurement locations above 65dBA. This particularly applied to light vehicles with loud exhausts and four-wheel drive vehicles.

Conclusion

It was ultimately concluded that the number of maximum noise level events at night time did not reflect the number of heavy vehicle movements during the night time period. It reflected the number of heavy vehicle movements as well as the number of loud light vehicle movements and the general road traffic noise level expressed as an L_{Aeq}.

References

1. Roads and Traffic Authority of NSW, Practice Note iii, RTA Noise Management Noise manual.
2. Environment Protection Authority of NSW, Environmental Criteria For Road Traffic Noise, May 1999.
3. Environment Protection Authority of NSW, Environmental Noise Control Manual.

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The Evolution of Aircraft Noise Descriptors in Australia Over the Past Decade

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Over the past decade the aircraft noise practitioner in Australia has faced a rapidly changing environment. The Australian Noise Exposure Forecast (ANEF) system has been under sustained attack as a result of the Environmental Impact Statement for the third runway at Sydney Airport. Standard tenets such as 'the best option is the one that affects the least number of people' are no longer true. Coupled with this, noise exposure patterns around airports have dramatically changed as the gains made through the phase out of Chapter 2 jets have been counterbalanced by a significant increase in aircraft movements. These developments have led to decision-makers and the community no longer considering ANEF contours as the best way to present a 'picture' of aircraft noise. The focus has moved to examination of flight paths and the temporal variations in the numbers of movements on those flight paths. However, the tools which allow us to meet these changing information demands have now appeared. Sophisticated noise and flight path monitoring systems are installed at major airports. The power of desktop computers to process the data from these systems and to produce high quality reports has exploded. This paper gives an overview of the challenges and opportunities presented by this changing environment.

Drivers of Change

In common with almost all aspects of our lives the demands faced by the aircraft noise practitioner today are very different to those faced in the early 1990s. While there have clearly been a large number of influences which have led to these changes three particular drivers stand out.

Firstly, and most importantly, the massive adverse public reaction to the opening of the third runway at Sydney Airport in late 1994 has resulted in an almost total rejection of using ANEF contours as a way to present a 'picture' of aircraft noise exposure. This reaction has led to a total rethink of the type of information that needs to be contained in an effective Environmental Impact Statement (EIS) and of the way aircraft noise information should be presented to the community and decision makers.

Secondly, the nature of noise exposure patterns around airports has changed very markedly. The noise environment around many airports used to be characterised by low numbers of total movements but by relatively loud aircraft. This has now changed to a situation today where we have relatively quiet aircraft but with high movement numbers. This has resulted in people being less focussed on the noise levels from individual aircraft and showing more interest in the ‘macro’ picture – the numbers of movements and the extent of the breaks or respite from noise.

Thirdly, technological advances have opened up many potential new ways for presenting aircraft noise information. A decade ago it would not have been feasible to produce the type of information we can produce today. Flight path monitoring systems were in their infancy and the capacity of desktop computing systems, both on the hardware and software sides, to cheaply process large amounts of data and to produce high quality graphical output was very limited.

Sydney Airport Third Runway EIS – The End of an Era

The Standard Approach

The Australian Noise Exposure Forecast (ANEF) system was introduced as a land use planning tool in the early 1980s. Over the next decade the use of ANEFs expanded and they also became to be used as the main tool for carrying out noise assessments in Environmental Impact Statements (EISs). In simple terms the EIS assessment method generally involved computing ANEF contours for each of the options under consideration and then giving preference to the option with the least number of people within the contours.

Typically in an EIS little cognisance was paid to areas outside the 20 ANEF as these were considered to have ‘acceptable’ levels of noise. Little specific information was provided on flight paths or on the numbers of movements in an EIS as this data had been factored into the ANEF and was therefore treated as being superfluous.

This standard ANEF analysis was used in the EIS for the third runway for Sydney Airport which was published in 1990 [1]. At the time, prior to the runway opening, there was general agreement amongst noise experts that the noise work in the EIS had been carried out very competently and that it represented a good implementation of an ANEF assessment.

However, when the runway opened in late 1994 there was a massive public outcry. There was a very strong feeling in the community that they had been misled by the EIS and in particular by the ANEF information that had been disseminated as part of the EIS process. This ultimately led in 1995 to the Federal Parliament setting up the Senate Select Committee on Aircraft Noise in Sydney. The report of this Committee very severely criticised the noise work in the EIS [2].

The Key Criticisms of the EIS

While hindsight revealed many failings with the way the ANEF system was used in the EIS to portray and assess the noise from the third runway project, one key issue underlay many of the problems - the already mentioned standard approach of deciding that there is a noise ‘cut-off’ at 20 ANEF. The EIS defined areas within the 20 ANEF as the ‘noise affected’ area and effectively gave little or no recognition to other areas. People incorrectly concluded that areas that were not defined as ‘noise affected’ would have no or little audible aircraft noise exposure. Many people had made personal decisions, such as buying a house or not objecting to the project, using this erroneous assumption. Not unnaturally many of these people were very angry after the runway opened and they discovered that the noise environment was vastly different to their expectations.

The focus on community reaction, which led to the concept of a noise 'cut-off' at 20 ANEF, also led to another highly controversial aspect of the EIS noise assessment – noise concentration. Conventionally the standard approach to aircraft noise assessment had been to try to aim for the lowest overall 'community affect' – that is to minimise the number of residents living within an airport's noise contours. This was the approach adopted in the third runway EIS.

However, this minimisation can be achieved in a number of ways. For example, the numbers of persons in the contours can be reduced through using quieter aircraft, routing aircraft away from residential areas or having less aircraft movements. On the other hand the same effect can be sometimes be achieved without making any 'real' noise reductions simply by concentrating as much noise as possible on a small number of people. In effect this is what happened with the third runway. The EIS did not clearly draw the attention of the community and decision makers to how the project was achieving its major reduction in the number of persons affected.

Noise concentration was an issue of particular concern to the Senate Committee which concluded that 'This is, quite simply, a form of discrimination' [3]. Ultimately this Committee finding led to the operating procedures at Sydney Airport being totally restructured through the adoption of a 'noise sharing' regime which deliberately increased the number of persons living within the noise contours.

The Outcomes for the Noise Practitioner

As a result of the breakdown in communication that occurred between the noise expert and the layperson in the third runway EIS we have been forced to find better ways to portray aircraft noise exposure patterns. A protracted period of consultation with the Sydney community in the late 1990s led to a number of 'new' approaches being adopted. These are explained in some detail in the Department's Discussion Paper 'Expanding Ways to Describe and Assess Aircraft Noise' [4].

In essence it has become apparent through this consultation process that flight path based information gives a much better and more 'accurate' 'picture' of aircraft noise than contour based information despite the fact that the former is not based on sound pressure level data.

Another important development has been that, as a result of the major problems created by using a noise 'cut-off' of 20 ANEF, the type of 'noise affected area' approach used in the third runway EIS is no longer considered valid. In effect any land where there is audible noise is now by definition taken to be 'noise affected'. The question is how significant is this 'affect' at any particular location for any particular individual. The focus has moved from community reaction to individual reaction.

Subsequent to the third runway EIS two recent Public Inquiries have also heavily criticised the conventional 'technical' approaches to aircraft noise assessment/reporting and have called for systems which enable an individual to be able to see for themselves what aircraft noise is 'really' like in the vicinity of their homes [5][6].

Our experience has been over the past year or so that if a noise exposure 'picture' is provided through describing where the flight paths are and through giving details about the numbers of movements and time distribution of those movements a person is able to form a picture in their own mind of what the aircraft noise will be like.

Changes in Noise Exposure Patterns

The old 'workhorse' Chapter 2 jets of the 1970s and 1980s the B727, DC9, etc were typically in excess of 10 dB(A) louder on departure than their current counterparts. Now that these Chapter 2 aircraft have been effectively phased out in Australia the mean sound pressure levels of almost all the common jet aircraft types measured at the noise monitoring terminals around airports lie broadly within a 1-2 dB(A) range – effectively only the B747 now stands out [7]. For example, applying the generally accepted principles of noise discrimination, an observer on the ground would not normally be expected to be able to differentiate between the noise from a B767 and a B737 despite the difference in the size of the aircraft.

On the other hand, there is great public awareness of the increase in aircraft movements. When the new runway opened at Sydney Airport one of the greatest sources of complaint was not the loudness of the aircraft per se. It was the disappearance of the time gaps between the planes. It was claimed that the noise never stops *'…now it is just constant, it just never goes away, plane after plane, after plane, after plane…'* [8].

Not surprisingly this change in noise exposure patterns has led to changes in the sort of information people want. The focus is no longer on getting rid of the 'noisy ones' – it is much more on seeking options for moving flight paths and if this is not achievable in reducing the total number of aircraft movements particularly at sensitive times. Therefore people are looking for monitoring data which enables them to track these parameters. The equal energy average day noise contour does not provide this type of information.

In order to track the disappearance of the time gaps between aircraft the community has asked for 'respite' to be monitored and reported [9]. This monitoring of the inverse of noise presents interesting challenges and it is considered that this will be a field of increasing importance in the future as the traffic levels at airports continue to grow.

Taking Advantage of Technological Advances

Concurrent with the changing information demands from the community and decision makers there has been an exciting expansion in the tools available to the noise practitioner which allow him/her to adapt to the changing circumstances.

One reason behind the focus of community demands changing from noise contour based information to flight path based information may simply be that we are now able to provide this type of data. The 1990s saw the advent of aircraft noise monitoring systems which are linked to flight path monitoring systems – a change that was largely pioneered by the Australian company Lochard which has now become the world leader in this field.

Ten years ago our horizons when processing data on a normal desktop computer were mainly limited to dealing with files in the kilobytes size range. We are now routinely dealing with files in the gigabyte range. Colour printers, powerful CPUs, rapid access storage media, user friendly software for geographical information systems, database and graphics applications have all become cheap and readily available. This means that it is now feasible to store and analyse large amounts of data and to produce high quality graphical reports without the commitment of major resources.

The Department is now developing an aircraft noise database interrogation/graphical reporting software package – TNIP (Transparent Noise Information Package) – which demonstrates how advantage can be taken of the recent advances in desktop computing power.

The internet would appear to present an enormous potential for communicating aircraft noise information to the community. This is a largely untapped area in Australia. However, certain overseas airports are now developing very useful applications – San Francisco has recently introduced a website showing 'almost live' flight paths which has generated significant community interest [10].

Enhancements in computing power clearly present the noise practitioner with enormous opportunities. On the one hand we are now able to do our standard tasks more 'accurately' – for example we are now able to include many more flight paths in our computer model when we produce ANEF contours. More excitingly, we have the tools to find new ways to present noise information – ways which provide the information in a form that the user of the information (whether it be a member of the public or a decision maker) is seeking.

The Expectations in the Year 2001

Probably the most fundamental change over the past decade is that the noise expert can no longer rely on providing reports and information in 'techno speak'. People, both members of the public and decision makers, are no longer looking for the noise expert to help them understand technical language – they now expect that they will be provided information based on 'everyday talk' and that it will be presented in a way that provides a noise 'picture' which they can readily relate to.

The type of information that is now being looked for in EISs is totally different – decision makers and members of the public will no longer accept the advice of noise experts that a certain amount of noise is 'acceptable'. An assessment document that does not allow the reader to readily see what the noise will be like at any location around an airport using 'real' noise descriptors is now considered deficient. It is fundamental that noise information in an EIS is structured so that an individual can see and understand for themselves what is, or is proposed to be, happening at their home.

If an assessment report provides quantitative information on the 'noise exposed' populations under different potential airspace/airport operating options, it is expected that the extent to which the noise is concentrated and/or shared over the exposed populations will be clearly demonstrated for each of the options.

Ultimately, in effect, this means that we have to move our focus from 'community reaction' to 'individual reaction'. Over the past few years our experience has demonstrated that this path has the potential to significantly reduce the level of misunderstanding between the expert and non-expert. The challenge for the noise practitioner is to now find ways to develop and enhance the 'real' information concepts that have emerged.

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AIRSERVICES AUSTRALIA'S NOISE AND FLIGHT PATH MONITORING SYSTEM

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Abstract
The Noise and Flight Path Monitoring System (NFPMS) operated by AA has been in existence since 1991. It has evolved from two stand alone systems installed at Sydney and Brisbane airports to a single centralized system covering 7 major Australian airports operated and managed by Airservices Australia Canberra office. During its development the NFPMS has received numerous upgrades, the latest enabling it to process data from The Australian Advanced Air Traffic System (TAAATS). This paper discusses the current system and how the NFPMS enables Airservices Australia to meet its environmental commitments.

Introduction

During the 1980s aircraft noise started to become an increasingly sensitive political issue. In 1982 the National Acoustic Laboratory produced a comprehensive report on aircraft noise. This report was concerned with how to best quantify aircraft noise in relation to its effects on the community. Shortly later the House of Representatives Select Committee on Aircraft Noise (HORSCAN) was set up to examine how to manage and reduce the effects of aircraft noise on the Australian community. This committee presented its report in 1985. Some of the recommendations were[1]:

- To establish a noise and flight path monitoring program (NFPMS) at each of the major Australian airports.
- Public displays be established at each airport.
- A facility be devised to access and analyze complaint data.

The federal government accepted these recommendations and provided $1.5 million in 1990 for the installation of an NFPMS at Sydney and Brisbane airports[2]. The task of installing and operating the NFPMS was assigned to the former Civil Aviation Authority (CAA). In 1995 the Authority's functions were split into Civil Aviation Safety Authority (CASA) and Airservices Australia, the NFPMS remained with the later.

The specifications for the NFPMS were drawn up by CAA and tenders were sought. A Melbourne-based company, now called Lochard Pty Ltd, was the successful bidder, and the Sydney and Brisbane systems became operational in 1991. Several configuration changes and two major upgrades of the NFPMS have resulted in the present system. Airservices Australia's NFPMS covers seven major airports, Perth, Adelaide, Melbourne, Sydney, Coolangatta, Brisbane and Cairns; Canberra airport will be included during 2002. Airservices

NFPMS is one of a few multi-airport monitoring system in the world and it certainly covers a much larger airspace volume than any other system.

System Configuration

Radar data is received via the aircraft's secondary surveillance radar (SSR). This data contains the position, height and a SSR code number, the latter identifies the aircraft. The radius of coverage for the radar data stored in the NFPMS is approximately 70km around the airport. Flight plans for all aircraft data are lodged electronically by the various aircraft operators, or are entered as needed by the air traffic controller. During the latter part of the 1990s the data handling facilities of Airservices Australia were significantly improved by the introduction of The Australian Advanced Air Traffic System (TAAATS). This system can handle data from many different input formats. From TAAATS the flight and track data enter the NFPMS as the one data set.

Noise Monitoring Terminals (NMTs) are located in noise sensitive areas in neighboring suburbs about the airport. Each NMT consists of a microphone at top of a 6m mast, a type 1 precision sound level meter with a dynamic range 30dBA to 130dBA and storage capacity for up to 7 days. As a NMT measures all the noise to which it is exposed, not just aircraft noise, there is a need to disinguish aircraft noise from noise from other sources. This process uses the concept of a noise event. Each time the noise level exceeds a predetermined threshold for a set amount of time the NMT records a noise event. Both the threshold level and above threshold time are adjustable from the airport or from Canberra. The NMT provides the following acoustic information:

- Lamax, Laeq, SEL, Laeq-1sec and the time and date for each noise event.
- Hourly Laeq, Lamax, L1, L5,L10,L50, L90, L95, L99 and number of noise events
- Daily Laeq, Lamax, L1, L5,L10,L50, L90, L95, L99 and number of noise events
- Night time (or curfew) Laeq, Lamax, L1, L5,L10,L50, L90, L95, L99 and number of noise events

For each noise event detected by the NMT the server will check radar data to determine if any aircraft were within a predetermined volume (referred to as the correlation zone) associated with the NMT. If a plane was in the correlation zone at the time of the noise event the server tags the noise event with the aircraft's flight plan data. A unique feature of the Lochard system is its ability to accommodate multiple correlation zones for each NMT.

An electrostatic actuator performs acoustic sensitivity checks of the NMT microphone daily, the complete NMT is re-calibrated yearly at which time the microphone is replaced. The permanent NMTs are connected to the airport server via fixed phone lines and are continuously sending noise information back to the server. Incorporated in a portable NMT is a mobile phone unit, this is dialed up once a day to download the data stored in the portable NMT.

Radar, Flight Plan and Noise data are recorded and processed by servers located at each airport. The servers, in real time, at the airport perform the process of first matching the plan data to track data and then correlating this with the noise data. Noise, flight and radar data are processed 24 hours a day, seven days a week. To enable the airport owner to handle aircraft noise complaints a computer terminal with access to the data contained within the local server has been provided. Each airport based server is linked to two other servers in Canberra, which contain the data from all seven airports. Up to two years of data from the seven airports can be stored in the Canberra based servers.

Analysis

The NFPMS has several analysis screens which can be used to extract and filter the data:

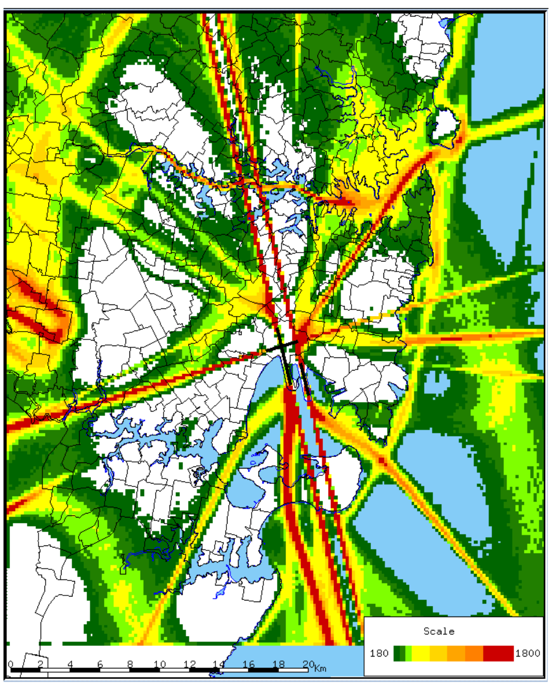
- Flight Analysis Screen for listing aircraft details.
- Noise Analysis Screen for listing results for each noise events.
- NMT hourly/24 hourly noise data.
- Weather data screen for listing the weather details.
- Mapping package which will display the aircraft track and the associated noise levels at each NMT correlated by the particular track.

Two maps are available, a real time map which show current aircraft movements and the NMTs with their current noise levels. The second map displays historical data, it is this last map which displays the results of any analysis of the data.

When a track is displayed on the historical map the operator can select any point along the track and display the following aircraft details:

- height, position and its speed.
- Operation (arrival, departure or flyover), aircraft type and call sign

In addition selection zones can be drawn on the map to include/exclude tracks passing through these zones. Provided is the ability to replay the track as it approaches or departs from the airport.



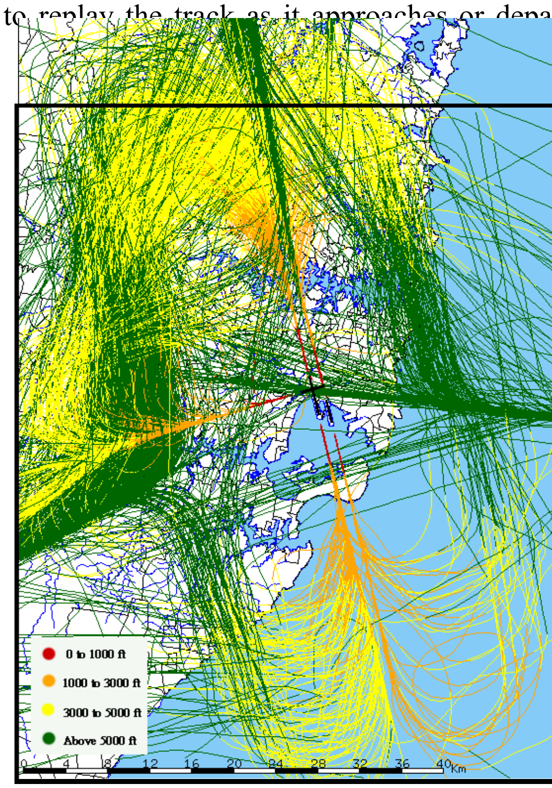


Figure 1 An example a track density plot (left) and individual tracks (right).

To help understand complex track patterns, which result when several hundred tracks are displayed, the NFPMS has a track density plot function. This is a plot displaying by color coding the number of aircraft movements over the area surrounding the airport on top of the historical map. In figure 1 the track density for a 3 month period (January to March 2001) is compared to the track plots for arrivals over a 2 week period. Even for a relatively short period of two weeks there are too many tracks to determine any patterns to the movements.

The track density plot clearly indicates which areas of the map have the greatest number of overflights. Note, in figure 1 the tracks are colored by height, which is a very useful feature of the analysis package. The database can be searched by aircraft type, call sign, time and date, route, NMT identifier, engine type and operation.

For those investigations which can not be performed using the various analysis screens the track, flight and noise data can be readily exported. Airservices often supplies to the industry or consultants raw or reduced data from the NFPMS.

Uses for the NFPMS

The NFPMS is used daily at most airports to investigate aircraft noise complaints. When a complaint is received, the NFPMS can be made to display all aircraft movements that occurred at about the time of the complaint. For each aircraft track displayed on the screen aircraft identifying information such as its registration and type as well as its speed, time and height at each point along the track can be displayed. Further analysis can be made by plotting other similar aircraft overflying the same position and examining their height at the same position. This helps indicate if the aircraft concerned with the complaint was operating in accordance with normal procedures or not.

The NFPMS also performs a monitoring function for:

- Curfew violations, certain aircraft types are not allowed to operate at certain periods of the day.
- Compliance with local Noise Abatement Procedures, which specify preferred runways and preferred flight paths.
- Noise Sharing policies (Sydney).
- Reverse thrust usage, where the jet engines are used to slow the aircraft after landing.
- Continuous Decent Approach

As a diagnostic tool the NFPMS has been used to evaluate the effectiveness of administrative procedures and regulations designed to lessen the aircraft noise. For example the impact of the Precision Radar Monitor for flights to the north of Sydney Airport during poor visability conditions was assessed by studying the noise levels and the flight tracks stored in the NFPMS database.

Regular quarterly reports for each airport where there is an NFPMS presence are produced from the data stored within the NFPMS. These cover runway usage, aircraft noise levels, track density plots and track height plots for aircraft operations as well as N70, N80, N90, LAeq at each NMT. These are provided freely to airport environment committees and can be made available to others, at a cost, by Airservices.

As an example of how the data collected by the NFPMS can be used as a research tool the measured noise levels for arriving B747 200 and 400 series aircraft are compared to the predicted noise level found in AS2021[4]. The noise levels from AS2021 are tabulated according to the distance from the touch down point (DL) and the lateral distance (DS). These levels were calculated using the Integrated Noise Model (INM) which is used world wide to quantify aircraft noise.

This comparison is possible because the NFPMS stores the aircraft's height and lateral distance to the NMT as well as the noise levels (Lamax, Laeq and 1 sec Laeq values) at the time of the noise event. From the aircraft height the distance from touch down (D_{TD}) can be found, assuming a 3^{o} glide slope for arrivals. The predicted noise level for each noise event can be read from the table for B747 200 and 400 series by selecting the level where the values of DL and DS are closest to D_{TD} and the lateral distance. Further improvement can be made by correcting this value for the difference in path distance between the AS2021 table and that associated with the noise event in the NFPMS. The results for a sample of noise data collected at various NMTs are tabulated in table 1.

The values for DS and DL in table 1 were the determined from the lateral distance and height recorded by the NFPMS at the time of the noise event. The uncertainty has been estimated from ±0.5 dBA in the tabulated values in AS2021 and allowing the noise event to have occurred between the closest point along the flight track to the NMT and at a point further along the track which makes an angle of 45^o to the flight track. This gives a range of lateral distances. By selecting data from four NMTs a range of DS and DL values have been examined.

Aircraft	Height, m	DS (lateral dist.), m	DL (dis. to touch down), m	Measured LAmax, dB	Predicted LAmax, dB	Uncertainty, dB
B744	316	213	6030	85	82	1
B744	347	951	6621	71	68	3
B742	396	1005	7556	68	68	3
B742	310	375	5915	85	80	2
B744	335	797	6392	69	70	3
B744	335	198	6392	86	82	2
B744	358	208	6831	86	81	1
B744	359	866	6850	70	70	3
B744	121	102	2309	96	93	1
B742	176	882	3358	68	70	4
B742	152	99	2900	95	93	1
B744	152	25	2900	96	92	1
B744	128	98	2442	95	93	2

Table 1 Sample of some of the data that resulted in figure 2.

The comparison between the predicted and measured noise levels are graphically shown in Figure 2. The predicted noise levels are shown as vertical lines indicating the uncertainty in their calculation.

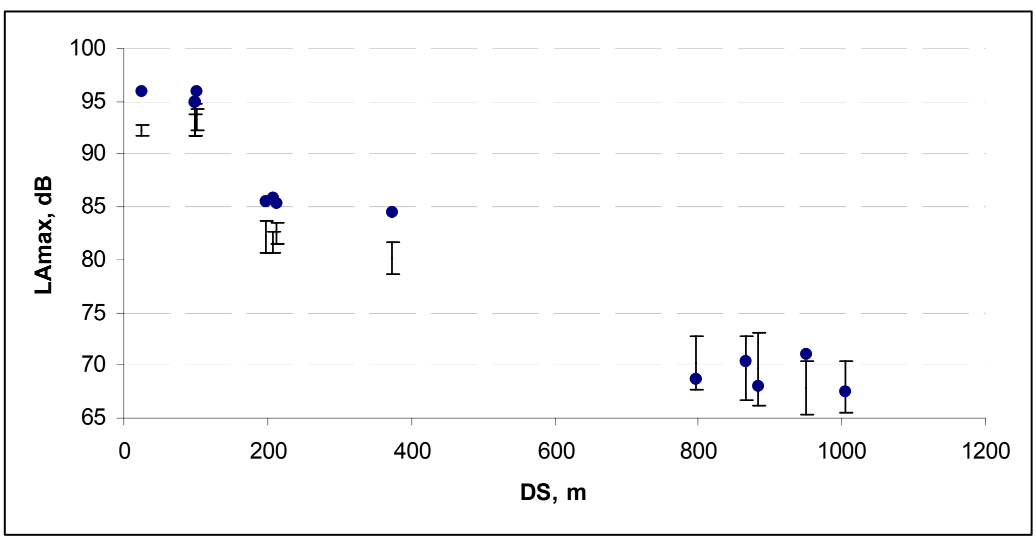


Figure 2 Difference between the measured and predicted noise levels.

The agreement between the predicted and measured noise levels for B747 200 and 400 series is quite good, the differences are less than 2 dB except for one data point for which a 5dB deviation occurred. This example illustrates how the data contained within the NFPMS can be used to confirm the accuracy or provide adjustments needed to be made to a noise model.

Conclusion

Airservices Australia established an Australian wide NFPMS to enable it to meet its environmental responsibilities under the Air Services Act 1995. The NFPMS is flexible, user friendly and able to produce analysis results in a relatively short time frame. As discussed in this paper the data obtained and data reduction that the NFPMS routinely stores has the potential to assess government policy and regulations, validate theoretical noise models and National Standards.

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ISIS - A MULTIMEDIA TOOLSFOR NOISE MANAGEMENT INFORMATION

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Abstract
"Real" noise examples, shaped to reflect local situations, are often considered the very best way to build an understanding of noise management issues. People can hear acoustical examples that depict the noise impacts of a proposal. The Interactive Sound Information System (ISIS) is an established world standard for delivery of noise management information to communities and decision-makers. The latest version makes full use of the latest technologies in multimedia presentations including 3D experiences in virtual reality. Information is direct, understandable, and demonstrably accurate. Program features that specifically address the needs of airport operators have been supported by the US Federal Aviation Administration. The system, proven worldwide in hundreds of training and community information situations, has recently been customised to include he Australian ANEF metric. The package combines noise prediction models, high quality digital recordings, precise sound controls and photorealistic terrain maps. By addition of local images, maps and sounds programs can be customized to fit specific noise management situations. The concepts such as the N70 metrics outlined in the DoTRS Discussion Paper on Alternative Metrics will also be included as an option in the program.

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AIRPORT NOISE MANAGEMENT – SPEAKING THE COMMUNITY'S LANGUAGE

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Abstract

Since the 1980s, airports worldwide have invested heavily in technologies to measure their noise impact. The 80s saw noise monitoring system collect reams of noise data which seldom found its way out of the acousticians offices. In the 90s we saw the emergence of integrated noise and flight track monitoring systems producing impressive graphical outputs of noise and flight track data. Despite this proliferation of monitoring technology, community groups worldwide have increasingly complained that airport noise information is too jargonistic and avoids their key concerns. Now in the third decade of airport noise monitoring, we are seeing the evolution of community focussed presentation and communication. This paper provides insights into the direction of airport noise monitoring and a look at some of the community focussed presentation tools that are currently on the drawing board.

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ACOUSTICS OF MULTIPLE OCCUPANCY DWELLINGS

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&
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Abstract
Regulation of acoustic quality of multiple occupancy dwellings is a local government responsibility, through the building approval process. Dissatisfaction among occupants of such dwellings is evident by an increasing level of litigation and media coverage. Regulatory controls on buildings are based on the Building Code of Australia, for which an upgrade is proposed by the ABCB. Separately from the ABCB, the AAAC has proposed a draft benchmarking system, based on a star rating. This paper reviews current BCA requirements and concludes that the document lacks essential benchmarks. Even if upgraded, some occupants will continue to seek higher standards. An upgraded BCA combined with a pragmatic rating system could provide a 'best practice' strategy to manage this problem, although this paper recommends that a well planned national standard would be preferred. This paper reviews the building regulatory process and concludes that critical pre-requisites to best practice will be an improved BCA, a commitment to proof of performance testing, a national building standard, and well structured but simple publicity.

1. BACKGROUND

The acoustics of multiple occupancy dwellings is an increasing society concern, due largely to the increased living density of Australian cities and the need to use such dwelling types to cater for that need. The regulation of the design and construction standards appropriate to these types of dwellings is, primarily, the responsibility of local government. In general, local authorities rely on the recommendations and guidance of the Building Code of Australia[1], published by the Australian Building Codes Board, under an agreement between the Commonwealth Government and each State and Territory Government. The ABCB is currently reviewing the sound insulation provisions of the BCA, outcomes of which are expected to be an expansion to the scope and an increase to the stringency of those provisions. This paper examines the building regulation process and some of the regulatory and technical issues arising from the current BCA amendment proposals.

2. MANAGING BUILDING ACOUSTICS FOR THE COMMUNITY

2.1. Stakeholders

Stakeholders who are affected by the regulatory and commercial processes affecting the acoustics of multiple occupancy dwellings are:

1. dwelling occupiers, through their occupancy;
2. owners and investors, through rental income;
3. designers, builders, developers, experts, advisers and suppliers who contribute to the building of dwellings, through income from the construction process;
4. regulatory authorities, through their obligation to respond to community needs, and also through income from fees and charges;
5. legal advisers, construction experts and the media, through income arising from deficiencies in such buildings; and
6. the public in general who wish to be part of a healthy community.

2.2. Typical Dwelling Acoustics Issues

Occupants are the primary stakeholders, with their interest being that the dwelling in which they live should provide an acceptable level of control of the following:

1. Their own privacy and privacy of others;
2. Noise from adjacent neighbours – both airborne and impact noise;
3. Noise from building services – such as plumbing or lift noise due to activities of other occupants, and plant such as fans and ventilation equipment;
4. External environmental noise such as traffic;
5. Noise from other members of the household.

All stakeholders have a consequential, or secondary, interest, being that the cost involved in satisfying occupant requirements must be manageable.

It is important to emphasise that occupant satisfaction is subjective. It is known that substantial variation exists within those occupant expectations and, unless building regulations are made so stringent that they satisfy the most sensitive of occupants, dissatisfaction for some is inevitable.

3. THE REGULATORY PROCESS

The building regulations provide the platform for the building design and construction process. If the BCA is to provide a foundation of technical standards for a specific building, then the regulatory process must be structured so that feedback from stakeholders can be used to constantly refine the BCA. Achieving this objective within the geographical and cultural diversity of Australia is unlikely to be simple, and this paper proposes a refinement to the responsibilities and objectives allocated to those stakeholders involved in the regulatory structure, summarised below in Figure 1.

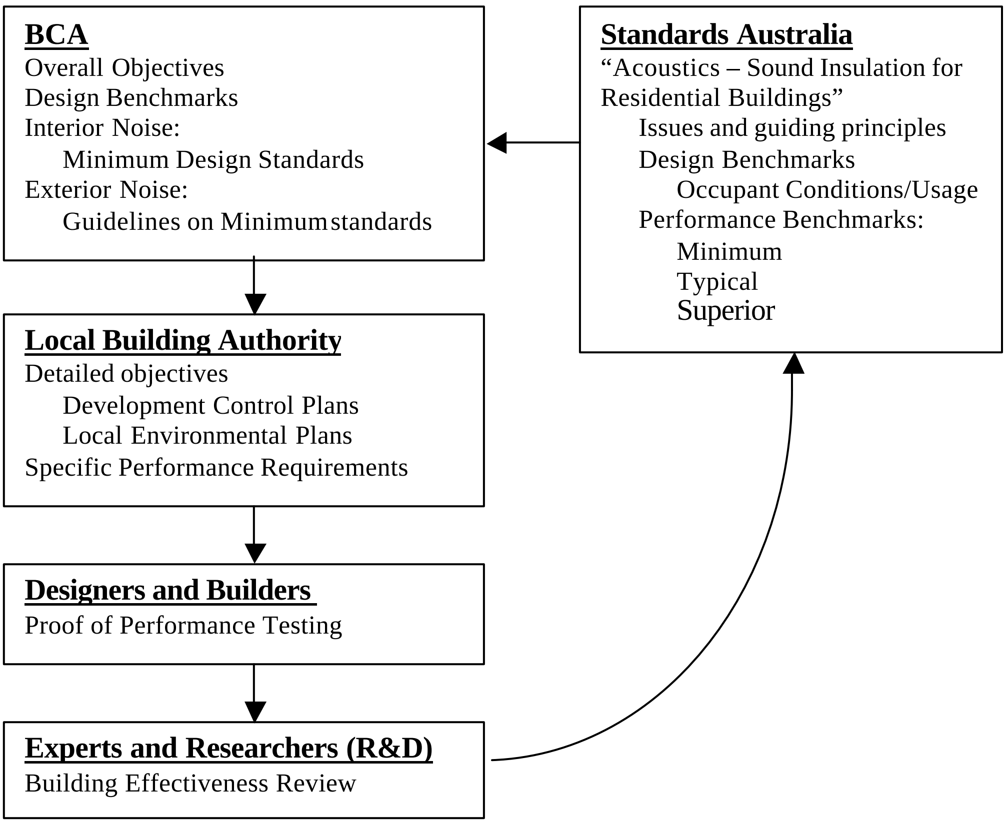

Figure 1: Ideal Building Regulation Process

The objective of Figure 1 is to establish Best Practice regulatory procedures, as the outcome of this will be Best Practice technical standards.

The BCA is the benchmark document within the Australian building regulation process and is given legal effect by legislation in each State and Territory. The goals of the BCA (p1,002) are to "enable the achievement and maintenance of acceptable standards for structural sufficiency, safety …., health and amenity for the benefit of the community now and in the future", and furthermore that "BCA extends no further than is necessary in the public interest, is cost effective, easily understood and is not needlessly onerous in its application". These are important goals that should be considered carefully when reviewing the adequacy of the National building regulation process.

The BCA provisions may be overridden by local legislation. This has occurred, effectively, through BCA being superseded by more stringent requirements under a local government Development Control Plan (e.g. City of Sydney 1999[2]).

4. NATIONAL BUILDING REGULATIONS – BCA

The structure the BCA requirements consists of three parts, the first two of which are included for guidance, and the third for compliance:

1. an objective,
2. an associated functional statement, which usually identifies one or more building elements or design principles which must be provided to achieve the objective, and
3. one or more performance requirements, which specify the technical standards for the building elements identified in the functional statement, necessary to achieve the objective.

The objective of Part F5 of the current BCA is to "safeguard occupants from illness or loss of amenity as a result of undue sound being transmitted" (p16,901). To assess the adequacy of the BCA requirements, and whether or not they achieve this objective, it is necessary to define the level of occupant health or amenity that the ABCB seeks to preserve, or alternatively to define the term "undue" more strictly.

A weakness in Part F5 of the BCA is that the performance requirement, which all deemed-to-comply constructions or alternative solutions are required to satisfy, lacks a benchmark. Paraphrased, the performance requirement is that each specified building element must provide "insulation…. against sound transmission….sufficient to prevent illness or loss of amenity…". That is, the minimum performance standard required to achieve the objective is that which achieves the objective. By comparison, Part F1, referring to Damp and Weatherproofing, specifies design benchmarks of 20 year and 100 year flood recurrence intervals, and describes design principles by which surface water is to be conveyed from a site (p16,022). Similarly, Part B1 Structural Provisions requires a design benchmark of "the most adverse combination of loads" (p4,021).

In all probability, the limitations within Part F5 are a result of the significant difficulty involved in quantifying non-auditory effects of noise on either health or amenity, while the source description of "undue" noise remains subjective. The Building Code is attempting to regulate the outcome achieved by sound isolation standards, for a source over which neither the code nor the designers have any control.

It is also worth noting that BCA addresses only inter-apartment, or apartment to common interior areas, noise control. Research by Fricke[3] (1977, p12-13), based on a survey of multi-unit dwelling occupants in Sydney eastern suburbs, identified exterior noise intrusion, from road traffic particularly, as the dominant source of annoyance to respondents. Professional experience[4] is that these findings remain representative of a more widespread community attitude, an opinion supported, in fact internationally, by more recent work reviewed by the Australian Building Codes Board[5] (p42) in the course of the BCA review process. In the context of building regulation, this is an important issue to consider further, as anecdotal experience is that many occupants who are dissatisfied with CBD apartment dwellings have previously lived in free standing suburban dwellings.

4.1. Comments on the Current Proposal to Upgrade BCA

The proposal to upgrade the BCA is a response to correspondence to ABCB, opinions of Home Unit Owners Association, AAAC and others[5]. The proposed upgrade aims to:

1. improve the consistency of performance achieved by deemed-to-comply constructions;
2. clarify the interpretation of those performance requirements, specifically with respect to distinction between in-situ and laboratory proven performance;
3. expand the application of impact noise control to include, more formally, both floors and walls, and
4. manage the potential cost implication which would arise if higher standards were uniformly imposed for all dwellings, including class 3 buildings.

An upgrade to the acoustic requirements of the BCA would appear to be well substantiated, regardless of whether this upgrade addresses scope, technical requirements, or both. However the BCA is a portion, only, of the building regulation process. The introduction of development control plans by a local council, for example the City of Sydney[2], introduces a layer of technical performance standards which are largely parallel with, and may perhaps erode, those of the BCA. This regulatory process may become counter-productive if the objectives of the BCA and a council development control plan are incompatible or non-complementary. There are a number of detailed aspects of the proposed BCA technical upgrade that warrant caution:

1. The introduction of a field performance parameter, R'w, in place of the STC rating previously stated in BCA, is an improvement as it unambiguously confirms that field rated performance requirements apply. However, the proposal to allow compliance based on <u>either</u> of $D_{nT,w}$ or R'w will permit equivocal standards. Should an owner or regulator require proof of performance, it is unclear how to proceed if the builder is able to provide certification based on R'w (whatever that may mean for a composite building), when there is uncertainty that the $D_{nT,w}$ complies.

2. The regulatory proposal recognises that the existing code does not impose in-situ performance verification but does state that the "BCA performance requirements are required after construction"[5](p8). Moderately simple, but routine, proof of performance tests would rapidly provide substantial data to assist future refinement to building regulations.

3. The regulatory proposal notes industry concern that deemed-to-satisfy provisions of part F5 do not safeguard occupants from loss of amenity, acknowledging that this is "difficult to ascertain" (p13). This is probably true, however given that amenity represents one of the two primary objectives to be addressed by part F5, further research into relationships between building performance and perceived amenity is clearly desirable.

4. The BCA document recognises that owners who have purchased a property and then learn the performance is below their expectations will complain. The risk associated with an upgrade to BCA is that the public will expect this to eliminate existing problems, though it can at best alleviate them. This problem will be difficult to alleviate unless the publicity generated by the upgrade can improve public understanding of sound isolation for residential buildings.

5. The mathematical relationship used for conversion from IIC to $L_{nT,w}$ in the ABCB regulatory document is inconsistent. The acceptance standards for impact isolation need careful review.

6. Field testing should be encouraged more strongly by the ACBC proposal. Testing will lead to increased education of builders and will benefit those who have completed testing and therefore better understand the issues that affect acoustical performance.

7. The regulatory document notes that proven acoustic performance could be rated - a concept already adopted in some jurisdictions with respect to energy consumption - but that this will not guarantee a rise in standards. This ignores market forces, and assumes that an enforced rise in standards is the most effective way to manage residential health and amenity. This assumption should be tested.

8. There is no argument with ABCB comment that it is better to get construction quality right in the first place and that expenditure on testing does not directly contribute to the quality of an individual apartment. The benefit derived from testing, however, is education, not necessarily regulation.

5. INTERNATIONAL BENCHMARKING

In a recent draft report by NSW Department of Health[6], threshold levels for annoyance, speech interference and sleep disturbance, proposed by World Health Organisation Guidelines on Community Noise in 2000, are reported as $L_{Aeq,8h}$ 35dB(A), 35dB(A) and 30dB(A) respectively. In the same report, previous work in which different metrics and, in some cases, higher threshold levels are suggested, is also reported. However, benchmarking sound isolation standards to achieve the WHO threshold levels, for a range of typical occupied dwelling noise levels, is clearly a prudent standard to seek for the BCA building regulations.

An example of a comprehensive design standards document is the German Standard DIN4109[7]. This standard covers a range of conditions affecting sound isolation design, dealing with typical residential building situations including both internal and external noise sources. DIN4109 proposes higher sound insulation standards (typical party wall and floor standard R'w 53dB) than those currently proposed for the BCA upgrade, but marginally below those of the City of Sydney Development Control Plan[2]. It is worth noting that DIN4109 requirements are "based on the assumption that unusually high levels of noise are not generated in neighbouring rooms" (p2).

5.1. Ecologically Sustainable Development

The City of Sydney Development Control Plan[2] approach to controlling environmental noise has brought into focus a conflict, at least for multiple occupancy dwellings in urban areas, between acoustic design and the principles of ecologically sustainable development. It can be forgotten that regulating high standards of sound isolation from external noise has important consequential effects. Masking noise is reduced so that higher performance inter-tenancy sound isolation is then required to maintain privacy, while mechanical ventilation is almost certainly mandatory.

5.2. AAAC Star Rating System

An emerging industry based initiative which has received some publicity is a star rating system, expected to be issued for public review by the Association of Australian Acoustical Consultants. This proposal reacts to the absence of a broadly based Australian design standard for residential buildings, such as DIN4109, and to the fact that Australian building regulations tend to impose minimum standards of performance only. The objective of the system is to facilitate occupant satisfaction by helping a prospective purchaser to compare the performance of one apartment with another. There are risks in the system, as the gradings remain subjectively derived, albeit by a skilled and experienced group of practitioners. The difficulty involved in benchmarking building services systems, particularly hydraulic services, must not be underestimated.

It will be important for building regulators to consider the benefit of a building benchmarking system and, if this is compatible with the national building regulation objectives, to endorse the system and support its publicity.

While it is not currently part of the terms of reference of the AAAC star grading system, the method could be extended to include free-standing dwellings. This may help residents who are considering moving from a free-standing dwelling into an apartment to be better informed about the differences that they should anticipate.

6. A PROPOSAL FOR FUTURE REGULATORY DEVELOPMENT

Within the present regulatory structure, in which minimum performance standards are prescribed by the BCA, it is recommended that the following improvements are sought:

1. Benchmarks for health and/or amenity that the BCA seeks to preserve,
2. Benchmark source noise levels on which the minimum standards are based, and
3. Technical benchmarks for noise isolation and noise control, expanding on both the functional statement and the performance requirements.

It is expected that social and clinical research will be required before the objectives for item 1 can be better quantified, and that this process will take some considerable time. In the interim, it will be necessary to rely on technical standards alone, through a process which could demonstrate to the community that both the source noise levels and sound isolation standards prescribed by the minimum standards are reasonable.

A national standard describing performance standards appropriate for residential buildings is required, in which guidance on more than one quality of accommodation is given, and to which regulatory documents such as the BCA and local council development control plans could then refer. In the short term, an AAAC star rating system could act as a surrogate standard, however a national standard which cross-references to other technical procedures is a superior regulatory structure.

It is recommended that the following research contributing to a Standards Australia residential building standard should occur:

1. Catalogue current international best practice building design standards;
2. Research and document typical occupied dwelling area noise sources and their levels;
3. Research the technical adequacy of current national and international building design standards based on these noise sources. The terms of reference for this evaluation would be based on numerical predictors such as privacy and WHO recipient noise levels, and should be referenced to both technical standards and standard architectural or engineering controls.

6.1. Critical Outcomes

It is essential that building regulations comprehensively address the factors that contribute to dwelling acoustic environments. This necessarily includes benchmarks for both source and receiver noise levels. Some of these sources may be difficult to regulate at all. However, this does not preclude regulations or design standards from identifying those sources and requiring that they are included in the design and construction process, as this will achieve future improvement to the state of the art.

The education process accompanying implementation of any new technical standards will be important, as it is essential that stakeholders are informed of the aspects that are addressed by any associated code, so that they can also identify those that are not.

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CHALLENGES WITH THE ACTIVE SOUND INSULATION OF WINDOWS

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Abstract
CSIRO Building, Construction and Engineering has conducted research on the active attenuation of windows for the last three years. The initial idea was to use piezo-electric film adhered to both sides of a single sheet of glass. The polyvinylidene fluoride (PVDF) piezo-electric film is clear and CSIRO Telecommunications and Industrial Physics successfully deposited experimental clear electrodes on a small sample of PVDF film. Unfortunately, the sound levels that could be cancelled were not high enough to justify the commercial cost. Experimentation was then switched to double-glazed windows whose cavity was driven by a horn loudspeaker driver unit. The sound levels that could be cancelled were sufficiently high. Successful feed forward control of a periodic signal was achieved using software from the Department of Mechanical Engineering at the University of Adelaide. Unfortunately, no feed forward control was achieved with random noise or traffic noise. Analogue feedback control was then used with random noise and gave some attenuation at some frequencies. It was not possible to obtain broadband attenuation.

Introduction

In 1997 the author [1] developed a draft acoustic certification scheme for the Residential (now Australian) Window Association. In Appendix 1 of that document, the author presented calculated values of the Outdoor–Indoor Transmission Class (OITC) [2], the Aircraft Noise Attenuation of a building component (ANA_c) (Appendix G of [3]) and the Sound Transmission Class (STC) [4] from 143 sound insulation measurements on fixed glazing.

The first 106 measurements were made by the National Research Council of Canada [5] on specimens measuring 1800 mm high by 2020 mm wide. The measurements were made down to the 80 Hz third octave band. The last 37 measurements were commissioned by Monsanto [6] and conducted by Riverbank Acoustical Laboratories on specimens measuring 914 mm by 2134 mm. The measurements were made down to the 100 Hz third octave band. For the determination of OITC, they were extrapolated to the 80 Hz third octave band by subtracting 2 dB from the 100 Hz third octave band results. The third octave band sound insulation data was supplied in machine-readable form by Alf Warnock of the National Research Council of Canada.

ANA_c was lower on average by 5.0 dB than STC. This agrees with [3]. OITC was less than ANA_c by a further 2.9 dB. Note, however, that there was a large variation in these differences for individual specimens.

The results for some of the double-glazing combinations were presented in graphic form as a function of cavity width by the author in [7]. It was apparent that if OITC was used to rate the acoustical performance of windows, there was no advantage in using double glazing unless a large air gap and heavy glazing was used. There was a small benefit in using large air gap double glazing if ANA_c was used to rate the acoustical performance of windows. It should be noted that ANA_c is very similar in value to $R_w + C_{tr}$ [8].

The reason there was no advantage with using double glazing was due to the very low sound insulation values at the mass–air–mass resonant frequency. It was decided to improve the sound insulation of a single-glazed window using active noise control via piezo-electric film adhered to both sides of the glass. The fall-back position was to try active noise control in the cavity of double-glazed windows.

Piezo-electric Film

Polyvinylidene fluoride (PVDF) piezo-electric film is clear. It is normally used with opaque thin metal film electrodes on each side. Clear electrodes, typically indium oxide tin doped materials, are used on the glass of aircraft windscreens for demisting purposes. Depositing electrodes that will adhere to PVDF is not an easy task, since PVDF is a close relative of teflon. However, Geoffrey Harding of CSIRO Telecommunications and Industrial Physics managed to deposit clear 0.13 µm thickness ITO electrodes on both sides of a small 20 mm wide sample of PVDF film. The electrodes had a resistance of 50 Ω per square. This compares with 2 Ω per square for copper–nickel electrodes and 0.1 Ω per square for silver ink electrodes that are commercially available. The PVDF film has to be kept reasonably cool during the electrode deposition vacuum spluttering process so that overheating does not damage it.

The plan was to electrically expand and contract PVDF film adhered to one or both sides of a glass sheet to counteract the bending produced in the glass by the incident sound wave. Calculations using some very simplistic assumptions suggested that a voltage of 100 V rms at a frequency of 100 Hz on the PVDF film would be able to cancel the bending induced in 3 mm thick glass by an incident sound wave of sound pressure level 65 dB. This estimate turned out to be surprisingly close to the experimental result! The simplistic theory also suggested that greater sound pressure levels could be cancelled with thicker glass. This was not the case experimentally.

The initial experiments were performed on a glass strip measuring 300 × 13 × 3 mm. This glass strip was mounted in a Bruel and Kjaer complex modulus apparatus type 3930. The displacement of the glass strip was measured with a Bruel and Kjaer capacitive transducer type MM 0004. The PVDF transducers were from an AMP Sensors Inc. piezo-electric PVDF basic design kit purchased from Irendos Pty Ltd. AMP Sensors Inc. has since sold its piezo-electric sensor operations to Measurement Specialty Inc. AMP Sensors Inc. was formerly Elf Atochem Sensors. The only other known suppliers of piezo-electric PVDF film are Piezotech in France and Airmar in the USA.

The piezo-electric PVDF film transducer was attached to the glass strip with double-sided tape. It was driven with a 125 V rms sinusoidal signal from a Bruel and Kjaer vacuum tube beat frequency oscillator type 1014. This produced rms displacements in the range of 0.6 to 1.1 μm in the 10 to 200 Hz range. It was calculated that this corresponded to sound pressure levels that could be cancelled from 82 to 104 dB.

We expected the piezo-electric PVDF transducers to work better as receivers than as sources. This was not the case. The signal-to-noise ratio of the PVDF receivers was disappointingly small, due to their relatively small capacitance and lack of shielding.

The Sound Insulation Demonstration Box

Experiments were continued with a sound insulation demonstration box with a top opening measuring 304 × 304 mm. A frame of this internal size was fitted with 2.2 mm thick glass. Piezo-electric PVDF film of area 22,000 mm^2 was glued to the top side of the 2.2 mm thick glass sheet mounted in the frame. The film was driven with an 80 V rms sinusoidal signal from a Crown DC300A power amplifier whose two stereo halves were operated in push–pull mode. The sound pressure level radiated from the glass sheet placed on top of the demonstration box was measured 250 mm above the box by a Bruel and Kjaer type 4179/2660 low noise one inch air condenser microphone and matching preamplifier in an anechoic room. The voltage was then removed from the film. A loudspeaker was driven inside the demonstration box. The drive voltage to the loudspeaker was adjusted until the same sound pressure level as generated by the film was measured at the microphone above the demonstration box. A Bruel and Kjaer type 4131/2619 standard one inch air condenser microphone and matching preamplifier was used to measured the sound pressure inside the demonstration box at a distance of 15 mm from the bottom surface of the glass; 6 dB was subtracted from the measured sound pressure level to account for pressure doubling due to reflection at the glass surface. This level was considered to be the maximum incident sinusoidal sound pressure level that could be cancelled by 80 V rms applied to the film. The measured values ranged from 70 to 80 dB over the third band centre frequencies from 50 to 400 Hz. The measured value at 100 Hz was 71 dB, which was only 6 dB greater than our early rough estimate of 65 dB; 90 dB was measured at 500 Hz.

With 22,000 mm^2 of film on 6 mm thick glass, maximum cancelable sound pressure levels ranging from 71 to 83 dB over the frequency range from 50 to 500 Hz were obtained. These levels were so similar to the values obtained with the 2.2 thick glass that planned experiments on 12 mm thick glass were not conducted. It was disappointing that both the 2.2 and 6 mm result ranges were significantly less than the 82 to 104 dB range estimated from the measurements on the 3 mm glass strip.

Local manual sinusoidal cancellation experiments were conducted on the 2.2 mm thick glass. The film and loudspeaker were driven simultaneously, and the relative amplitude and phase of the signal to the loudspeaker were adjusted to obtain the minimum sound pressure level at the microphone 250 mm above the glass. The phase of the signal to the loudspeaker was adjusted using a 'bucket brigade' delay line. The cancellation achieved ranged from 16 to 44 dB over the third octave band centre frequencies from 50 to 1000 Hz. The sinusoidal sound pressure levels that could be cancelled with 80 V rms applied to the film ranged from 71 to 91 dB. The apparent insertion loss of the glass without cancellation ranged from 17 to 45 dB. The residual cancelled sound pressure levels at 250 mm above the glass ranged from 3 to 38 dB. This was the reason that the experiment had to be conducted with a low noise microphone in a vibration-isolated anechoic room.

It was reluctantly realised that the levels that could be cancelled with the film were far too low to be commercially useful. The A-weighting curve is down 19 dB at 100 Hz and the noise crest factor would be at least 10 dB greater than the sinusoidal crest factor of 3 dB. Thus, the A-weighted external noise level that could be cancelled would be at most 42 dB. A window without active attenuation would be more than adequate for this task! It should also be mentioned that one of our PVDF samples was destroyed when being driven with white noise via a high voltage step-up transformer. There was a resonance due to the capacitance of the film and the inductance of the transformer. The voltage should still have been within safe limits. We believe than the film initially suffered mechanical damage due to inadequate adhesion to the glass and this caused an electrical short circuit that burnt the film.

Double Glazing

Experimentation was switched to a frame glazed with two 3 mm glass panes 40 mm apart. A horn loudspeaker driver unit driving at one of the cavity corners was used to excite the double-glazed cavity. Most currently available horn driver units are piezo-electric units. A KSH1188 driver was driven with a 20 V rms sinusoidal signal. Its cancellation levels were the same as those of the PVDF film in the 63 to 125 Hz range. The cancellation levels then rose rapidly and were in the 105 to 130 dB range from 200 to 1000 Hz. To obtain higher low frequency cancellation levels, a Toa TU50 electrodynamic horn driver was used. With 10 V rms sinusoidal input, the Toa unit was capable of cancelling sound pressure levels in the 90 to 102 dB range from 50 to 125 Hz, and 105 to 130 dB in the 160 to 1000 Hz range.

Initially, a sinusoidal signal was picked up by a microphone 15 mm below the bottom glass surface and fed to the horn driver via a third octave band filter and power amplifier. Phase changes of 180° were obtained by reversing the connections on the horn driver. The attenuations ranged from –3 to 21 dB at the third octave band centre frequencies from 50 to 1000 Hz. A similar experiment was tried with pink noise. To minimise delay, the signal was picked up electrically. The attenuation ranged from –3 to 7 dB in the third octave bands from 80 to 1000 Hz. The 630, 800 and 1000 Hz bands all gave –3 dB.

We then used a digital signal processor and adaptive feed forward control software, which was supplied by Scott Snyder of the Department of Mechanical Engineering, University of Adelaide. Although the software was only intended for demonstration and teaching, it worked well when controlling periodic sound signals. The reference microphone was placed inside the demonstration box, 15 mm below the bottom glass surface. The error microphone was placed outside the box, 250 mm above the top glass surface. A periodic signal consisting of 160 and 320 Hz sinusoidal signals was attenuated by 12 dB at 160 Hz and 26 dB at 320 Hz.

Because external noise is incident on a window from a wide range of different directions, it is not feasible to place the reference microphone at a large distance in front of the window in order to gain the extra signal processing time that is necessary for random noise signals. With a slowly varying periodic signal, the processing time does not matter, providing the phase is correct. Note that much of the signal processing time is the fundamental delay in the filtering being used and is not due to the processing speed of the computer. In the case of the digital signal processing board being used for these experiments, there is considerable delay in the digitisation. The digitisation is performed at high frequency but low resolution with random noise dither. High resolution lower frequency digitisation is obtained by digitally low pass filtering the digitised signal. The delay in the digital low pass filter is significant. This is in addition to the delays in the filter being implemented in the processor for active noise control and the delays due to filtering in the digital to analogue output conversion. The adaptive feed forward controller was tried with a random noise input. As expected, no attenuation was achieved. It was then tried with tape recorded road traffic noise. It was thought that there might be enough correlation in real road traffic noise for some active feed forward attenuation to occur but such was not the case.

Feedback Control

At this stage we began to investigate the use of active feedback control. A Bruel and Kjaer type 4133/2619 half inch condenser microphone and matching preamplifier were mounted in the middle of one of the cavity frame sides adjacent to the corner with the horn loudspeaker driver unit. The microphone signal was fed to the horn loudspeaker driver unit via one channel of a Stanford Research type SR640 low pass filter. The cut-off frequency of the filter was set to 400 Hz and both normal and reversed connections to the horn driver unit were tested. The attenuations obtained with sinusoidal signals ranged from –5 to 5 dB across the frequency range from 160 to 400 Hz. To limit the attenuations to positive values, it was necessary to change the polarity of the connection to the horn driver unit a number of times across the frequency range.

The calculated mass–air–mass resonance of the double-glazed system was 160 Hz. The actual measured resonance frequency was 242 Hz. This was due to the stiffness of the mounted small glass panes increasing the effective stiffness of the air cavity. It was noted that when the gain of the feedback system was too large, the system oscillated at 407 Hz. This frequency was the resonant frequency of the horn driver. The low pass cut-off frequency of the filter was reduced to 350 Hz and experimentation was concentrated on the resonant frequency of the double glazing. Attenuation ranging from 9 to 18 dB was obtained with a 242 Hz sinusoidal signal. With a one third octave band of random noise centred at 250 Hz, attenuations ranging from 7 to 11 dB were obtained depending on how close to oscillation the feedback was set. A one-twelfth octave analysis gave attenuations of 4, 15 and 6 dB at 229, 242 and 257 Hz. With an octave band excitation centred at 250 Hz, the reduction in the third octave band centred at 250 Hz ranged from 5 to 8 dB. A one-twelfth octave analysis gave attenuations of 1 to 3 dB at 229 Hz, 12 to 18 dB at 243 Hz and 5 to 7 at 257 Hz. With white noise excitation to 20 kHz, the cancellation in the 250 Hz third octave band was 8 dB. A one-twelfth octave analysis gave attenuations of –0.3, 10.1 and 1.5 dB at 229, 242 and 257 Hz. Reducing the cut-off frequency of the low pass filter to 300 Hz gave one-twelfth octave attenuations of 2.9, 3.7 and –8.2 dB at 229, 242 and 257 Hz.

No significant attenuation of random noise was obtained away from the resonant frequency. An extensive series of group delay measurements on all components of the feedback loop was conducted. It was concluded that feedback control of random noise at the resonance frequency was feasible because of the long group delay due to energy storage by the resonance. Feedback control at other frequencies was going to be difficult because of the short group delay times.

The open loop frequency response of the feedback system was measured. Using the measured frequency response, a series of custom low pass filters was designed and constructed. Unfortunately none of these achieved significantly greater cancellation than the Stanford Research low pass filter set to a cut-off frequency of 350 Hz. It appeared to be impossible to obtain significant attenuation outside the 220 to 300 Hz frequency range, even when the measured open loop frequency response showed that such attenuation should be possible. Display of the sound pressure waveform generated by the horn driver in the double-glazed cavity showed that the waveform was badly distorted below 220 Hz and immediately above 250 Hz. Horn drivers are designed to drive the high impedance load at the throat of a horn. But even without a horn, the Toa TU50 did not produce significant distortion when radiating into a free field in an anechoic room. Clearly the impedance presented to the horn driver by the double-glazed cavity was even lower than that of the driver throat radiating into a free field. The low impedance caused the displacement of the horn driver to be greater than normal and hence to distort. The effect of the low impedance was observable as a deep notch at 200 Hz in the cavity frequency response. This notch disappeared when the microphone was replaced by an accelerometer on one of the glass panes. The low cavity impedance was presumably due to a resonance in the glass pane. Adding sound absorbing material to the double-glazed cavity failed to suppress the deep notch in frequency response at 200 Hz. A number of frequency responses were measured with different cavity thicknesses and widths, and different glass thicknesses. Although the resonance frequency could be moved around, it was basically impossible to remove the deep notch immediately below the resonance frequency.

The top of the demonstration box has outside dimensions of 480 × 480 mm. A new double-glazed frame with an internal opening of 400 × 400 mm and an air cavity thickness of 40 mm was constructed. Its measured mass–air–mass resonance frequency was 170 Hz. Again, cancellation could be obtained in the neighbourhood of the resonance and in some other frequency ranges. At the other frequencies amplification occurred.

Conclusion

It is possible to use feedback to actively improve the sound insulation of double glazing in the neighbourhood of the mass–air–mass resonance frequency. These experiments failed to achieve significant broadband active attenuation of windows. This suggests that significant broadband active attenuation of windows will be very difficult, if not impossible, to achieve.

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IMPACT NOISE RATINGS FOR WALL PARTITIONS: BUILDING CODE OF AUSTRALIA

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Abstract

The existing provisions of the 1996 BCA Equivalence Test have a number of difficulties in their implementation. The current proposal before the Australian Building Codes Board for a 'new' measurement and rating scheme was developed to address the shortcomings of the existing code.

This paper suggests an alternative single number rating system could be developed using airborne transmission test data. Computations using three different schemes are compared. A major advantage of a computed scheme is its ease of use in applying to existing airborne data. No additional expense testing is required.

Introduction

The Building Code of Australia (BCA) has as an objective FO5 *"to safeguard occupants from illness or loss of amenity as a result of undue sound being transmitted - a) between adjoining sole-occupancy units; and b) from common spaces to sole-occupancy units."* (2001 January-b, pg. 26/FP5.1).

The BCA includes performance specifications for impact noise transmission for wall partitions. These specifications are included in Part F5 of the Code.

Clause F5.5 (2001 January-b, pp. 26-27) introduces the requirements in "*Walls between a bathroom, sanitary compartment, laundry or kitchen and a habitable room in adjoining unit"* for impact sound insulation. Table F5.5 provides three acceptable masonry wall types. Further, it provides *"for walls other than masonry comprising 2 or more separate leaves without rigid mechanical connection except at their periphery"*.

Where these provisions do not encompass the desired wall partitioning, the BCA Specification F5.5 provides a *'Test of Equivalence'*. Unfortunately, these provisions for wall impact insulation don't provide flexible, performance based and verifiable wall insulation.

Discussion

1990-6 BCA Equivalence Test

In a nutshell the BCA requires the resistance of a *prototype* wall to be compared with the known performance of a *'standard wall'* from Table F5.5. It requires both the *standard wall* and the *prototype wall* to be tested, with identical equipment, procedures and testing position, allowing comparisons of the relative performance of the prototype wall and the standard construction.

The test requires:

- A steel platform (510x460x10mm) is placed in continuous and direct contact (long edge) with the prototype wall on the expected impact noise side.
- A tapping machine, complying to ISO 140/6-1998 (E), is mounted centrally on the plate.
- Sound transmission determined in accordance with AS 1191 is measured using the tapping machine as the sound source.
- The impact sound pressure levels in the receiving room are normalised to a reference equivalent absorption area of 10m²

$$L_n = L_i + 10Log_{10}\left(\frac{A}{A_o}\right)dB$$

Where A_0 is 10m²

A is the equivalent absorption in the receiving room (m²).

L_i is the impact sound pressure level corrected for ambient noise

- Calculation of the equivalent absorption from the reverberation time measured in the receiving room according to the Sabine formula:

$$A = \frac{0.163V}{T}$$

Where V is the volume of the receiving room (m³)

T is the measured reverberation time in each frequency.

Problems in the 1990-6 BCA Equivalence Test

A major cause of concern to industry is the *'Test of Equivalence'* as typified in the Plasterboard Building Systems: Masonry Acoustic Impact Systems Publication:

"However, this does not fully explain the details of the test, nor does it explain how comparisons are made. ... In the absence of a revised method under the Building Code of Australia, it is not possible to state categorically that a tested wall meets the requirements for a 'satisfactory level of insulation'." (Boral 1999b, pg. 3)

There have been uncertainties regarding the usability and repeatability of the *Equivalence Test* for some time. In 1995 the author had discussions with the CSIRO and a local Western Australian consultant regarding implementing a testing procedure. The procedure under discussion raised many questions for repeatability that little testing was undertaken. Others including (Cook, KR) and (Debevc, MA and Cook, KR) have also highlighted potential problems in the *Equivalence Test*:

- There is no uniformity in either results or testing procedures between laboratories.
- What are the relative performances of the three different standard walls? To be objective all three walls need to be tested to allow comparison of the prototype wall to all three standard walls.
- The Equivalence Test does not detail the method of comparing the prototype wall "is no less resistant to the transmission of sound" than those listed in table F5.5 or the frequency range intended
- The method does not take into account workmanship or acoustic performance of the standard wall (Eg. Rw).
- There is no mechanism used to correlate the impact performances of the source/plate levels. Depending on the method of attaching the support frame to the plate, the expected vibration at the contact edge should differ. Ie velocity measurement at three points on the long edge, plus a standard horizontal force of the plate against the wall. Eg ribbed block, rough surfaces, flush render surface, etc.
- The specific location of the test plate against the wall. Eg. The height above the 'floor'; over studs; between studs; average of a number of measurements or the plate pressure on the wall.
- Debevc (Debevc, MA and Cook, KR) points out that the sampling time and numbers of microphone positions are not covered.
- Qualification of the measuring laboratory. (Cook, KR) points to some significant issues in that the code specifies compliance to AS 1191 and to the issue of flanking noise. Whilst airborne sound transmission test comply with the standards, he found that there was considerable flanking transmission when a) the source was applied to another wall of the facility; and b) similar problems when the source was moved 'slightly' away from the test wall.

Proposed Measurement Methods

The Australian Association of Acoustical Consultants (AAAC) and others have spent significant resources and time in attempting to develop better testing and rating schemes, which address the deficiencies of the 1990-6 BCA *Test of Equivalence*.

The AAAC proposes a rating system called the Wall Impact Isolation Class (WIC). This is incorporated into the BCA Proposed Specification F5.5: Wall Impact Sound Level: Measurement and Rating:

"This specification describes the method of test to determine the Weighted Standardised Impact Sound Level ($L_{nT,w}$) of walls for both Laboratory and Field measurement. This test procedure is intended to provide a method whereby an impact noise rating can be obtained from a directly propagated sound measurement which is substantially free of interfering effects from the surrounding environment." (2001 January-a, pg. 63)

The proposed method addresses the flanking transmission problems by the use of near field measurements:

"The near field measurement is considered necessary in order to determine the level of transmitted energy before it has a chance to react with the reverberant environment enclosed on the other side of the test sample or any interfering effects due to acoustical energy reflections from the walls, ceiling or floor of the measurement room." (2001 January-a pg. 63)

Other specific requirements are given for microphone measurement integration times and locations for both solid constructions and framed constructions. Asymmetrical walls are tested in both directions. Resonance in the wall panel has been considered in the microphone locations.

There is no indication of mechanisms for ‘soft’ surfaces, surface ‘roughness’ or curved surfaces in the proposed procedure. A damaged surface might transmit greater noise. Ribbed blocks provide a different scenario in measurement position as would curved surfaces.

The impact noise source has been changed from a multiple strike-tapping machine to a single strike spring-operated impact-test apparatus delivering an impact energy of 0.5 +/- 0.05 Nm. This type of hammer is used in the electrical industry, though would need modification for this application specifically *“The radius of curvature of the head shall be 100mm and the minimum cross-sectional dimension shall be 35mm.”* (2001 January-a, pg 64)

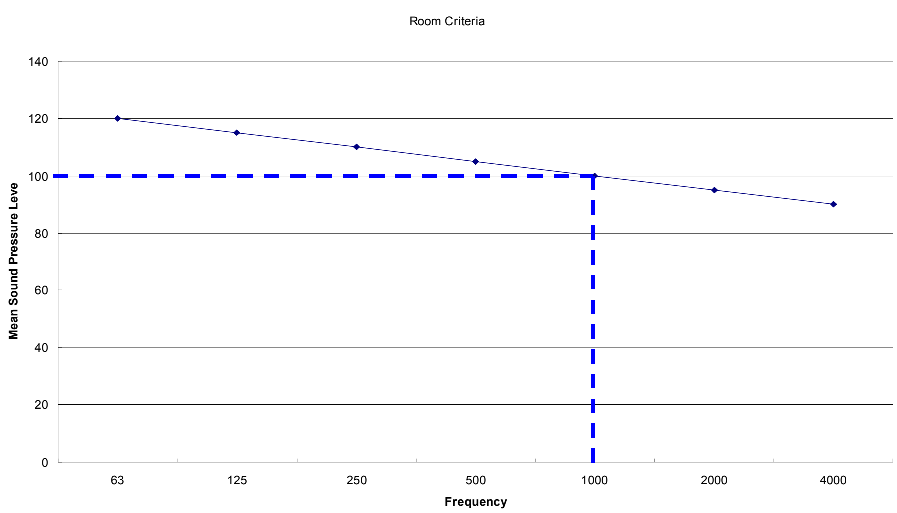
The measurement frequency range is 100 Hz to 5000 Hz. (The airborne measurement for the calculation of Rw (AS/NZS 1276.1-1999) in third octaves is 100 Hz to 3150 Hz or 50 Hz to 5000 Hz when using additional spectrum adaptation terms.) Measurements are done using MAX HOLD (rms).

To provide a single number rating system, a Room Criteria (RC) is applied (see Figure 1). The method of applying the room criteria is by a modified form of the previously used STC curve fitting methodology. The ‘best fit’ is the lowest RC curve in which:

- Total of all deviations between the test spectrum and the RC’ curve is no greater than 32.0 dB
- Maximum deviation in any frequency band is 5.0 dB
- The RC’ is derived from the RC’ spectral value at 1000 Hz.
- The RC’ curve is incremented up/down in 1 dB intervals.

It is interesting that measurement range in third octaves is 100 to 5000 Hz whilst the RC’ curve is 63 to 4000 Hz in octave bands. A 5dB per octave shift the curve can be easily interpolated.

Figure 1 Room Criteria

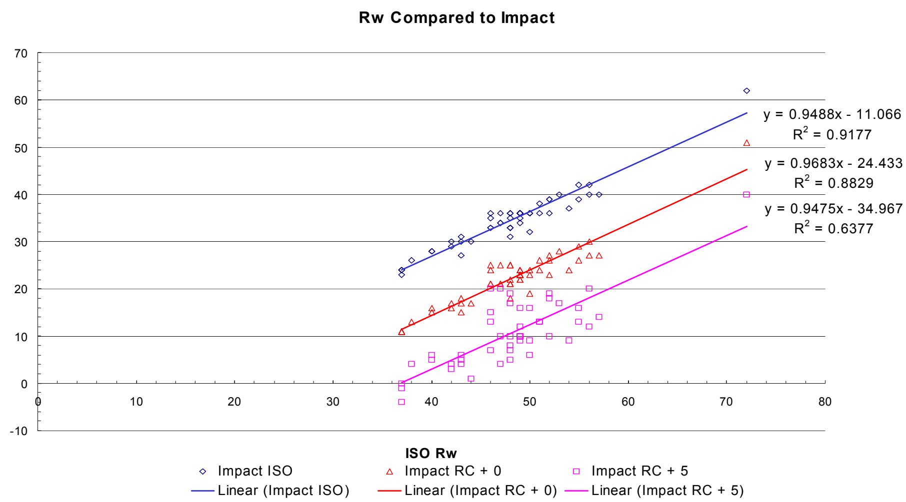


Alternative Single Number Impact Noise Rating Schemes

Cook (1996) found that *'moving the impact plate slightly away from contact with the wall… the results in the other room did not change significantly'.* This suggests that a valuable single number criteria for *'wall impact'* ratings might be developed using a different weighting/calculation procedure in conjunction with the existing airborne *R* values.

Figure 2 displays the results of 3 different schemes for calculating a 'Wall Impact Rating'. The data set is based on published wall systems (Boral 1999a, pg 7). The data set comprised 49 wall systems comprising 17 steel stud; 2 staggered stud; 4 'D-stud'; 3 timber stud; 1 'Quietzone'; 4 shaft wall; and 18 masonry wall systems.

Figure 2 Rw compared to Various Proposed Impact Ratings

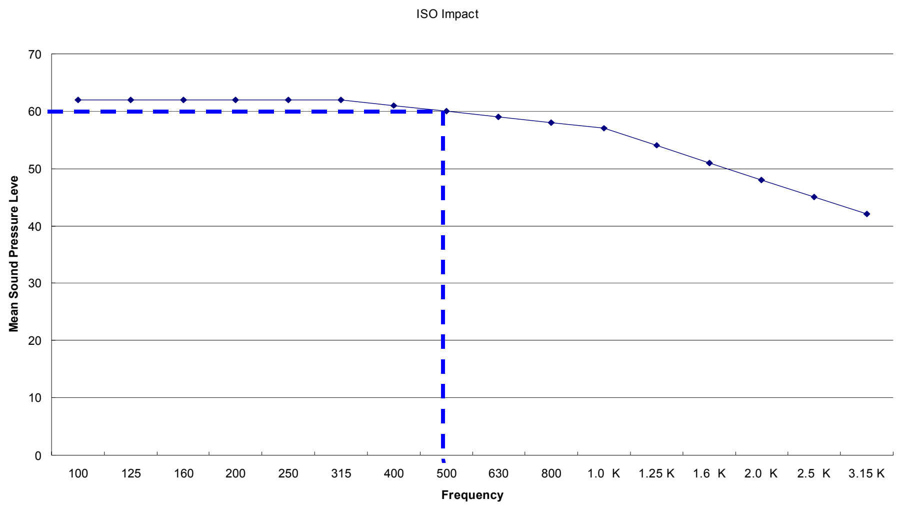


The three rating systems are:

(i) Impact ISO

This scheme uses the floor impact sound reference curve from table 3 in (1982) (see Figure 3). There is no maximum for unfavourable deviations in any one-third-octave band. The total unfavourable deviations are less than or equal to 32. The value is given by the reference curve spectral value at 500 Hz.

Figure 3 Standard Impact Reference Curve (1982)



(ii) Impact RC + 0

This scheme uses the proposed Room Criteria curve as described above and in (2001 January-a) (see Figure 1) with the exception that there is no maximum for unfavourable deviations in any one-third-octave band. The total unfavourable deviations are less than or equal to 32. The RC' value is given by the RC' spectral value at 1000 Hz.

(iii) Impact RC + 5

This scheme is essentially the same as 'Impact RC + 0' above. The maximum deviation in any single frequency band must not exceed 5.0 dB.

The trend line associated with *'Impact ISO'* has the best 'fit' with a correlation coefficient of 0.91. This confirms that there is 'less' scatter in the data and the impact rating more closely is related to the airborne R_w value.

Conclusions

The existing provisions of the 1996 BCA Equivalence Test have a number of difficulties in their implementation. The proposal in 'Specification F5.5: Wall Impact Sound Level: Measurement And Rating' (2001 January-a, pp. 63-67) has been developed to address the shortcomings of the existing code. Unfortunately the impact hammer specified is a modification of one used in the electrical fields. As such the hammer maybe difficult and expensive to purchase as it not used elsewhere in the world.

This paper suggests, in line with the existing provisions, a single number rating system could be developed using airborne transmission test data. Computations using three different schemes are compared. Of these schemes a rating scheme utilising the floor impact sound reference curve has the best correlation coefficient and shows promise. A major advantage to these schemes is its ease in computing based on normally existing airborne data. No additional expense testing is required.

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SOUND TRANSMISSION THROUGH LIGHTWEIGHT FLOOR STRUCTURES

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Abstract
A model that extends previous proposals for prediction of impact noise transmission through lightweight floors is presented and its verification described. Measurements of jumping and basketball impacts are reported and analysed. Using the measured impact data, the prediction model is applied through four specially written independent software modules. The modules comprise force analysis, floor response, receiving room behaviour and overall combination to give predicted sound pressure levels. Experimental testing of the model and software is reported for four floor arrangements including concrete and timber constructions and non-uniform (joist and board) floors. Good correlation is obtained for jumping impacts on all four floors but agreement in the ball impact cases is limited.

Introduction

In modern building construction the trend is towards lightweight forms of construction and consequently sound transmission through the structure has become a more significant issue. Accurate evaluation of sound transmission is difficult, particularly for impact loads. The object of the study presented here is the development of a model of behaviour for impact noise transmission through lightweight floors. Typically such loads are due to running, jumping and ball impacts.

Several writers have addressed the sound transmission of impact noise through floors and walls. The major points which emerge from the literature are:

- The frequency content of footfall impacts is significantly different from that generated by standard equipment used for assessing impact performance [1,2].
- The mechanism of sound generation is primarily via transient vibration of the floor subsequent to the impact [3].
- The average RMS velocity is a measure of the energy of the floor and hence of the impact [4].
- The impedance of the slab can be used to relate the vibration velocity to the impact force [5,6].
- There appears to be no basis for assessing the nuisance value of sound transmission through floors due to impact loads.

The basis used here for developing a mathematical model of lightweight floor behaviour is the work of Kimura and Inoue [5]. Extensions and modifications to the Kimura and Inoue model are made: the concept of an equivalent plate is added; the concept of equivalent radiation ratio is developed; and the impedance response function at resonance is expanded.

Four independent software modules have been developed to simplify practical application of the model. The modules deal with force analysis, floor response, receiving room behaviour and the combination of the previous three modules to produce level predictions. Experimental testing of the model was carried out on four different floor constructions. All procedures and results are described by Gaston [7].

Nature of Floor Impact Loads

The types of impact force being considered divide into two categories: footfall impacts due to walking, running and jumping; and ball impact due to sporting activities. These forces are of ill-defined magnitude, duration and position and are of a nature different from the “ideal” impulse (duration tending to zero and force tending to infinite). The characteristics of footfall and ball impacts have been determined by experiment.

The force profiles of the jumping and running of a 75 kg male and a bouncing basketball were measured on a force platform developed by the Department of Mechanical Engineering and installed in the Department of Physiotherapy at the University of Queensland. The platform can resolve forces in three orthogonal directions and also measure the moment about the vertical axis, but for this work only the vertical component of the impact load was recorded.

Time domain profiles of footfall impacts were measured for jumps from 100 and 500 mm, for both full foot landing and toe then heel with flexed knees, and for running (toe contact) and jogging (full foot). The profiles measured were generally consistent apart from the 500 mm jumps and correspond well with those reported by Kimura and Inoue [5]. The ball impact results were highly consistent, approximately a half-sinusoidal impact of duration 13 to 14 ms and amplitude of the order of 1000 N. Examples are shown in Figures 1 and 2. For prediction calculations the time profiles are converted to frequency representation as discrete spectral densities using a Fast Fourier Transform algorithm.

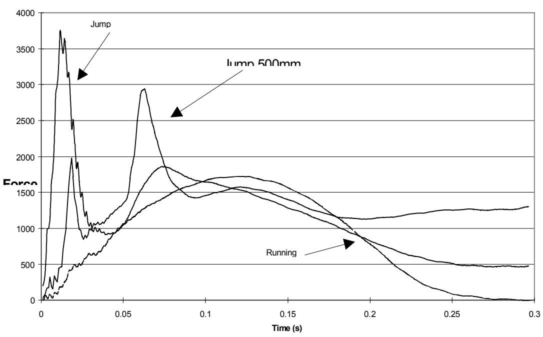

Figure 1. Footfall impacts

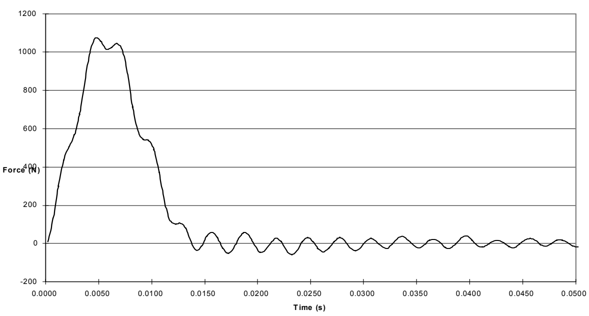

Figure 2. Ball impact

It is noted that these profiles are quite different from the input produced by the standard tapping machine commonly used for assessing impact noise. Japanese Standard JIS A 1418 [7] specifies an impact fall of a car tyre, producing a force characteristic of duration between 20 and 22 ms and maximum value between 3600 and 4200 N.

Floor Response

The calculation of floor response is based on the input force spectrum, the duration of the force and the impedance of the floor. The response is determined in each frequency band as the steady state vibration velocity due to the appropriate force spectral component. The approach now presented follows the technique given by Kimura and Inoue [5]. It is based on the use of the driving point impedance for an infinite plate. The impedance is modified by either empirical or calculated factors to take into account boundary conditions and resonances.

Ver and Holmer [9] state, "the average input admittance can be well approximated by the point admittance of the equivalent infinite plate". Kimura and Inoue experimentally verified this assumption. It is then necessary to derive impedance modifiers to model the detail (non-average) behaviour of a finite plate. A finite plate will have resonances and anti-resonances and therefore the impedance will oscillate about the base value as frequency increases. Kimura and Inoue developed an impedance envelope describing the fluctuation of impedance with frequency, based on three zones of interest.

- Below the fundamental natural frequency the response is stiffness controlled and the impedance (squared) will be inversely related to frequency with a -6 dB/octave characteristic.
- At the fundamental natural frequency resonance the impedance will be reduced to an extent dependent on the damping present. The reduction expressed in decibels is 20 log(loss factor). For the dimensions of most common floor slabs the natural frequency lies in the 63 Hz or lower octave band and resonant excitation by footfall and ball impacts is likely.
- Above the fundamental natural frequency there will be a progression of resonances and anti-resonances. The range of impedance variation will depend on the level of damping present. Kimura and Inoue examined experimentally the variation of loss factor for 41 concrete floors and confirmed the expectation that loss factor is independent of frequency. They observed that an average loss factor for concrete slabs is around 0.06. A consequence of the independence with frequency is that the vibration energy decays with frequency at 3 dB/octave and therefore the impedance-squared term will approach the theoretical (infinite plate) driving point impedance at 3 dB/octave. At very high frequencies the flexural wavelength will be so small that the slab will act as an infinite plate.

Combining the characteristics described, Kimura and Inoue developed an idealised impedance curve as shown in Figure 3. This shows response at individual frequencies rather than in frequency bands. They found experimentally that on an octave band basis, for floors with a fundamental natural frequency in the 31.5 octave band, the reduction in impedance in that band was 6 dB less than predicted on an individual frequency basis, which they suggested is due to the averaging effect of using octave bands. For floors with fundamental natural frequency in the 63 Hz octave band, a corresponding reduction of 2 to 4 dB less than predicted was observed. Since the impedance characteristic above the fundamental natural frequency is also 3 dB/octave, a basic impedance envelope for concrete floors of various sizes was adopted as shown in Figure 4.

It is proposed here that the octave band impedance response curve can be expanded to cater for the more generalised cases where the fundamental natural frequency may fall in any octave band, and where the loss factor may be different from that used by Kimura and Inoue, i.e., the curve may be used for other materials. With decreasing octave band frequency the bandwidth decreases and the number of resonant modes covered by each band will on average decrease, so that the average deviation from the base impedance will decrease. At the lower frequencies it would be expected that the impedance dip for the octave band will be close to the full value predicted on a frequency spectrum basis (i.e., 20 log(loss factor)). This supposition is supported by extrapolating to lower frequencies from the curve generated by Kimura and Inoue. For a fundamental natural frequency in the 8 Hz band, this results in the full reduction. For resonances below the 8 Hz band, the resonant dip would be unchanged. Hence the modified octave band impedance response envelopes of Figure 5 are proposed. The curves are dependent on the loss factor for the floor and the appropriate envelope is chosen according to the relevant fundamental natural frequency.

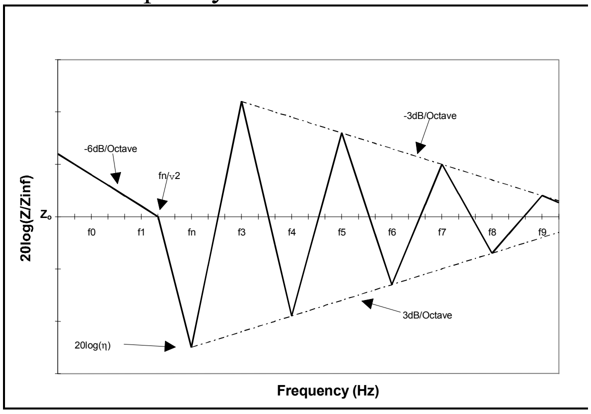

Figure 3. Idealised impedance (Z) response [5].

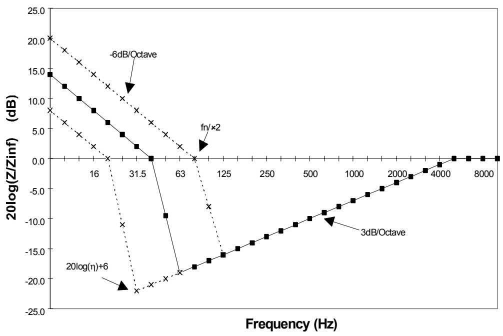

Figure 4. Octave band impedance envelope

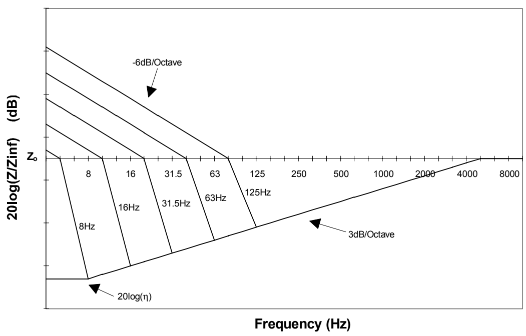

Figure 5. Proposed octave band impedance.

If the exciting force is located close to a boundary the floor impedance may be modified by early reflections and greater stiffness. Again on the basis of experiment, Kimura and Inoue note impedance increases of 10 to 15 dB and give regression formulae to apply when the force location is closer than half a wavelength from the boundary. The present work does not include any such cases.

Equivalent Plate

Lightweight floors are commonly of non-uniform thickness or of composite construction or both. An example is the joist and board floor. The procedures described above are in terms of a single material floor of constant thickness. For wider application an **equivalent plate** approach can be formulated. Floor behaviour is principally related to the bending stiffness EI, (Young's modulus by second moment of area). An equivalent uniform plate of the same EI as a non-uniform construction is readily formulated using simple bending theory. By choosing a convenient E (for example based on tension in the cross-section), equivalent values for thickness and density can be calculated. An equivalent loss factor can also be determined from bending theory. The "equivalent" approach was used in this work and the details of the derivations are described by Gaston [7].

Radiation to Space Below

Transmission of sound to the space below the floor is developed from the concept of Radiation Ratio, defined as the acoustic power radiated by a plate into a half-space, divided by the power that an infinite piston would radiate into the same half-space if the piston were vibrating at the same rms velocity as the plate. The ill-defined nature of the transient floor vibration is treated by Kimura and Inoue by using an initial area of disturbance as a radiation area. The area is derived as a circle, formed by propagation of the disturbance from the commencement of impact until the cessation of impact. It is argued that this region will contain all the energy that is generated in the plate. The rms velocity derived from the point impedance is taken as an approximation to the level of vibration in this circular portion of the plate. This area and vibration level are considered "equivalent" to the effect generated by the complete plate during one cycle of steady conditions.

Kimura and Inoue make a further assumption by using a constant value for the propagation velocity of the bending wave, based on the principal impact frequency. Their final results are supported by experimental results. In this work, a more representative calculation of initial disturbance area is adopted by making the area dependent on the frequency content of the input. By using the initial area of disturbance rather than the full area of the floor, an equivalent radiation area can be derived. The equivalent radiation ratio can then be used as if the vibration field in the plate is uniform and steady state. From the energy input and radiation ratio, the sound level in the space below can be calculated using conventional absorption and reverberation procedures.

Computer Modelling

The calculation programs are set up in four separate modules. There are three primary modules: force analysis, floor response and room behaviour. Each of these three is independent, and hence many combinations can be examined easily. The fourth module (the "project" module) uses the results of the three primary modules to predict the sound pressure level for a particular combination of force, floor and receiving space. All working is developed in one-third octave bands.

The force module is essentially a Fast Fourier Transform algorithm to generate the Discrete Fourier Transform and hence the mean square frequency domain representation of a particular force time history, in one-third octave bands. The frequency representation is the input to the floor response module. The force analysis module allows the input of either actual or theoretical time histories and also allows comparisons of results with published spectra.

The main objective of the floor response module is to determine the characteristics of the equivalent plate. For a simple floor that can be represented as a plate it is not necessary to use this module. For other than a simple floor the module calculates the equivalent properties.

The room behaviour module principally determines the absorption characteristics of the receiving room. This can be done from data for the room surfaces or measured results can be entered directly. The calculation is based on reverberant behaviour in the space.

In the project module, the output from the three primary modules is used to calculate a predicted sound level for a particular set of circumstances. It is within this module that impedance modifiers are applied to model the finite case.

Experimental Verification

Experiments to test the accuracy of the predictions of the model were undertaken at four locations over three sites:

1. Kindergarten / Church Hall
2. Community Centre / Church Hall - Undercroft
3. Community Centre / Church Hall - Annex
4. University College Assembly Hall

The building of location 1 consists of a two-storey concrete structure of approximately 100 m^2 per floor. The intermediate floor is 200 mm thick concrete with no ceiling or floor coverings. The floor is bisected by a concrete beam to give panels of approximately 9.0 m x 7.1 m. The point of impact was in the centre of a panel. The floor cannot be classed as of lightweight construction but it resembles the floor tested by Kimura and Inoue and therefore provides a basis for judging the performance of the Kimura and Inoue model with the refinements added. The material properties chosen for predictions were elastic modulus 29 GPa, density 2300 kg/m3, loss factor 0.01. The modelling taken was for an impact in the centre of a panel with beam supports on all sides.

At locations 2 and 3, the floor is polished timber tongue and groove (22 mm) on 140 mm joists at 450 mm centres. The Undercroft (lower) area had no ceiling but in the Annex there was a ceiling in the lower area and the floor above was carpeted. An equivalent plate was determined based on the 450 mm module width. Material properties used for timber were modulus 17 GPa, density 900 kg/m^3 and loss factor 0.04. The corresponding properties for plasterboard were 2 GPa, 760 kg/m^3 and 0.1.

The College building consists of an approximately 12 m diameter circular two-storey structure with a timber intermediate floor covered by a thin carpet, with a plaster ceiling in the lower space. Two large steel girders across the floor form a panel 4.2 m x 12.0 m. The details of the floor structure are not known but it is assumed to be 18 mm floorboards on 150 mm joists at 600 mm centres. The centre (tested) panel has an additional layer of 25 mm plaster acoustic tiles.

At each site the characteristics of the receiving room were determined from reverberation time measurements and sound pressure levels measured for impacts due to jumping from 100 mm and due to basketball impact. These inputs were chosen because they were the most consistent in force measurement studies. Sound levels were compared with predictions based on previously measured force profiles, floor construction and measured reverberation behaviour.

Results are shown in Figures 6 to 13. The agreement between measured and predicted levels for jumping impacts is generally good and comparable with the variation of measured levels from one jump to the next. In two cases - location 3 and 4, this agreement is maintained with carpeted floor, for which no allowance was made in prediction calculation. For ball bounce tests, the agreement is not good. Although general trends might be described as similar, predictions varied from measured results by 10 dB and more, both above and below measured levels.

Conclusion

Extensions of the Kimura and Inoue technique have been developed. The impedance response function at resonance has been expanded to cater for floors with a natural frequency in any octave band and an equivalent plate procedure presented for floor structures of non-uniform nature including cases of composite construction. The concept of radiation area has been expanded to account for the full frequency content of the force spectrum rather than just the principal impact frequency. Appropriate software has been written to simplify practical application of the procedures.

Testing over four floor arrangements was carried out to give a verification of the prediction model. Results for the ball bouncing impacts were limited but close correlation between predicted and measured sound pressure levels was achieved for jumping impacts for all four floors.

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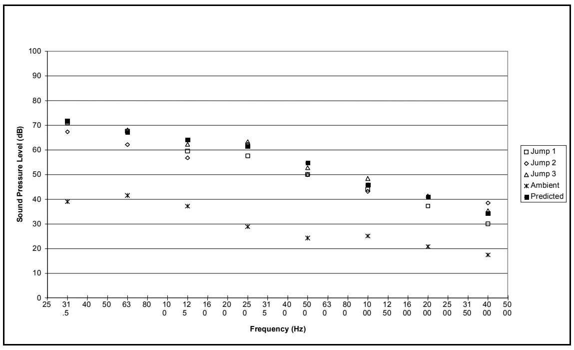

Figure 6. Kindergarten, jumping impacts.

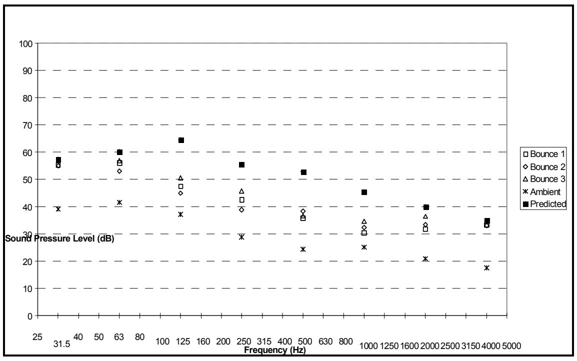

Figure 7. Kindergarten, ball impacts

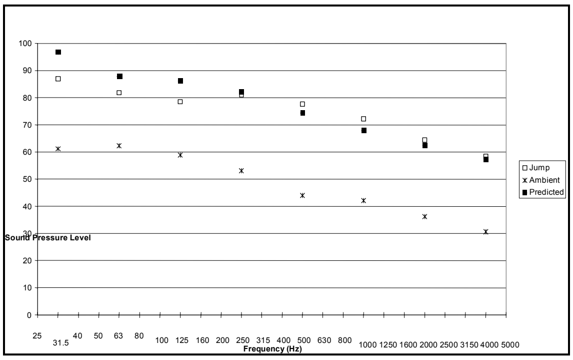

Figure 8. Undercroft, jumping impacts.

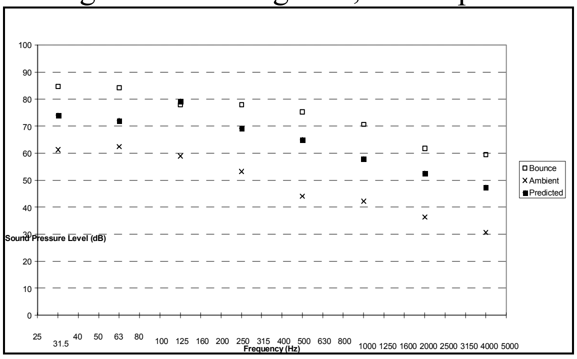

Figure 9. Undercroft, ball impacts.

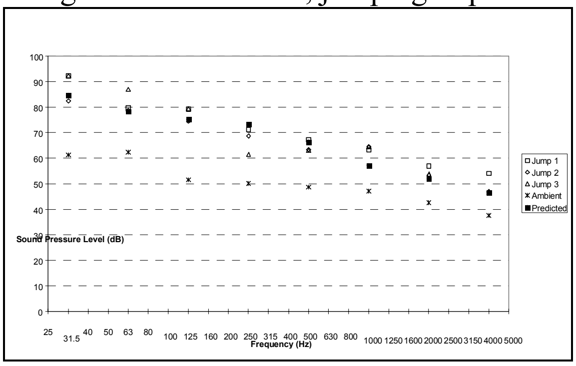

Figure 10. Annex, Jumping impacts.

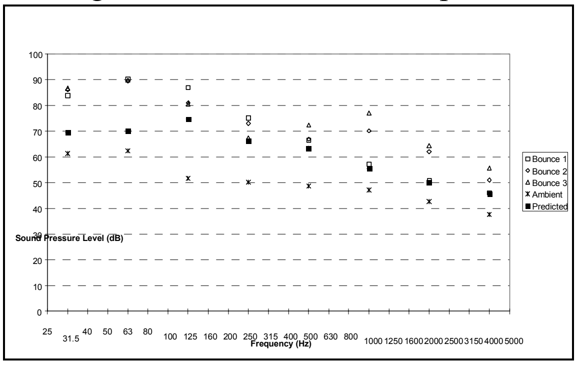

Figure 11. Annex, ball impacts.

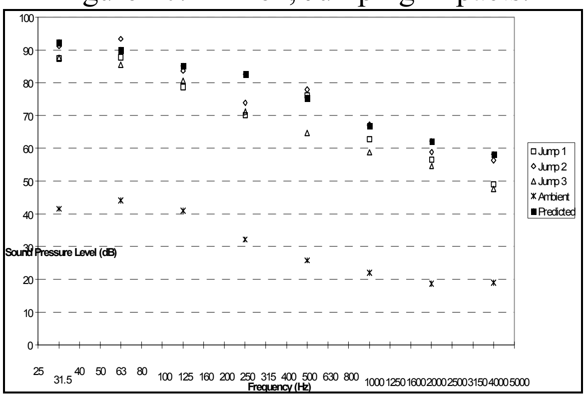

Figure 12. College, jumping impacts.

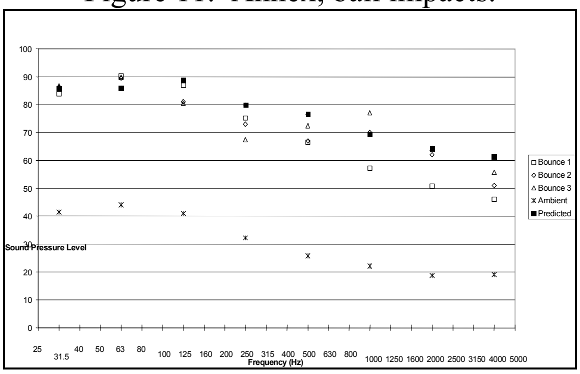

Figure 13. College, ball impacts.

Acoustics 2001
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LOW FREQUENCY FOOTFALL SOUNDS: AUDIBILITY AND PERFORMANCE OF LIGHT TIMBER FRAMED FLOORING SYSTEMS.

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Abstract
An audio recording of a bag-drop simulating footfall sound was recorded on a light timber framed / plasterboard intertenancy floor-ceiling system. Subjects listening to the recording via headphones performed three tasks:

- *Judgement of noticeable differences of impact sound.*
- *Judgement of impact loudness.*
- *Judgement of threshold of detectability of impact sound*

Additionally, impact sound transmission of a variety of floor-ceiling systems were measured in controlled conditions in a reverberation suite. Low frequency transmission of the different systems were compared to illustrate the range of impact levels for different types of systems (eg higher mass; resilient mounts). The significance of the impact performance of the different floor-ceiling systems was assessed using the results from the subjective sensitivity experiments. The pilot study shows that for hard surface floor coverings, high frequency transmission tends to govern impact loudness. In the context of the audibility tests, Gib Sound Barrier Board is shown to offer practical and effective impact sound attenuation.

1. Introduction

Comfortable, healthy homes are central to the business motivation of Winstone Wallboards NZ Ltd (Gib). Research and development into acoustic health and comfort is a fundamental part of this effort. This project is a pilot study of the audibility of impact sounds and how alterations to floors change perceptions. Real impact sounds from actual floor ceiling systems were used. The results give an idea of the benefits that “improvements” to floor-ceiling systems may provide. The successful performance of Gib Sound Barrier Board is used to demonstrate such improvement in action, and highlight some of the practical implications of such an approach.

2. Method & Results

Two high quality mono audio recordings where made beneath a typical New Zealand light timber framed intertenancy floor-ceiling (20mm particle board on 250mm joists at 450mm centres; 2 x layers of 12.5mm fire rated plasterboard (Gib® Fyreline™) on a steel clip-batten system without resilient mounts); 75mm glass fiber blanket in the cavity). The impact source was a 2.5kg bag of flour dropped from 1m. One recording was of the impact on the bare particle board floor; the other with wool carpet on rubber underlay covering the floor.

2.1 Just Noticeable Differences (j.n.d) – Linear Gain

The gain of the impact recordings was linearly adjusted (0dB to 8dB gain; minimum of 0.5dB steps) and ordered using digital audio editing software into a sequence of paired stimuli. Subjects listening through headphones (calibrated to closely match the actual sound level radiated beneath the ceiling) responded to a two-alternative-forced-choice task. J.n.d's for carpeted and bare floors were calculated as the change at which 50% of the subjects detected a difference.

For the typical NZ timber framed intertenancy floor the j.n.ds' were found to be 3.5dB carpeted, 2.5dB bare floor. [Note: using a method of magnitude estimation, the bare floor j.n.d was 1.6dB]

Table 1 shows the improvements in impact isolation produced by various modifications to the standard bare floor - measured in the laboratory. The standard bare floor had IIC44, Ln'w66, Ln'w(C1)65, Lnw ($C1_{50\text{-}2500}$)67 (By way of comparison, the carpeted floor had IIC>70).

TABLE 1

Additions to the standard floor:	Reduction at 63Hz (1/3 oct.) (dB)	Reduction at 500Hz (1/3 oct.) (dB)	Increase in IIC	Reduction in Lnw	Reduction in Lnw+C1	Reduction in Lnw+ $C1_{50\text{-}2500}$
+1 layer ceiling board	**0.9**	**0**	**2**	**2**	**2**	**1**
+2 layer ceiling board	**2.6**	**1.8**	**3**	**3**	**3**	**2**
+1 layer floor board	**2.4**	**4.3**	**6**	**6**	**5**	**4**
+resilient mounted clip	**12.9**	**0**	**3**	**3**	**4**	**5**
+1 ceiling layer; +2 floor layers	**5.4**	**10**	**10**	**10**	**9**	**7**
+1 floor layer; +25mm glass fiber board between floor layers	**2.8**	**27.2**	**7**	**11**	**8**	**3**

2.2 Loudness Magnitude Estimation – linear gain

Specified Loudness Changes	Spectrum Linear Level Difference (dB)
Same loudness	**1.45** (stdev 0.3)
0.25 x loud	**15.4** (stdev 6.2)
0.5 x loud	**9.0** (stdev 3.0)
2 x loud	**9.5** (stdev 0.7)
3 x loud	**12.3** (stdev 2.9)

TABLE 2

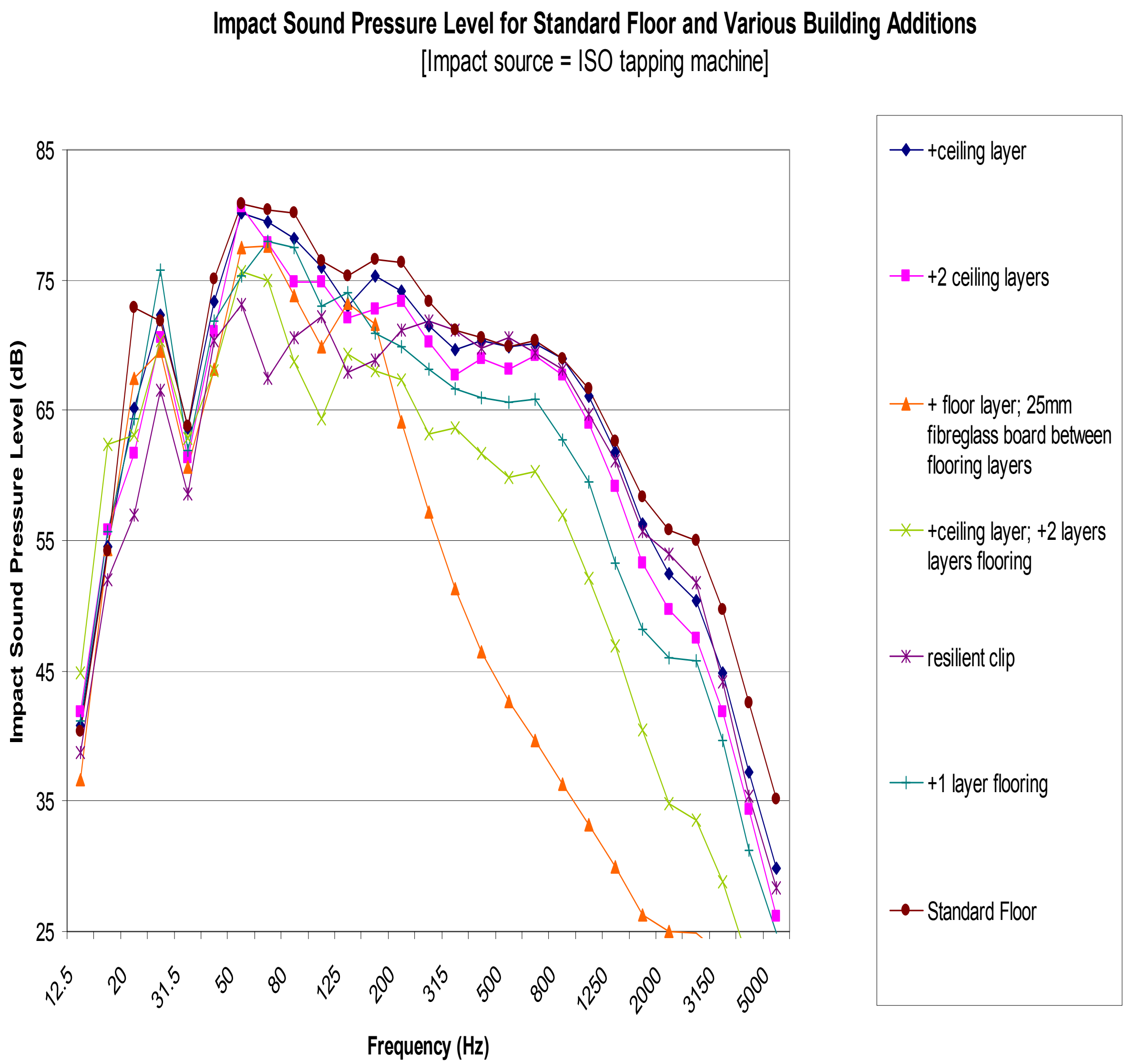
Subjects' loudness response function was measured by having the level of the standard bare floor impact sound adjusted (by the experimenter) until various specified loudness changes were achieved. An iterative method was used to find the specified loudness. The standard impact spectrum always preceded the adjusted impact spectrum. Results are shown in table 2

2.3 Equal Loudness between Standard and Altered Floors

Additions to the standard floor:	Level adjustment to equate loudness with the standard floor
+1 layer ceiling board	**1.5**
+2 layer ceiling board	**2.4**
+1 layer floor board	**6**
+resilient mounted clip	**2.9**
+1 ceiling layer; +2 floor layers	**6.9**
+1 floor layer; +25mm glass fiber board between floor layers	**9.3**

TABLE 3

A similar procedure was used to estimate subjects judgement of the loudness of the impact sounds from modified floors with that of the standard floor. Results are in table 3. Spectra for the altered floors are shown in graph 1.



2.4 Detectability

It may be considered that detectability of impact sound may be the criterion by which to judge building element sound isolation suitability (c.f Craik). The enormity of the challenge presented by a detectability criterion was demonstrated by increasing / decreasing the level of the recorded impacts to the threshold of hearing (as detected by 50% of subjects). The results indicate that, for the carpeted floor, the radiated spectrum would need to be reduced by 43dB, and for the bare floor, by 55dB.

2.5 Discussion

It is noted that the addition of a resilient mounted clip reduced low frequency sound pressure level by about 12db at some frequencies, and the addition of a extra layer of board to the floor reduced low frequency sound pressure level by about 2.5dB at some frequencies. However, subjectively, the additional layer of flooring board improved performance by more than 2 j.n.d's, while the resilient mount improved performance slightly more than 1 j.n.d. This demonstrates that reducing the sound pressure level in the mid to high frequency portion of the spectra improves occupant satisfaction for hard surfaced floor coverings. A possible reason (by way of hypothesis) for the unexpected effect of low frequency SPL reduction on occupant satisfaction is dynamic limiting of the ear by the inner ears reflex muscle.
It is hoped to show results from field comparisons at the conference.

3. Gib Sound Barrier Board

Gib Sound Barrier board is an optimization of the overlayment approach. The gypsum fiber formulation has both high mass (1400kg/m^2) and good intrinsic damping properties (compared with other common building materials). The system has been tested in the field, and in A-B comparison tests subjects have been impressed by the difference. Other performance benefits from the system are stiffening of the floor (calculated at 16% more stiffness), and improved fire resistance. From a construction perspective, it is easier to fix to floors than to ceilings, and there is little room for trade errors leading to compromised acoustic performance. Additionally, Gib Sound Barrier provides a tile and vinyl substrate significantly superior to particleboard.

4. Conclusions

- A pilot experiment has investigated sensitivity to impact sounds on typical LTF floors.
- This produced information on the relative loudness of impact sounds from modified floors. Comparing this with the j.n.d of a standard impact indicated the effectiveness of various floor additions at providing impact sound reduction. Hence,
  -adding either one or two additional layers of plasterboard changes the radiated impact level by less than 1 j.n.d;
  -adding a resilient clip, by 1 j.n.d;
  -adding 2 floor layers and 1 ceiling layer, by 2 j.n.d's;
  -adding 1 floor layer, by 2 jn.d's;
  -adding an extra floor layer and floating the floor, by 3 j.n.d's.
- The findings suggest that a linear level increase or reduction of about 10dB for a typical LTF impact sound spectrum doubles or halves the loudness.
- Although the addition of a resilient clip significantly reduced the radiated low frequency energy, the resulting spectrum was judged nearly as loud as the standard system. The addition of flooring board, although only slightly changing the low frequency sound pressure level, reduced the loudness by more than 2 j.n.d's – almost the same as for adding a ceiling layer plus two floor layers. The findings of this study support the view that for hard floor coverings on typical intertenancy floors, high frequency attenuation affects occupant satisfaction more than low frequency. It is hypothesized that this is due to dynamic limiting of the auditory system.
- Comparison of the difference in single number ratings for various floor additions with the level adjustments to make the floor addition impacts as loud as for a standard floor, suggests that certain single number ratings are more suited to certain types of construction.
- Achieving inaudibility of impact sounds is likely to be beyond the possibility of what would be considered to be Light Timber Frame construction.
- Gib Sound Barrier Board is an embodiment of an effective acoustic floor overlayment. Field comparisons show increased occupant satisfaction for hard floor surfaces. Such an approach has additional performance and construction benefits.

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IMPACT ISOLATION OF HARD FLOOR SURFACES IN CONCRETE STRUCTURES

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Abstract
This paper reviews acoustic treatment of elevated concrete floors to isolate impact noise which might arise from use of hard flooring such as timber, tiles, marble etc, in residential and/or commercial environments.

INTRODUCTION

Typical building elements would comprise a structural concrete sub floor with the selected hard surface materials set upon it. To isolate impact noise, a resilient material may be interposed between the structural slab and the trafficable floor surface with a range of flexible products available and suitably matched to these applications.

Such constructions are typically rated by an IIC value, being a particular measure of airborne sound level in the space below the floor, the sound energy being generated by a standard tapping machine placed on the floor above.

Alternative impact noise standards are available but the IIC rating is perhaps most widely used. Its usefulness relative to other standards in assessing impact isolation is not examined here.

FLOOR CONFIGURATIONS – Some Options

The following paragraphs define acoustical treatments for a range of hard floor surfacing materials which might typically be applied to a structural concrete sub-floor.

Concrete Raft – with isolation blanket laid over structural sub-floor (See Table 1)

- Wooden parquetry, ceramic tiles, marble, stone or other hard surfaces may be laid onto a reinforced concrete raft which in turn is cast directly onto a flexible blanket isolation material. The isolation material is placed unbonded directly onto the subfloor with a moisture barrier if required. Minimum thickness of the raft (for structural integrity) should be 25mm but even at this dimension load capacity may be limited.
- Where limitations on the floor loading are not acceptable, raft thickness should be at least 50mm with maximum thickness usually being restricted by setdown allowances (to permit adequate ceiling height) and sub-floor load carrying capacity.

Fully Floating Concrete Raft – high performance specification **(**See Table 2)

- The fully floating concrete floor, which occupies the high end of the spectrum for reduction of impact noise (and sound transmission) performance, is not common in residential or commercial office situations because of its relative expense but its characteristics are described here for completeness
- Such a configuration generally comprises a relatively thick (typically 100mm) raft supported by discrete flexible mountings forming an airgap between the structural and floating slabs

Timber Raft (See Table 3)

- Parquetry or Strip Timber Flooring laid onto a plywood base raft which is in turn set on to
  - an unbonded blanket isolation material placed onto the sub-floor, or
  - discrete pads of isolation material as defines **Sports Floor Construction**
- The pads must be bonded to the underside of the plywood.
- The plywood base must be continuous, that is two layers of 12mm ply laid ashlar pattern.
- One layer of 12mm ply can be used provided that it is tongue and groove connected on all four sides and shear plate connectors used. A flexible adhesive should be used in this case.

Timber Raft with Battens (See Table 4)

- Parquetry or Strip Timber flooring laid onto a structural plywood or particle board overlay mounted on battens. In turn, the battens are supported from the concrete sub-floor by strips or pads of isolation material which must themselves be bonded to either the underside of the battens or to the sub- floor. Battens should be kiln dried or well seasoned hardwood. For strip flooring, the board overlay may be deleted but the batten size must be sufficient to control expansion and contraction, cupping and warping of the timber due to humidity changes.
- Floors constructed in this way, although providing significant improvement in impact isolation between associated occupied areas, can suffer from a level of sound amplification in the source area due to a drumming effect. This can be reduced by introduction of a full cavity infill with medium density sound absorptive material will reduce this effect and would typically also improve the overall impact isolation.

Direct Bond Timber (See Table 5)

- The direct bonding of timber to a flexible blanket underlay without an intermediate board layer.
- The isolation blanket must be bonded to the structural floor and the timber bonded to the blanket using high strength adhesives such as 2 pack polyurethane at a minimum, so that movement in the timber due to environmental changes can be controlled.
- When using parquetry, this type of floor can not be completely sealed with conventional solvent based coatings because the potential for movement between blocks due to floor loadings may fracture the coating.

Loose Lay 3 Ply Veneer Flooring (See Table 6)

- Commonly called a "timber floating floor", this construction uses prefinished tongued and grooved laminated veneer construction timber.
- Stability of the floor relies upon its resistance to movement with humidity changes
- A thin foam layer is used as a bedding in layer but although it may improve initially isolation of impact noise, it compresses slowly and should not be relied on to retain its resilience and perform effectively in the long term.
- This system is not recommended for conventional solid tongued and grooved strip timber flooring because cupping and warping which may occur with humidity changes cannot be controlled.

·

Direct Bond Ceramic Tiles or Similar (See Table 7)

- In this configuration, ceramic tiles or similar hard flooring are directly adhered to a flexible blanket underlay without an intermediate board layer.
- The isolation blanket must be bonded to the structural floor and the tiles bonded to the blanket. Conventional latex modified cementitious adhesives can be used for both surfaces.
- It must be recognised that laying brittle materials on to a flexible blanket may limit floor loadings so that cracking of tiles does not occur.
- Intertile movement due to differential floor loadings may make a completely flexible joint sealing system necessary if it is to be waterproof.

HEIGHT REQUIREMENTS (SET DOWNS)

The greater the reduction of impact noise sought, the greater will be the overall thickness of the floor treatment required. High levels of impact noise reduction for hard floor surfacings cannot be achieved without some sacrifice of floor to ceiling height.

The smallest installed height for isolating treatment (20mm to 30mm as for direct stick systems), have the lowest impact isolation. Medium installed height treatments (40mm to 70mm for double ply overlays, strip timber with battens or thin concrete rafts) offer a moderate result whilst greater installed height treatments (80 to 150mm for deep timber joist floors with double layer panelling and cavity insulation or 100mm concrete floating floors on rubber mounts) have the highest isolation.

THE INFLUENCE OF SYSTEM MASS & STIFFNESS

In basic vibration theory, the lower the isolation system stiffness for a given mass, the lower will be the natural or resonant frequency, and the higher the degree of isolation for any particular frequency of applied vibration.

In shock isolation, where the inputs are of high level but short duration, the lower the isolation system stiffness, the greater will be the attenuation of shock into the foundation, but at the expense of higher system motion. Motion response is reduced by increasing the isolated mass.

Impact isolation of floors will sit somewhere between the two extremes, sharing characteristics of both. However, the basic premise that lower stiffness coupled with higher mass will lead to better reduction of impact, still applies.

Low isolation stiffness installations however must be tempered by a number of factors:

- The perception of being uncomfortable to walk on if a low mass floor.
- Some difficulty in catering for maximum design live loads on a low mass floor.
- Possibility of sealing problems with ceramic tiles.

At the other end of the spectrum, high mass systems must be take into account:

- Greater height occupied by the isolated floor system.
- Increased structural floor load bearing requirements.
- Significant increases in cost.

For most practical and economical systems, mass tends to be at the lower end, and stiffness at the higher end of design ranges, such that impact isolation resulting from floor treatment tends to be moderate only.

Another important factor is frequency range because although isolation performance at frequencies above 500Hz is usually satisfactory regardless of construction, overall performance at lower frequencies, which are most influential in determination of IIC data, can be improved by significantly increasing mass and air space of the isolated floor.

And whilst there is no substitute for impact isolation treatment at the source, that is, at the floor where the impact noise is generated, installation of a separate ceiling in the occupied area below can also contribute appreciably to enhanced low frequency performance.

Ceiling constructions can vary from plasterboard fastened to the slab soffit with standard furring channels through to a fully rubber isolated ceiling with a large insulation filled airgap and multiple layers of plasterboard. The more sophisticated the system, the higher the performance.

COMPARISON OF FIELD TESTS

As more impact isolation products become available, performance comparison has become increasingly difficult. Field IIC tests can be a valuable guide as to typical floor isolation, but must be always viewed in relation to:

- Background noise levels
- Flanking paths
- The presence (or not) of a separate ceiling in the receiving area
- An assessment of the bare (untreated) structural slab IIC

Overall IIC values can be misleading unless the above characteristics are known and reported with the data.

Often more meaningful than absolute values is the presentation of performance data in terms of improvement in IIC rating arising from isolating floor and ceiling treatments compared with results from the bare slab.

The likely IIC for any new floor construction can then be estimated from the sum of the component values

- IIC of the bare structural slab (Typically in the range 25 to 35)
- IIC Improvement due to isolated floor treatment (Typically in the range 15 to 25)
- IIC Improvement due to isolated ceiling treatment (Typically in the range 5 to 10)
  (When used in conjunction with an isolated floor)

BUILDING CODE OF AUSTRALIA

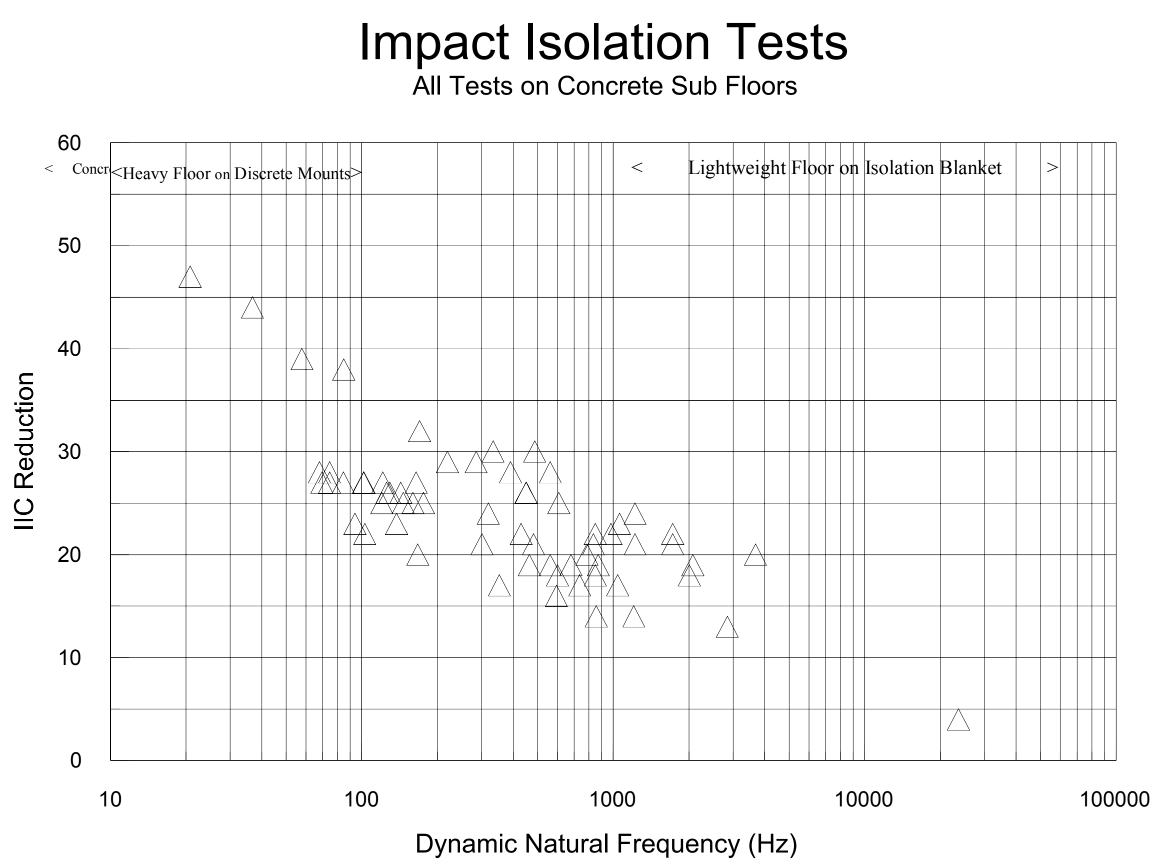
Currently there is no requirement for the impact sound insulation for floors. The ABCB RD2001/02, May 2001 is proposing a minimum value of IIC 50, although higher values are currently being used in other countries.

OVERVIEW OF SYSTEM PERFORMANCE

It is useful to be able to assess relative effectiveness as between various types of isolating floor treatments to guide designers towards selections appropriate to particular projects. With this in mind, Figure 1 is included as an overview to illustrate impact isolation performance of typical systems. The basis for the analysis is as follows:

- All data refers to a concrete structural sub-floor- without attempting to correct for its mass and stiffness.
- Where bare sub-floor IIC values have not been available, a value of IIC 31 has been taken to convert overall IIC values to an "improvement value".
- Where a separate ceiling in the occupied area below formed part of the tested construction, an average correction of IIC 7 has been used.
- The mass of the isolated floor treatment has been calculated from available trade information.
- Isolation layer stiffness has been calculated from available trade information or Embelton published data.
- An allowance for the stiffness of the air gap (where appropriate) has been included.
- Dynamic Natural Frequency has been calculated accounting for the above mass and stiffness factors.

The data is presented in the form of IIC Improvement vs Dynamic Natural Frequency for the isolated floor, and is split broadly into isolated floor construction types.



ACKNOWLEDGEMENTS
The following companies have graciously provided information and data associated with presentation of Graph 1:
Acoustic Logic Consultancy, ASA Structural Adhesives, Boral Plasterboard, Graeme Harding and Associates, Peter Knowland and Associates, Marshall Day Acoustics, Ron Rumble, Watson Moss Growcott Acoustics.

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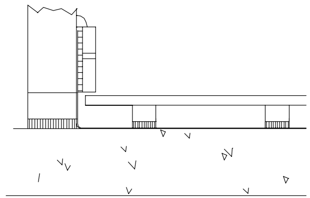
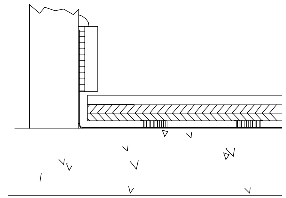
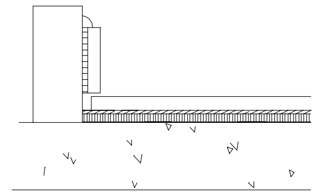


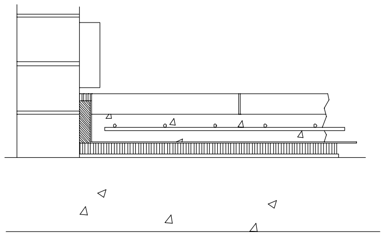
Timber Strip Floor on Battens
With Isolated Wall



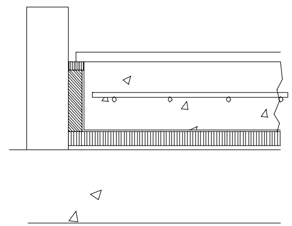
Double Ply Raft Sports Floor



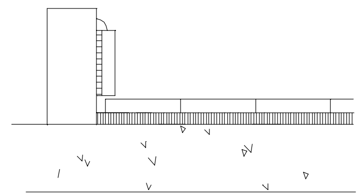
Loose Lay 3 Ply Veneer Timber



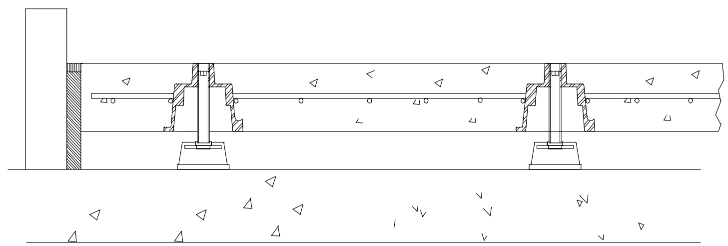
Ceramic Tiles/Marble/Slate
Using thin Concrete Raft



Multi- Purpose Concrete Raft



Strip Timber/Block Parquet/Ceramic Tile
-Direct Bond



Commercial Floating Floor - Jack-up Mountings

TABLE 1 - CONCRETE RAFT on Isolating Blanket

Concrete Raft Thickness	ImpactaMat* Isolating Blanket - Product ID			Likely IIC Range		REMARKS
	IM-CR	IM-750	IM-900	Overall Rating	Gain vs Bare Slab	
(mm)	Thickness Range (mm)					
25	3-10	5-10	3-15	58-63	27-32	Load Limitations
50	3-15	5-15	3-20	60-65	29-34	
100	10-30	10-30	10-30	65-70	34-39	

TABLE 2 - CONCRETE Fully Floating Floor (Rubber mountings +Airgap)

Concrete Raft Dimensions	Rubber Mountings (Type NR/RMA)*	Likely IIC Range		REMARKS
		Overall Rating	Gain vs Bare Slab	
Thickness 100mm Airgap 50mm	Natural Frequency 6-10 Hz	65-75	34-44	Mainly Commercial Installations

TABLE 3 -TIMBER RAFT on Blanket Underlay or Discrete Pads

Construction of Floor	ImpactaMat* Isolating Blanket - Product ID			Likely IIC Range		REMARKS
	IM-CR	IM-750	IM-900	Overall Rating	Gain vs Bare Slab	
	Thickness Range (mm)					
1Ply Raft+Blanket	3-10	5-10	5-10	48-52	17-21	Fibreglass Infill
2Ply Raft+Blanket	3-15	5-15	5-20	48-52	17-21	
1Ply Raft+Pads	NA	5-10	5-10	50-55	19-24	Point Load Limits
2Ply Raft+Pads	NA	5-10	5-15	52-57	21-27	Sports Flooring

*ImpactaMat, Polymat, Shearflex, NR/NRD, EmbarQuet are trade names of G P Embelton & Co Pty Ltd

TABLE 4 -TIMBER RAFT on Battens with Discrete Pads or Strips

Construction of Floor	ImpactaMat* Isolating Blanket - Product ID			Likely IIC Range		REMARKS
	IM-CR	IM-750	IM-900	Overall Rating	Gain vs Bare Slab	
	Thickness Range (mm)					
Battens on Pads or Strips	NA	5-10	5-15	52-60	21-30	Fibreglass Infill

TABLE 5 -DIRECT BOND OF TIMBER on Blanket Underlay

Construction of Floor	ImpactaMat* Isolating Blanket - Product ID			Likely IIC Range		REMARKS
	IM-CR	IM-750	IM-900	Overall Rating	Gain vs Bare Slab	
	Thickness Range (mm)					
19mm Block Parquet	5-5	5-10	5-15	45-52	14-21	Block Movement
12mm Strip Flooring	5-5	5-10	5-15	45-52	14-21	

TABLE 6 -LOOSE LAID 3PLY FLOORING on Blanket Underlay

Construction of Floor	ImpactaMat* Isolating Blanket - Product ID			Likely IIC Range		REMARKS
	IM-CR	IM-750	IM-900	Overall Rating	Gain vs Bare Slab	
	Thickness Range (mm)					
EmbarQuet* 3Ply Engineered "Floating" Floor	3-10	5-10	NA	45-53	14-22	

TABLE 7 -DIRECT BOND OF CERAMIC TILES on Blanket Underlay

Construction of Floor	ImpactaMat* Isolating Blanket - Product ID			Likely IIC Range		REMARKS
	IM-CR	IM-750	IM-900	Overall Rating	Gain vs Bare Slab	
	Thickness Range (mm)					
Ceramic Tiles	3-10	5-10	NA	44-47	13-16	Point Load Limits

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RAILWAY VIBRATION ISOLATION FOR MELBOURNE'S FEDERATION SQUARE PROJECT

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Abstract
Federation Square is a major new civic and cultural facility on the edge of the Melbourne CBD. The project, which is now approaching completion, forms a link between the city and the Yarra River, utilizing airspace over 13 parallel railway tracks and associated railway junctions adjacent to Flinders Street Station. The major facilities within Federation Square will include SBS radio and television studios, film library, cinemas, an interactive "cinemedia gallery" and a new museum of Australian art, managed by the National Gallery of Victoria. Other public spaces include a large civic plaza, restaurants, cafes and a 450 seat amphitheatre within a large glazed atrium.

As a result of the proximity to the railway and the particular noise and vibration sensitivity of the facilities, vibration isolation became a critical design issue. Acoustically sensitive facilities such as radio and television studios and, to a lesser extent the cinemas and galleries, cannot be used to their potential if they are periodically affected by noise from trains. Initial studies concluded that vibration isolation was required, however further studies showed that track based anti-vibration treatments, such as ballast mat or under sleeper pads would not provide sufficient vibration isolation for critical spaces. Long term maintenance and performance of these systems would also fall outside the control of the owners and operators of Federation Square. For these reasons, it was determined that the vibration isolation should occur within the building structure rather than at track level.

Vibration isolation was proposed immediately below the deck structure, but above the crash walls in order to provide a simple plane of isolation and to enable the above deck building works to proceed unimpeded. In areas with high vibration sensitivity, 3.5 Hz coil spring isolators were used, this being the first installation of steel springs to base-isolate a major Australian building. In areas of medium sensitivity, 7 Hz elastomeric bearings were utilized.

Introduction

The need to meet stringent project objectives despite significant site constraints is a familiar dilemma for many engineers, including acoustical practitioners. The Federation Square project is one such instance, which presented a unique set of challenges to the design team.

On this project, the designers were required to provide a satisfactory environment for acoustically sensitive radio and television studios in a location that is arguably the most noise and vibration affected development site in the Melbourne business district. The reason the site is so highly affected is that it spans across multiple railway tracks and railway junctions adjacent to Flinders Street Station. Virtually all of the building's substructure is located between or adjacent to the railway tracks, exposing the structure to high levels of vibration.

The difficulty of achieving the necessary structural vibration isolation was apparent from the early stages of the project, however as the design task progressed, it became further complicated by other design considerations, such as the conflict between vibration isolation requirements and the need to accommodate large transient loads in the event of a train derailment.

The following paper discusses the primary measures implemented to control vibration and structure-borne noise at Federation Square. Other acoustic challenges have also been faced by the project's design team, however the subject of this paper is limited to the vibration isolation measures incorporated into the design of the structural deck.

Project Description

Federation Square is a Victorian Government initiative to provide a major new civic and cultural facility on the edge of the Melbourne Central Business District. In addition, the project creates an accessible link between the CBD and the nearby Yarra River.

The majority of the project is constructed as an "air space" development above the 13 parallel railway tracks, immediately adjacent to Flinders Street station. The 3.5 hectare site is bounded by Flinders Street, Swanson Street, Batman Avenue and an extension of Russell Street.

The development contains four main components, these being:

- The Ian Potter Centre: NGV, which will be a museum and gallery of Australian Art, managed by the National Gallery of Victoria
- The Australian Centre for the Moving Image, which has been described as the nations first cultural institution associated with exhibiting film and screen culture, broadcasting, and multi-media technologies. This facility will house radio and television studios for SBS, plus cinemas, film library, and a Cinemedia exhibition gallery.
- A large glazed atrium incorporating a 450 seat amphitheatre at its southern end
- Open Plaza areas with capacity for 10,000 or more people

The Federation Square Project is linked to a rationalisation of the Jolimont Rail Yards and the associated trackwork immediately adjacent to Flinders Street Station. Even following the rationalisation, the area beneath Federation Square contains 13 parallel railway tracks with junctions comprising over twenty turnouts and/or diamond crossings. The trains are predominantly electric multiple unit suburban trains, however diesel hauled passenger services and freight services also run through the site.

In order to comply with PTC safety requirements, reinforced concrete "crash walls" were constructed at all support points adjacent to railway tracks. The deck was then constructed to provide a safe working platform for construction of the superstructure. In most areas, the deck structure involved steel beams and a reinforced concrete slab. Concrete and/or steel diaphragm and transfer beams were incorporated where necessary to distribute column loads onto the vibration isolation bearings.

Sensitivity of Occupancies

The facilities on the Federation Square site will range from a relatively low sensitivity to noise and vibration through to very high sensitivity. The proposed radio and television studies and (to a lesser extent) cinemas, require very low background noise levels in order to fulfil their normal functions.

Patron's experience of the galleries could also be affected by structure-borne train noise and vibration, and gallery officials have expressed concern that precious artworks should not be exposed to excessive vibration levels.

The design goals set out in Table 1 were adopted early in the project to address train noise and vibration. These apply to a "typical maximum" train passby event (ie the level which should be exceeded by no more than 10% of events). These design goals were based on AS 2107-1987 and AS 2670-1990, with appropriate adjustments to account for the intermittent nature of railway noise and vibration.

Table 1 Structure-borne Train Noise and Vibration Design Goals

Space	Sensitivity	AS2107-1987 Recommended Steady Noise Levels	Structure-borne Noise Design Goal * (dBA)	Floor Vibration Design Goal * (mm/s - rms)
Television and radio studios	Very high	NR20 – NR25	25	0.14
Cinemas	High	NR25 – NR30	35	0.2
Art Gallery	Moderate	40 – 50 dBA	40 - 50	0.2
Offices	Moderate	35 – 45 dBA	40 - 45	0.4
Restaurants, cafes and retail	Low	40 – 50 dBA	50	0.4
Outdoor spaces	Very Low	N/A	N/A	0.8

* Typical maximum event. The noise level of the average train event would be approximately 5 dBA lower.

Initial Assessment

The initial assessment involved a programme of vibration measurements, followed by a review of the options for vibration isolation leading to a preferred design concept. These investigations were carried out prior to completion of the architectural competition for the project, as the nature of the isolation treatments needed to be agreed prior to various early works, including the design and construction of the crash walls and the reconfiguration of the railway tracks.

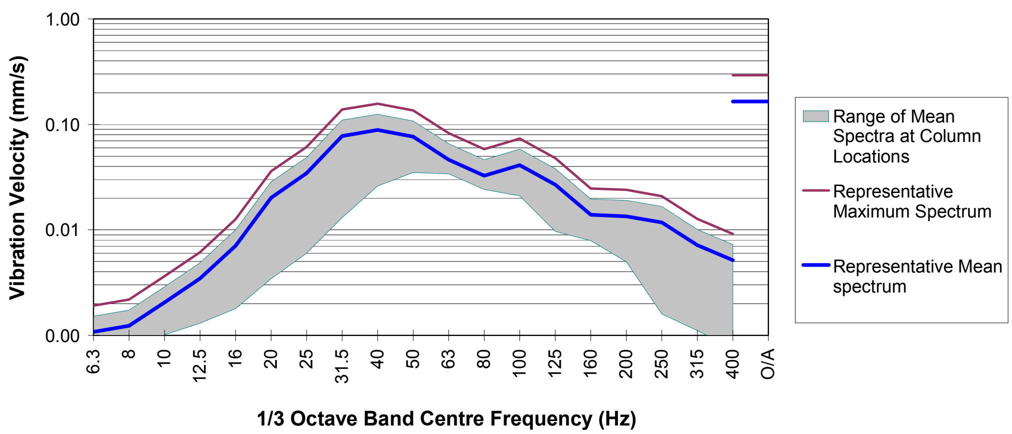
Vibration from PTC trains was measured in April 1997, primarily on the Princes Gate/Gas and Fuel Building structure, which had been demolished to street level, leaving a concrete deck with columns between the existing tracks. As such, this structure provided useful similarities to a possible non-isolated Federation Square deck structure.

Supplementary measurements were also carried out on the Northern Loop ramp and on mid-track columns for the Box Hill Central structure.

From the measurement results, representative vertical column vibration spectra were determined for mean and maximum train events at locations with and without rail running surface discontinuities (ie rail joints, diamond crossings, turnouts, etc). The representative vibration spectra for track adjacent to discontinuities are presented in Figure 1, together with the range of mean vibration levels measured at the various locations.

For the purposes of design, the “representative” vibration level for the mean train event was set at 3 dB below the highest mean level in each frequency band for any of the relevant locations. The level for the typical maximum train event was set 5 dB above this representative mean level.

Figure 1 Representative Vibration Spectra Adjacent to Track with Discontinuities



Vibration and structure-borne noise levels were predicted on the basis of the measurement results and methodologies in References 1 and 2.

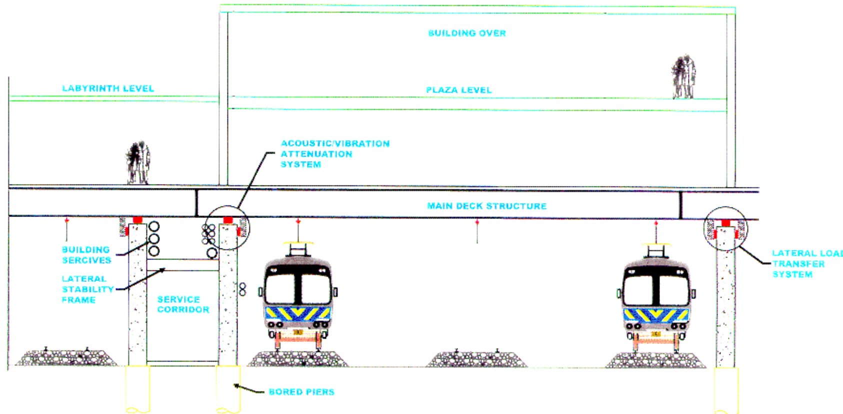
The initial assesments showed that track based anti-vibration treatments, such as ballast mat or under sleeper pads would not provide sufficient vibration isolation for critical spaces. Long term maintenance and performance of these systems would also fall outside the control of the owners and operators of Federation Square. For these reasons, it was determined that the vibration isolation should occur within the building structure rather than at track level.

Design of the Deck Vibration Isolation

The preferred option was for vibration isolation immediately below the deck structure, but above the crash walls, in order to provide a simple plane of isolation and to enable the above deck building works to proceed unimpeded. Initially, this concept involved most areas being isolated using high deflection multi-coil spring isolators, but for reasons of cost efficiency the deck was subsequently divided into zones, each with different vibration sensitivities.

In areas with high sensitivity, coil spring isolators were used. These ranged in capacity from 312 kN to 2724 kN. In areas of medium sensitivity, elastomeric bearings used, ranging in capacity from 156 kN (263 mm square bearing) to 1680 kN (422 mm square bearing). In non-critical zones, such as plazas and public access areas, no vibration isolation was employed. A cross section showing the location of the bearings is presented in Figure 2.

Figure 2 Cross Section of Typical Deck with Elastomeric Bearings



Vibration isolation systems are often referred to using simple single degree of freedom (SDOF) terminology. In the case of whole-building isolation, however, SDOF transmissibility theory results in considerable over-prediction of the isolation performance, which must be compensated by some other means.

In order to provide an appropriate prediction process for this project, measured reductions in vibration across the vibration isolation were examined for several existing isolated buildings. The measured performance in each frequency band was then approximated by modified SDOF theory, assuming that active mass is lost to the isolation system as frequency increases. By this method, an empirical relationship was developed, to enable performance estimates to be made for notional building and isolation systems.

Isolation performance was predicted for a nominal 3.5 Hz steel spring vibration isolation system and a nominal elastomeric vibration isolation system (9 Hz, subsequently revised to 7 Hz). The spring bearing units are shown in Figure 3 and the performance values are indicated in Figure 4.

Figure 3 Spring Bearings During Construction

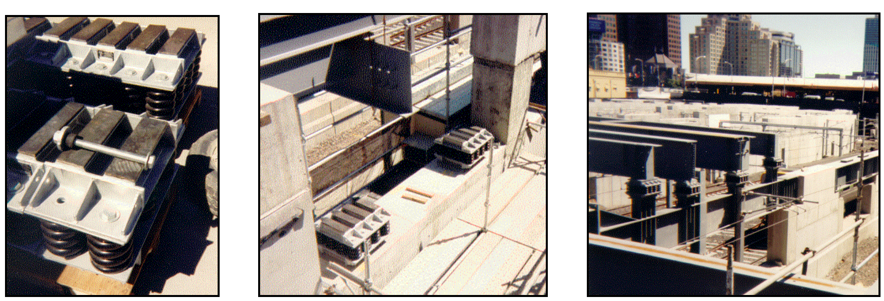
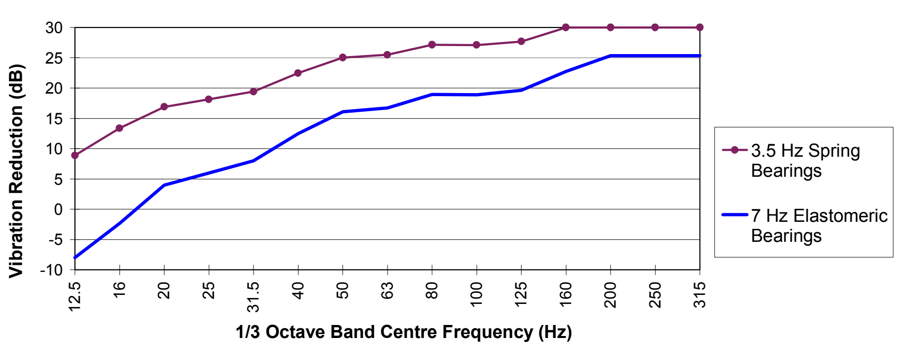


Figure 4 Predicted Vibration Reduction Across Isolators



The need for vibration isolators resulted in several complex consequences for the designers. In particular, the engineers had to design not only for the maximum loads, but also to avoid under-loading the bearings, which would reduce the vibration isolation performance. For the purposes of bearing design, the Normal Working Load was taken to be the unfactored Dead Load plus 30% of the design Live Load.

Whist the spring bearing units can support loads in all axes, an arrangement of both vertical and horizontal elastomeric bearings was required to accommodate the various load cases, while still providing sufficient vibration isolation in each direction. The design requirements for train impact loads in the event of derailments were such that the "crash walls" between tracks could not be designed to be free standing, and required restraint at the top via the deck structure. The conflicting objectives of providing restraint against high loads without bridging the vibration isolation were achieved by providing a small clearance between the impact restraint bearings and the crash walls, whereas the bearings for restraint against normal load cases (eg wind loads) are in constant contact.

Conclusion

The Federation Square project will reach completion in mid 2002. All of the deck vibration isolation measures are in place, and vibration measurements are planned for the near future.

Overall, the project has required more than 500 steel spring isolators and 1000 elastomeric bearings supporting a total mass of 75,000 tonnes. Installation has required particular attention to detail, often under the difficult time constraints imposed by the requirement to work within limited PTC occupations.

The combination of coil spring and elastomeric isolation systems makes Federation Square an interesting case study in design, and will provide opportunities for direct comparison of both short term and long term performance of the different isolation systems.

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Mason Industries (Bearing Manufacturer)

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A New Analytical Model for Sound Absorption Performance of Micro-Perforated Panel Absorber

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Abstract
A new analytical model based on the outdoor sound propagation theory and the classical Dah-You Maa's theory is established for the sound absorption performance of micro-perforated panel (MPP) absorber. Compared to Dah-You Maa's theory, this model is more general because it includes the sound attenuation by interference effect above the MPP absorber and the absorption performance of the absorber. The sound attenuation and absorption coefficient of the MPP absorber have been measured by the maximum length sequence (MLS) analyzer and impedance tube measurement respectively. The theoretical prediction from the present model shows a good agreement with both our and Maa's experimental results.

Introduction

Outdoor sound propagation theory is commonly used in the determination of attenuation of sound field over an impedance surface or ground. The classical theory for the sound field due to a point source above an impedance plane can be solved by the well-known Weyl van der Pol formula[1,2]. It has been used by many researchers for the formulation of sound field propagation over a locally or non-locally reacting boundary. In this research paper, a new modeling method is established for the absorption performance of micro-perforated panel (MPP) absorber. The main purpose of this paper is to realize the sound attenuation by interference effect and the sound absorption over the MPP absorber by outdoor sound prediction. Literature surveys[3,4,5] show that although many researchers have investigated the attenuation of sound field over an impedance plane, they used porous materials as the testing samples. For MPP absorber, no report has been found in this aspect in detail. The derivation of the sound energy absorption over the absorber by outdoor sound prediction has not been reported in the literature.

The classical Maa's theory of MPP absorber is not general enough because it just considers plane wave propagation without any interference between the direct and the reflected waves[6,7]. In real life, the sound generated from a point source would be a spherical wave and the sound energy absorption is influenced by the interference effect as well as the impedance of the absorber. These effects have been taken account in the proposed new model, which is therefore more general in MPP absorber performance prediction. Outdoor sound measurement is carried out to determine the sound attenuation by interference effect over the MPP absorber. It shows a good agreement with the proposed theory. The numerical prediction of the absorption coefficient of MPP absorber based on the proposed model shows a good agreement with the experimental result as reported by Dr. Maa Dah-You[8].

Theory

A. Review of Maa's Theory

The micro-perforated panel absorber may be considered as a thin metal sheet with a lot of holes backed by an air cavity. The normal acoustic impedance of single layer MPP absorber is[6]

$$Z_{mpp} = r + ix_m + z_D$$
$$= r + ix_m - \frac{i}{\cos\vartheta}\cot(kD) \tag{1}$$

also the oblique acoustic impedance of single layer MPP absorber can be written as

$$Z_{mpp\vartheta} = Z_{mpp}\cos\vartheta \tag{2}$$

where r is the resistance of MPP absorber, x_m is the reactance of MPP absorber, z_D is the impedance due to air cavity, i is the imaginary number, k is the wave number, D is the depth of air cavity and ϑ is the angle of incidence.
The normal acoustic impedance of double layer MPP absorber is

$$Z_{dmpp} = r + ix_m + \frac{(r + ix_m + z_{D2})z_{D1}}{r + ix_m + z_{D1} + z_{D2}} \tag{3}$$

also the oblique acoustic impedance of double layer MPP absorber can be written as

$$Z_{dmpp\vartheta} = Z_{dmpp}\cos\vartheta \tag{4}$$

where

z_{D1} is the impedance due to air cavity in first layer ,

z_{D2} is the impedance due to air cavity in second layer.

B. Theoretical prediction of sound attenuation over MPP absorber

For outdoor sound propagation prediction, a useful model is to consider a two-media problem with the plane interface lying at $z = 0$ in a rectangular co-ordinate system with x and y as the horizontal axes and z as the vertical axis. The acoustic pressure field p over impedance surface or ground can be represented by the Helmholtz equation:

$$\nabla^2 p + k^2 p = S(X_s) \tag{5}$$

where k is the wave number. For the sound field at the location $X = (x, y, z)$ due to a point monopole source situated at X_s where $S(X_s)$ is the source term at the point X_s and

$$\mathrm{S}(X_s) = -\delta(x)\delta(y)\delta(z - z_s) \tag{6}$$

To find the solution for the inhomogeneous equation (5), a Fourier transform pair is introduced as follows.

$$\hat{p}(k_x, k_{y,} z) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} p(x, y, z)e^{-ik_x x - ik_y y}dxdy \tag{7}$$

and

$$p(x, y, z) = \frac{1}{4\pi^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\hat{p}(k_x, k_y, z)e^{ik_x x + ik_y y}dk_x dk_y \tag{8}$$

Hence the Eq. (5) becomes

$$\frac{d^2\hat{p}}{dz^2} + k_z^2\hat{p} = -\delta(z - z_s) \tag{9}$$

where $k_z = \sqrt{k^2 - k_x^2 - k_y^2}$

Using the boundary condition of the impedance surface at $z = 0$,
Eq. (9) may be rewritten as

$$\frac{d^2\hat{p}}{dz^2} + k_z^2\hat{p} = 0 \tag{10}$$

Eq. (10) may also be rewritten as

$$\frac{d\hat{p}}{dz} + ik\beta\,\hat{p} = 0 \tag{11}$$

where β is the specific admittance of impedance surface.
The sound pressure field p can be approximated by Eq. (11) as[1]

$$p = \frac{e^{ikR_1}}{4\pi R_1} + \left\{R_p + (1 - R_p)F(w)\frac{e^{ikR_2}}{4\pi R_2}\right\} \tag{12}$$

where

$$w = (\frac{1}{2}ikR_2)^{1/2}(Z_e\cos\vartheta + 1)$$

$$R_p = \frac{Z_e\cos\vartheta - 1}{Z_e\cos\vartheta + 1}$$

As shown in Fig.1, R_1 is the distance between the source of the direct sound wave and the receiver. R_2 is the distance between the point of reflection of the reflected sound wave and the receiver. R_p is the plane wave reflection coefficient. $F(w)$ is the boundary loss factor. w is the numerical distance. Z_e is the specific normal acoustic impedance and ϑ is the angle of incidence. Thus the sound pressure p can be simply represented by the sum of two terms as shown in Eq. (12) which is also known as the Wely van der Pol formula of the outdoor sound propagation theory[1]. The first and the second terms can be interpreted as the direct wave and the reflected waves respectively.

We propose to use both the Maa's theory of MPP absorber and the outdoor sound propagation theory to predict the sound attenuation over MPP absorber with an arbitrary angle of incidence of sound wave. The sound pressure field above a single layer MPP absorber $p_{mpp\vartheta}$ is obtained by subsituting the oblique acoustic impedance $Z_{mpp\vartheta}$ into Eq.(12). Similarly, the sound pressure field of double layer MPP absorber $p_{dmpp\vartheta}$ is obtained by subsituting the oblique acoustic impedance $Z_{dmpp\vartheta}$ into the Eq.(12).

Therefore, the sound attenuation in dB over single layer MPP absorber is $20\,log\left|\frac{p_{mpp\vartheta}}{e^{ikR}/4\pi R}\right|$

and the sound attenuation in dB over double layer MPP absorber is $20\,log\left|\frac{p_{dmpp\vartheta}}{e^{ikR}/4\pi R}\right|$

where $R = R_1\cos\Phi$ is the horizontal distance between sound source and receiver.

C. Numerical prediction for absorption on MPP absorber using outdoor sound propagation theory

The sound energy absorption coefficient of MPP absorber with random incidence of sound waves is derived in the following. The sound energy distribution over the MPP absorber is illustrated in Fig. 1. $W_{mpp\vartheta}$ is the sound energy over the MPP absorber and W_H is the sound energy over the reference hard ground. The sound energy distribution over the micro-perforated panel absorber is dervied below:

$$
\begin{aligned}
W_{mpp\vartheta} &= \int_s I ds \\
&= \int_s p_{mpp\vartheta} v ds \\
&= \int_s \frac{p^*_{mpp\vartheta} p_{mpp\vartheta}}{\rho c} ds \\
&= \int_{\Phi}^{\frac{\pi}{2}} \frac{p^*_{mpp\vartheta} p_{mpp\vartheta}}{\rho c} 2\pi R_1^2 \cos\Phi \, d\Phi \\
&\approx \frac{2\pi R_1^2}{\rho c} \sum_{N=1}^{\infty} p_{mpp\vartheta_{(N)}} p^*_{mpp\vartheta_{(N)}} \cos\Phi_N (\Phi_N - \Phi_{N-1})
\end{aligned}
\qquad (15)
$$

where I is acoustic intensity, s is the surface area, v is the acoustic velocity, p^* is the conjugate of p, ρ is the density of air, c is the speed of sound in air and $N = 1,2,3,\ldots$. Thus, the sound energy absorption coefficient of MPP absorber is

$$
\alpha_{mpp\vartheta} = 1 - \frac{W_{mpp\vartheta}}{W_H} \qquad (16)
$$

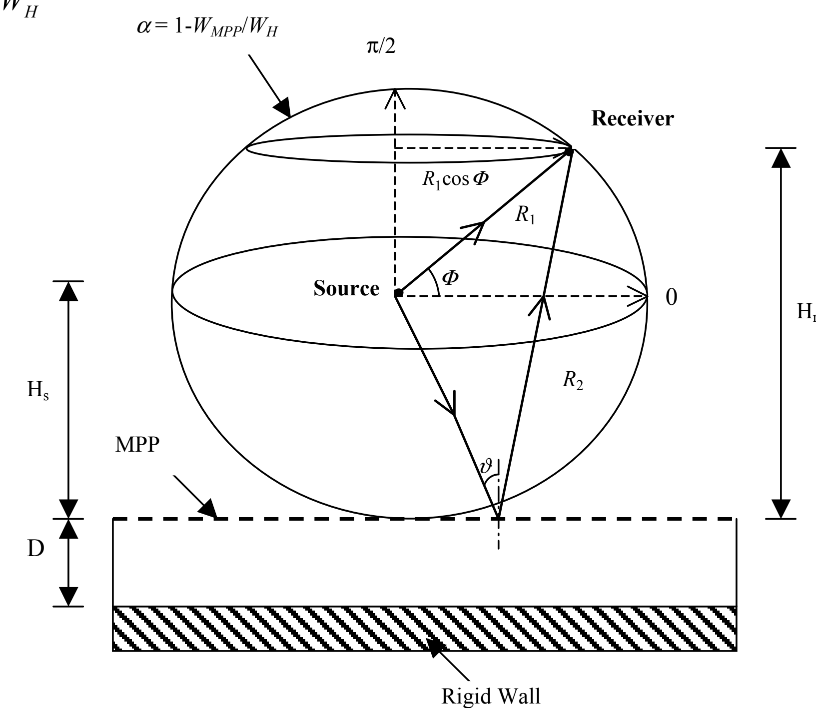

Fig.1 Schematic diagram of sound energy distribution over the MPP absorber where W_{mpp} is the sound energy over the MPP absorber and W_H is the sound energy over the hard ground as the reference.

Experiments and Discussions

A. Anecholic chamber

Experimental testing of the sound attenuation of a micro-perforated panel (MPP) absorber was carried out in the anecholic chamber with the maximum length sequence (MLS) system. In the experiment, the micro-perforated sheet is made of stainless steel. The sound attenuation was measured for different configuration of source and receiver position. Sound attenuation of a double layer MPP absorber had also been tested in the experiment for further validating the proposed model. The results for the single and double layers MPP are shown in Fig.2 and Fig.3 respectively. The experimental tests show good agreement with the numerical results using the proposed model. From Fig. 2, it is seen that several dips appear with sound attenuation against frequencies. These dips can be classified into two types: (I) A significant dip appears at the lower frequency is caused by the resonance occur in air cavity of MPP absorber so that it can draw sound attenuation about 5-10dB in the range 600 - 1k Hz. (II) A sharp dip appears which is caused by the effect of interference of the direct and reflecting waves above the MPP absorber so that it can draw sound attenuation about 20-30dB at a higher frequency around 10kHz. Both the frequency and size of these attenuation dips would be functions of the parameters of the MPP and the source and receiver positions.

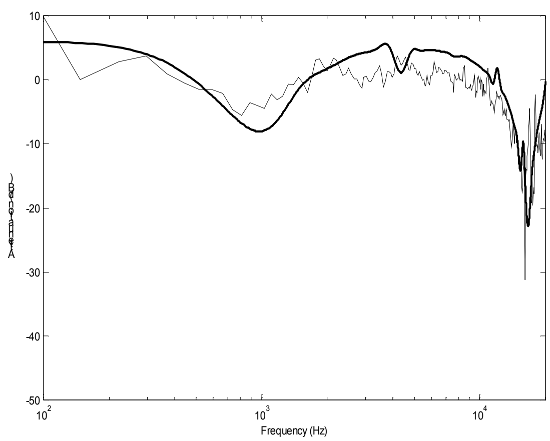

Fig.2 Sound attenuation of single layer MPP absorber source height = 1.7cm, receiver height = 21.7 cm, range = 60cm and angle of incidence = 68.7°.Parameters: d=0.3mm, b=3mm, t=0.15mm and D= 12cmExperimental result - thin solid line Theoretical result - thick solid line

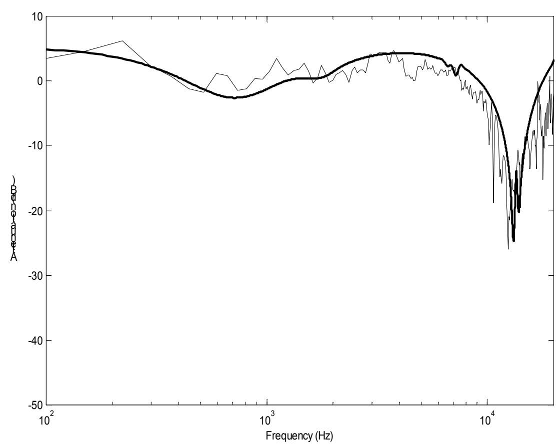

Fig.3 Sound attenuation of double layer MPP absorber source height = 1.7cm, receiver height = 22.3 cm, range = 50cm and angle of incidence = 64.4°. Parameters: d=0.3mm, b=3mm, t=0.15mm, D_1=6cm and D_2=6cm Experimental result - thin solid line Theoretical result - thick solid line

B. Impedance tube and Reverberation room

The absorption coefficient of MPP absorber was measured by two microphones impedance tube method. For impedance tube measurement, the measured frequency range was 100 Hz to 6.4k Hz. In Fig. 4, it is seen that the experimental tests show good agreement with the theoretical result. In Fig. 5, the experimental result of the absorption coefficient of MPP absorber measured in a reverberation room as reported by Maa[8] is compared to the numerical prediction by the proposed model. The parameter of MPP absorber are d = 0.4mm, b = 7mm, t = 0.4mm and D = 50mm. No edge effect occurs in the measured MPP absorber and therefore it is useful for further validating the proposed model. Reasonably agreement between calculation and measurement is obtained. It shows that the proposed theory can be used to model the absorption performance of MPP absorber.

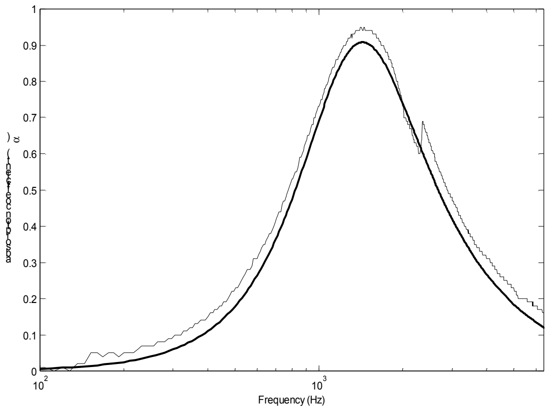

Fig.4 Absorption coefficient of MPP absorber by impedance tube measurement. Parameter of the absorber: d=0.2mm, t=0.2mm, b=2.3mm and D =18 mm. Experimental result - thin solid line
Numerical result - thick solid line

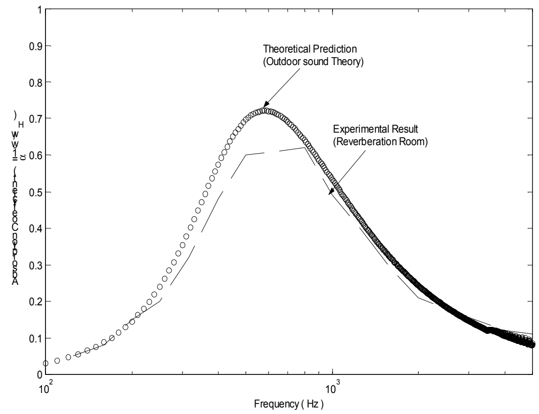

Fig.5 Absorption coefficient of MPP by reverberation room measurement.
Parameter of the absorber: d=0.4mm, t=0.4mm, b=7mm and D =50 mm

Conclusions

A new analytical model for sound absorption performance of MPP absorber based on the Maa's theory[6] and outdoor sound propagation theory[1] is proposed and tested numerically and experimentally. The numerical predictions based on this model agree well with the experimental measurement results. Since the proposed model can provide detail information of sound absorption of MPP absorbers of different configuration, it can be used for design optimisation of MPP absorber for environmental noise absorption applications. The research results also improve our understanding of the sound absorption performance of MPP absorber.

Acknowledgments

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The Parameters Contributing to the Acoustic Quality of Concert Halls

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Abstract

This study is aimed at investigating the factors that contribute to the overall acoustic quality (AQI) of concert halls and providing designers with alternative methods for predicting concert hall acoustic performance. The analysis was undertaken using some of Beranek's objective parameters (EDT, T_I, IACC, G_{mid}, and BR) and other geometric factors; number of seats, volume, the ratio of volume to seats (V/N), the ratio of length to width (L/W), the ratio of height to width (H/W) and shapes. A neural network analysis was carried with these inputs over four octave band frequencies from 125 Hz to 1000 Hz. Various combinations of acoustic factors were tried to determine which of Beranek's parameters are most significant in accurately predicting AQI and what other factors are important. It is shown that some of Beranek's factors can give good predictions of AQI and some other combinations of parameters can give predictions as good as those using Beranek's parameters.

Introduction

The science of concert hall acoustics began with Joseph Henry [1] who made the first major contribution in architectural acoustics by discovering "the precedence effect", which he called "the limit of perceptibility" in 1857. He suggested that the acoustic factors which are related to good quality acoustics are the size of the room, the strength of the sound, the position of the reflecting surfaces and the material of the reflecting surfaces. Over the past century, numerous studies have elucidated the requirement for the successful design of concert halls and also demonstrated how necessary acoustical details should be incorporated.

Beranek [2] postulated that there are seven acoustical attributes that are needed to provide good acoustic quality. These attributes were obtained from the technical literature on concert hall design in the past 30 years. More recently Beranek identified six orthogonal acoustical features [3] for achieving good acoustics. The six acoustical parameters with the definition and the preferred values are the following:

- *Early Decay Time* (EDT) is the time takes for a sound to decay from 0 to -10 dB relative to its steady state value. Berenek's preferred value of EDT is 2.2 s.
- *Inter-Aural Cross Correlation* (*IACC*) is a measure of the difference in the sounds arriving at the two ears of a listener. The measure Beranek used is $IACC_{E3}$: *IACC* determined over a time period of 0 to 80 ms with the average value in the three octave bands, 500 Hz, 1 kHz and 2 kHz. An $IACC_{E3}$ of 0.3 is preferable.
- *Strength* (G_{mid}) is defined as the average intensity of the sound from a standard sound source at mid-frequencies (500 Hz to 1 kHz) and the optimum value is 4 to 5.5 dB.
- *The initial-time-delay gap* (T_I) is the time interval in msec between the arrival at a seat in the hall of the direct sound from a source on stage to the arrival of the first reflection and a T_I of 20ms or less is preferable.

- *Bass Ratio* (BR) is described as the ratio of the average of the RT at low frequencies (125 to 250 Hz) to the average of the RT at mid frequencies (500 to 1 kHz). The preferred value is approximately 1.2.
- *Surface Diffusivity Index* (SDI) indicates the diffusing properties of the sound field produced by irregularities on all reflecting surfaces and the optimum value of SDI is 1.0.

Beranek's method is based on Ando's investigation [4] with the two added factors of BR and SDI. Ando [5] pointed out the uncertainty of the two added factors and their orthogonality. There is still a considerable need for further practical information to give a more rigorous basis for Beranek's method.

Essentially, a good or a bad hall is determined by the geometrical factors such as hall size and shape. Some studies have concentrated on using a 'geometrical' approach while others have used acoustical factors to predict acoustic quality of halls. To investigate what the change in acoustic quality of the halls would be if geometrical variables were changed, Fricke and Han [6] undertook a neural network analysis with ten geometrical inputs: volume, surface area of the wall and ceiling, number of seats, length, width and height of the auditorium, rake angle of the seats, a surface diffusion index, stage height and extent of stage shell/enclosure.

In previous studies, Fricke [7] and Choi and Fricke [8] showed that a modified version of Beranek's theory that used a combination of some of Beranek's acoustical inputs with geometrical parameters, such as the volume and the number of seats, can give predictions as good as those using Beranek's six attributes. The present work is intended to take the previous studies one step further by investigating parameters relating the acoustic quality of concert halls to a combination of five acoustical measures and six geometrical factors. Five of Beranek's acoustic measures (EDT, T_I, *IACC*, G_{mid}, and BR) were used together with the number of seats (N), the volume (V), the ratio of volume to seats (V/N), the ratio of length to width (L/W), the ratio of height to width (H/W) and shapes. The shapes are grouped into rectangular and non-rectangular. Rectangular and shoebox type halls are classified into rectangular and other geometric types are included into non-rectangular. The Surface Diffusivity Index (SDI), which is one of Beranek's six orthogonal factors, was not used as input since the subjectivity in assessing SDI values and no objective measurement has been standardized. The output is acoustic quality grade (AQG). AQG is a measure of AQI in three classifications: AQG (A)-those with an AQI of 0.7 or greater, AQG (B)-those with an AQI of 0.5 to 0.6 and AQG (C)-those with an AQI of less than 0.5. Because majority of halls is in an AQI of 0.4 to 0.6, we grouped into three categories that each has enough halls to give accurate analyses.

Neural Network Analysis

Neural Network Analysis (NNA) is a system loosely modeled on the human brain. It is composed of a large number of highly interconnected processing elements that are analogous to neurons and are tied together with weighted connections that are analogous to synapses. Learning typically occurs by example through training, or exposure to a truth set of input and output data where the training algorithm iteratively adjusts the connection weights to minimize the error in the output. The connection weights store the knowledge necessary to solve specific problems.

In the past two decades, NNA has been extensively studied and widely applied in solving a wide variety of problems, such as classification, approximation, feature extraction, generalization and signal processing problems. In particular, NNA [9] is good at pattern recognition and classification that inbuilt precedures to cope with imprecise input data which in effect generalize the flow of decisions within the model.

Figure 1 shows the neural network architecture used in this research. In the present study, eleven inputs (a maximum of seven inputs was used for any one network) and one output were used. A neural network with one hidden layer containing three neurons was trained using Statistica Neural Networks [10].

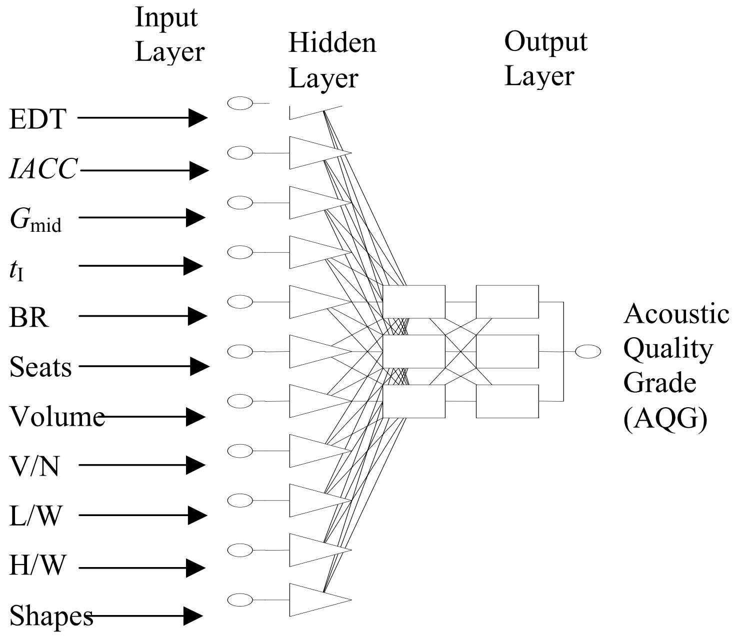

Figure 1. Multi-Layer Perception architecture used in the present work: not all the inputs are used in any one model trained.

Results

Neural Network Analyses were carried out to determine the parameters which are important for judgements of the acoustical quality of concert halls. In the present analysis, the acoustical and geometrical data for concert halls from Beranek's book [3] were mainly used. The data for some halls were contributed by other researchers: Bradley (National Research Council of Ottawa, Canada), Gade (Technical University of Denmark, Denmark) and Hidaka (Takenaka Research Institute of Chiba, Japan). Only thirty-two halls with sufficient acoustical data were available in Beranek's book and from other researchers. Neural Networks having different combinations of acoustical and geometrical input parameters were trained over the four frequency bands 125 Hz, 250 Hz, 500 Hz and 1 kHz. The higher octave bands 2 kHz and 4 kHz were dropped due to the lack of adequate data for all halls studied.

The 32 halls, which were chosen in this work, are listed in Table 1, in three categories of acoustic quality along with objective and geometrical parameters: group A, group B and group C. An acoustic quality index (AQI) shows the degree for how acoustically good auditoria are. The values for acoustic quality were used on Fricke and Haan's work [11]. Ratings of AQI were obtained using a self-administered questionnaire to musicians and conductors who were asked to express their opinion on the acoustics of up to 75 concert halls.

A total of thirty-nine networks, having different combinations of input variables, were trained. A maximum of seven acoustical and geometrical attributes were used as inputs. A network function was set up as follows;

$$\text{AQI} = f\,(\text{EDT}, IACC, G_{\text{mid}}, \text{T}_\text{I}, \text{BR}, \text{V/N and shapes})$$

Before a NNA was carried out, the correlations between the input variables were obtained to determine the orthogonality of the inputs. The correlation matrix for eleven input parameters in the 125 Hz band is given in Table 2. As shown in Table 2, the inputs are approximately orthogonal. The correlations in each octave are slightly different, but the acoustical parameters EDT and G_{mid} are most the highly correlated for every frequency band.

Of the thirty-two halls, twenty-six cases were used for training, three for verification and three for testing. Three hidden neurons and one output neuron were used.

Table 1. The Thirty-two halls for a Neural Network Analysis.

Group	Hall Name (City)	EDT** (s)	$1\text{-}IACC_{E3}$	G_{mid}** (dB)	T_I (ms)	BR**	N	V (m^3)	V/N (m^3)	H/W	L/W	Shapes*	AQI
A (an AQI of 0.7-1.0)	Concertgebouw (Amsterdam)	2.61	0.62	5.8	21	1.08	2,037	18,780	9.20	0.62	0.94	REC	0.9
	Berlin Philharmonie Hall (Berlin)	2.05	0.46	4.9	21	1.01	2,335	21,000	9.00	0.30	0.68	GEO	0.8
	Boston Symphony Hall (Boston)	2.04	0.65	4.7	15	1.03	2,625	18,740	7.14	0.81	1.71	REC	1.0
	Severance Hall (Cleveland)	1.68	0.59	3.0	20	1.14	2,101	15,690	7.50	0.61	1.20	HOR	0.8
	Herkulessaal (Munich) [c]	2.46	0.96	4.4	24	0.98	1,287	13,600	10.60	0.71	1.46	REC	0.7
	Symphony Hall (Osaka)	2.10	0.56	4.6	35	1.00	1,702	17,800	10.50	0.65	0.89	REC	0.9
	De Doelen Concertgebouw (Rotterdam)[e]	2.30	0.55	3.2	35	0.95	2,242	24,070	10.70	0.59	0.61	GEO	0.8
	Grosser Musikvereinssaal (Vienna)	2.96	0.71	7.1	12	1.11	1,680	15,000	8.93	0.88	1.80	REC	1.0
B (an AQI of 0.5-0.6)	Stadt-Casino (Basel)[c]	2.55	0.64	8.1	16	1.17	1,448	10,500	7.25	0.72	1.12	REC	0.6
	St. David's Hall (Cardiff)	1.91	0.60	3.6	25	0.96	1,952	22,000	11.20	0.66	1.00	GEO	0.6
	Tivoli Koncertsal (Copenhagen)[b]	1.90	-	5.2	16	0.92	1,780	12,700	7.10	0.41	0.97	FAN	0.5
	Usher Hall (Edinburgh)	1.99	-	4.0	33	1.17	2,564	15,700	6.16	0.72	1.28	HOR	0.5
	Philharmonie Hall (Liverpool)	1.89	0.60	3.3	25	1.00	1,824	13,560	7.43	0.47	0.96	FAN	0.5
	Salle Pleyel (Paris)	2.61	0.54	2.8	35	1.23	2,386	15,500	6.50	0.73	1.19	REC	0.5
	Academy of Music (Philadelpia)	1.21	0.47	1.5	19	1.12	2,921	15,800	5.38	1.10	1.76	HOR	0.6
	Festspielhaus (Salzburg) [d]	1.63	0.54	4.2	27	1.10	2,158	15,500	7.20	0.44	0.90	FAN	0.6
	Liederhalle, Beethovensaal (Stuttgart)	1.60	0.44	3.7	29	1.00	2,000	16,000	8.00	0.37	1.15	GEO	0.5
	The Mechanics Hall (Worcester)[a]	1.99	0.57	6.0	28	1.16	1,343	10,760	8.01	0.51	1.10	REC	0.6
	Grosser Tonhallesaal (Zurich)	3.58	0.71	8.6	14	1.23	1,546	11,400	7.37	0.70	2.03	REC	0.6
C (less than 0.4)	Colston Hall (Bristol)	2.08	0.63	5.2	21	1.05	2,121	13,450	6.34	0.78	1.21	REC	0.4
	Radiohuset Studio 1 (Copenhagen)	1.59	0.58	5.8	29	1.07	1,081	11,890	11.00	0.53	0.55	FAN	0.4
	Boettcher Concert Hall (Denver)[a]	2.88	0.81	1.1	-	1.14	2,750	37,240	13.54	0.33	1.10	GEO	0.3
	Barbican Concert Hall (London)	1.88	0.46	3.6	27	1.07	2,026	17,750	8.76	0.36	0.70	GEO	0.2
	Royal Albert Hall (London)	2.53	0.52	-0.7	15	1.13	5,080	86,650	17.00	0.76	0.94	GEO	0.2
	Royal Festival Hall (London)	1.92	0.63	2.1	34	1.17	2,901	21,950	7.56	0.47	1.14	REC	0.4
	Free Trade Hall (Manchester)	1.47	-	3.5	25	0.82	2,351	15,430	6.60	0.85	1.15	REC	0.4
	Gasteig Philharmonie Hall (Munich)[d]	2.30	0.49	1.9	29	1.00	2,487	29,737	12.40	0.29	0.80	FAN	0.4
	Avery Fisher Hall (New York) [c]	-	0.54	3.8	30	0.93	2,742	20,400	7.44	0.65	1.50	REC	0.3
	Eastman Theatre (Rochester)	2.32	0.82	3.6	2	1.21	3,347	25,470	7.62	0.56	0.97	FAN	0.4
	L.M.Davies Symphoney Hall (SanFrancisco)	2.69	0.44	3.4	12	1.11	2,743	24,070	8.78	0.74	1.16	GEO	0.4
	Roy Thomson Hall (Toronto)	2.23	0.54	3.3	35	1.10	2,812	28,300	10.10	0.74	0.87	GEO	0.4
	JFK Concert Hall (Washington)	1.67	0.61	2.6	25	1.06	2,759	19,300	6.08	0.54	1.00	REC	0.4

[a] Data from J.S. Bradley, National Research Council of Ottawa, Canada.
[b] Data from A.C.Gade, Technical University of Denmark, Denmark.
[c] Data from T.Hidaka, Takenaka Research Institute of Chiba, Japan.
[d] *IACC* data from T.Hidaka, Takenaka Research Institute of Chiba, Japan.
[e] Data for H/W and L/W used Lower values:H/W=0.59(Lower), L/W=0.61 (Lower), H/W=0.44 (Upper) and L/W=0.98 (Upper).
* Shapes are divided into two types: Rectangular (Rectangular and Horseshoe) and Non Rectangular (Fan shape and Geometric).
** Unoccupied data used. The EDT is used the 125 Hz value.
N = number of seats.
V(m^3) = volume.
V/N(m^3) = ratio of volume to seats.
H/W = ratio of height to width.
L/W = ratio of length to width.

The results are summarized in Table 3, with the root mean square errors (RMS errors) of testing data that show how well the network performed, over the four octaves 125 Hz, 250 Hz, 500 Hz and 1 kHz. Each network was trained five times using different training, verification and testing data that were randomly selected to give more confidence in the results. The RMS errors in Table 3 are the averages of five performances. Other networks are not shown with their RMS errors in this table as they performed poorly.

Table2. Correlation matrix for eleven parameters in the 125 Hz band.

	Parameters											
	EDT	1-$IACC_{E3}$	G_{mid}	T_I	BR	N	V	V/N	H/W	L/W	Shapes	AQI
EDT	1.00											
1-$IACC_{E3}$	0.37	1.00										
G_{mid}	**0.43**	0.36	1.00									
T_I	-0.35	-0.35	-0.22	1.00								
BR	0.34	0.12	0.16	-0.35	1.00							
N	-0.03	-0.23	-0.75	-0.25	0.20	1.00						
V	0.14	-0.20	-0.63	-0.15	0.02	0.84	1.00					
V/N	0.21	-0.08	-0.33	0.10	-0.32	0.33	0.75	1.00				
H/W	0.22	0.24	0.05	-0.34	0.26	0.16	0.07	-0.13	1.00			
L/W	0.36	0.39	0.30	-0.46	0.35	-0.08	-0.22	-0.40	0.65	1.00		
Shapes	-0.18	-0.41	-0.35	0.07	-0.34	0.26	0.37	0.47	-0.49	-0.63	1.00	
AQI	-0.12	-0.22	-0.35	0.00	0.29	0.40	0.30	0.09	-0.16	-0.27	0.37	1.00

Table 3. Root Mean Square errors (RMS errors) of testing data for the best networks over the four bands 125 Hz-1 kHz.

Network Function	Octave Bands			
	125Hz	250Hz	500Hz	1kHz
AQI = f (EDT, *IACC*, G_{mid}, BR, V/N and Shapes)	0.47	0.45	0.48	0.39
AQI = f (EDT, *IACC*, G_{mid}, BR and Shapes)	0.43	0.45	0.48	0.41
AQI = f (EDT, *IACC*, G_{mid}, V and Shapes)	0.47	0.47	0.37	0.44
AQI = f (EDT, *IACC*, G_{mid}, N and Shapes)	0.46	0.45	0.44	0.44
AQI = f (EDT, G_{mid}, T_I, V/N and Shapes)	0.41	0.45	0.48	0.44
AQI = f (EDT, G_{mid}, BR and Shapes)	0.44	0.44	0.46	0.48
AQI = f (EDT, *IACC*, BR and Shapes)	0.44	0.46	0.47	0.46
AQI = f (EDT, G_{mid}, V and Shapes)	0.45	0.53	0.51	0.44

The RMS error ranges are 0.37 to 0.53 through the eight best networks and indicate a slightly different trend over each frequency band, though the network has same input variables. EDT is the only frequency dependent factor used in this analysis and the correlations show the importance of EDT in the mid frequencies (500 Hz and 1 kHz), those are respectively -0.28 and -0.37. Several networks, such as, a six parameter model (EDT, *IACC*, G_{mid}, BR, V/N and Shapes), a five parameter model (EDT, *IACC*, G_{mid}, BR and Shapes), two other five parameter models (EDT, *IACC*, G_{mid}, N or V and Shapes) are in agreement with this but others are not.

Three of the major geometrical attributes predict acoustic quality as well as acoustical factors [see Table 2]: the number of seats, the shapes and volume. For instance, a five parameter model having EDT, *IACC*, G_{mid}, N and Shapes is as good as a network model using EDT, *IACC*, G_{mid}, BR and Shapes with approximately a RMS error of 0.45. This is in accordance with the author's previous finding [7, 8] that indicated geometrical factors such as the number of seats and volume are significant parameters as well as acoustical parameters in determining good acoustic quality.

Conclusions

The present study is an attempt to provide further information concerning the factors that are important for designing high acoustic quality of concert halls. Neural networks were trained with different combinations of some of Beranek's parameters combined with geometrical factors in four octave bands from 125 Hz to 1 kHz bands. Firstly, according to these results, several network models predict AQI well without using SDI as an input. Those networks consist of some of Beranek's factors together with geometrical parameters such as, the shapes, the volume (V) and the number of seats (N). This suggests the possibility that geometrical inputs could be used with or without acoustic inputs in order to predict good acoustical quality.

Secondly, a different trend is seen for RMS errors in different frequency bands. From this study, EDT is important in determining the acoustic quality of concert halls, since EDT is the only frequency dependent factor used in the present analysis. The correlation matrix also shows the importance of EDT in the mid frequencies.

Finally, even though some of Beranek's parameters present one approach to predicting AQI, there is still a considerable need for further practical investigation of Beranek's approach on the preferred values and weightings.

There are several limitations of this study. The first is still the lack of cases to train, verify and test the neural networks because of the difficulty of getting measurement data for real halls. The reliability of his data is questionable since most measurement data presented in Beranek's book is the average of measurements made by two or more experimenters. There are significant differences in the results obtained in different studies. This is quite important in the case of *IACC*, EDT and BR since the range of values within the data is very small. Also, the data used for training, verification and testing should have similar statistical distributions of values of all inputs.

Because of the importance of those parameters for good acoustics, and also the difficulty of collecting measurement data for halls, further studies will be carried out with only geometrical parameters as inputs to get acoustically ideal halls. In addition, a numerical method and subjective test using these results will be carried out to verify the results of the present study.

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BROADBAND ACOUSTIC SCATTERING OF SUBMERGED OBJECTS

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Abstract
Target echo simulation is useful in the development and evaluation of underwater active detection systems. Realistic simulation of echoes requires a multi-frequency evaluation of acoustic scattering. This can be achieved by numerically modelling the surface of the object of interest as a collection of facets and calculating the scattered field using the Helmholtz-Kirchhoff approximation. Time and frequency analysis of simple objects (e.g. a sphere) and complex structures are given as examples.

Introduction

The development and evaluation of signal processing algorithms for underwater active detection systems can be greatly enhanced in terms of robustness and accuracy if realistic signal/target models are used. In the past, very simple models were used for algorithm development because realistic models were computationally costly and of little benefit to low- resolution systems operating in benign environments. For example, the target echo of an echolocation system was modeled as an attenuated time-delayed and Doppler-shifted replica of the transmitted signal. Measurements of actual target echoes show that this is a first order approximation at best, even for very simple targets such as spheres. With recent advances in computing software and hardware the use of more realistic models becomes feasible and cost effective. For the same reasons, sensor and processing technologies now have increased resolution and fidelity, allowing the opportunity for greater exploitation of the information carried by the received signal and hence the need for high fidelity modelling of this signal.

In this paper we show some results of high fidelity modelling and simulation of echoes from underwater targets. The acoustic scattering is multi-frequency, i.e., broadband in nature to match what is possible in actual systems. Many previous results in this area have concentrated on single frequencies, narrowband approximations, or calculated averaged/integrated quantities such as target strength, rather than echo time series. The plan for the rest of the paper is as follows: We first review the modelling methodology and then present the case of a sphere and compare the results of the numerical model with analytic ones. This is followed by some results from the scattering of a target complex. The results are presented in both the time and frequency domains. It will be shown that the results for high-frequency scattering are more intuitive in terms of interpretation when viewed in the time domain. Finally, some examples of applications to detection and classification processing are given and the paper concludes with some comments.

Model of Acoustic Scattering

The model for acoustic scattering [1] is based on the evaluation of the Helmhotz-Kirchhoff integral over the surface of the object under consideration. The surface of the object is modelled by a mesh of triangular facets. The Helmholtz-Kirchhoff integral can be evaluated analytically for each triangular facet, which helps reduce the amount of computation needed. The total scattered field from the target of interest is then obtained by a coherent summation of the scattered field from all the individual facets. The material properties of the target are encapsulated in the local reflection and transmission coefficients of the target. Additional computational complications such as multiple transmission layers, scattering from several layers, hidden surface removal and first-order multiple scattering have been found to be necessary inclusions to make the results realistic. Also note that at lower frequencies, diffraction of sound around components of the object can be significant and is only crudely approximated. However, the diffraction that gives rise to the forward scattering lobe with bistatic calculations is fairly well approximated.

The model has been well tested against known results for the monostatic scattering of basic shapes and scale models of components of complex targets. However, no rigorous tests of a target with a high level of complexity are available. Currently, for large size complex targets, the model is expected to give less accurate results at the lower frequencies, where structural resonance and diffractive effects become important. At the other end of the spectrum, there is no high frequency limit of validity since the technique is intrinsically a high frequency one. In practice, however, the upper frequency limit is determined by the need to accurately represent the target surface by plane facets to some fractional-wavelength accuracy. Therefore, at higher frequencies the number of facets, and hence the amount of computation, required for curved surfaces can be very large. For example, with a 500 MHz Pentium PC, it takes about one minute per frequency per aspect angle to calculate the scattering response of a complex structure represented by 260,000 facets. Simpler objects can take considerably less time.

This model can be used to compute a number of quantities characterising the acoustic wave scattering from an arbitrary object. Traditionally, in sonar and underwater acoustics, the target strength [2] has been used to quantify the amount of energy reflected from an object, i.e.,

$$TS \equiv 10 \log_{10}\left(\frac{I_s}{I_i}\right)\Bigg|_{r=1m} \quad (1)$$

where I_i is the incident intensity (assuming plane waves) and I_s is the intensity of the scattered field measured at the reference distance of $r = 1\,\text{m}$ from the scattering centre of the target. The measurement or calculation of the field intensities is usually made per single frequency. However, in many applications, there is a need to characterize the target scattering response over a band of frequencies. This can be done in two basic ways. The first is the target's transfer function, which is a measure of its frequency response and is defined as

$$H_T(f) = \frac{p_s(f)}{p_i(f)} \quad (2)$$

where $p_i(f)$ and $p_s(f)$ are the Fourier transforms of the incident and scattered pressures over the frequency band of interest, respectively[1]. The other way is to use a time domain description of the target, i.e., the impulse response. The impulse response, $h_T(t)$, is related to the transfer function via a Fourier transformation:

[1] Note that the transfer function and the impulse response are also functions of the distance between the target and the receiver measuring its scattered field.

$$h_T(t) = \int H_T(f) e^{i2\pi ft} df \ . \quad (3)$$

In the following, examples of both representations of the target response will be shown.

Rigid Sphere

The sphere is very useful for verifying the accuracy of numerical models because it is one of the few shapes that have analytical (closed-form) solutions [3] for wave scattering. In the same way, these solutions also provide a check and guidance for experimental measurements of target responses.

In order to illustrate the accuracy and the limitation of the numerical model, the scattering from a rigid sphere of radius, a, is calculated and compared to the analytical result. The scattered field of the rigid sphere is computed as a function of bistatic angle over a band of frequencies such that its wavenumber, ka, varies from 17 to 42. The bistatic angle is defined as the angle subtended by the source-target-receiver vertex. Figure 1 shows the target strength of a rigid sphere for the beginning and end values of the frequency band. The numerical model, using 84,462 facets to model the surface of the sphere, is fairly accurate except for large bistatic angle region just before the main forward scattering lobe.

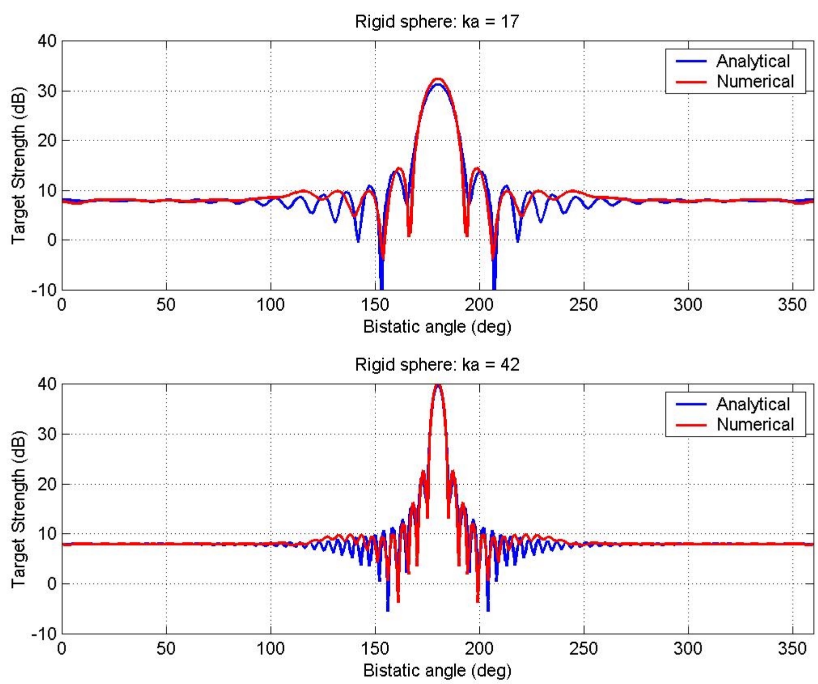

Fig. 1. The bistatic target strength of a rigid sphere calculated using numerical and analytical methods are compared.

The transfer function and the impulse response of the rigid sphere over the frequency band of interest are shown in Fig. 2. Once again, the numerical model can approximate the exact solution to a high degree of accuracy.

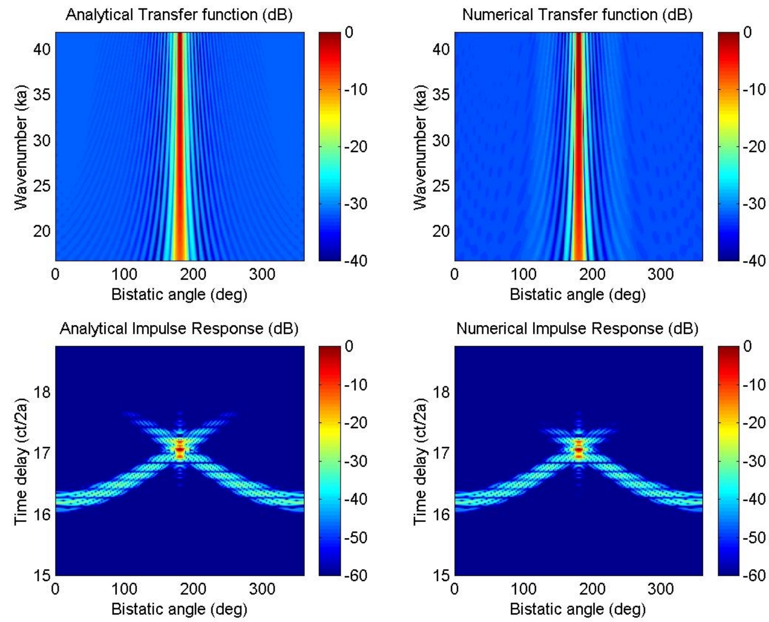

Fig. 2. The magnitudes of the transfer function and the impulse response of a rigid sphere calculated using numerical and analytical methods.

Target Complex

The main reason for the development and use of numerical models is that analytical solutions do not exist for complex structures. By the same token, this makes it difficult to directly verify the correctness and accuracy of these models. However, the following examples will show how confidence in the results can be gained by considering both the time and frequency domain representations of the target response.

The target under investigation is a submarine-like structure built from a combination of simple shapes (e.g., cylindrical hull, spherical end, conical tail and airfoil sail/fins). For simplicity, the structure is assumed to be rigid. The geometry of the target complex is shown in Fig. 3. The major dimensions of this structure are the length, L, and the width, $2a$. Over 24,000 facets were used to model all the parts of the structure.

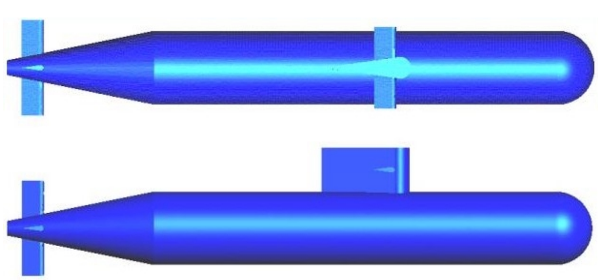

Fig. 3. The plan and side views of the target complex.

The transfer function and the impulse response for target backscattering (also referred to as monostatic scattering), as a function of target aspect, are shown in Figs. 4 and 5. Note that the transfer function confirms that the hull specular at broadside is independent of frequency. The impulse response, on the other hand, reveals the highlight structure of various components that make up the target complex. For sufficiently high frequencies, the relative time delays of these highlights are found to be consistent with what is expected from simple geometrical considerations. All these are indications that the model is doing what it should and thereby providing the user with some confidence in the model.

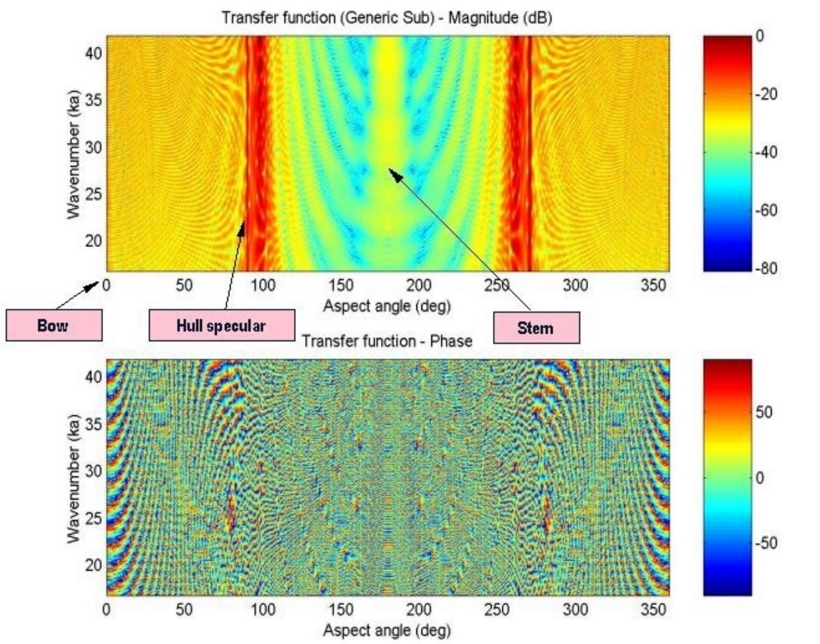

Fig. 4. The magnitude and phase of the transfer function (frequency response) of the target complex.

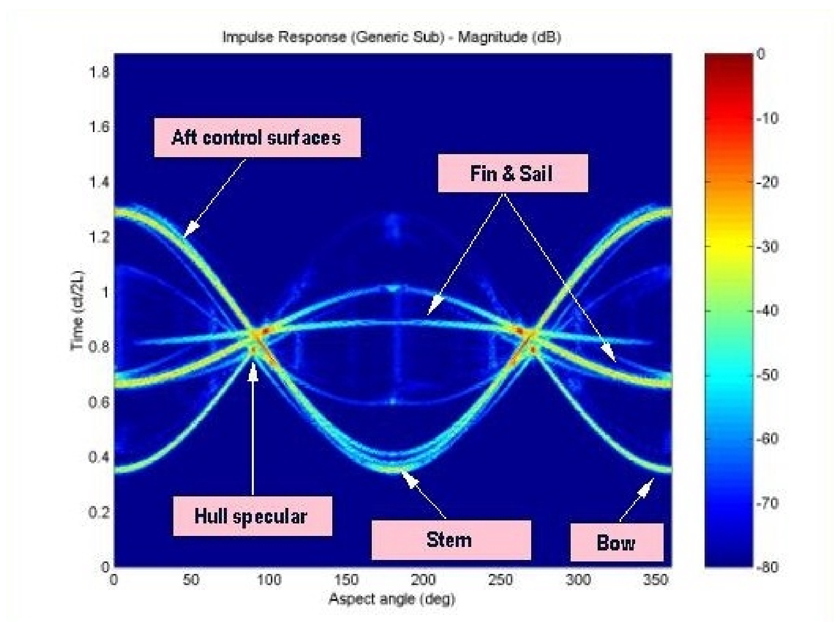

Fig. 5. The magnitude of the impulse response of the target complex

Applications

A major motivation for modeling the impulse response of a target is to be able to simulate the time series of the scattered field from a complex structure. This capability is important in the development and evaluation of detection and classification algorithms. Two typical examples of active sonar signal processing for a complex target are shown below. Figure 6(a) shows a range-Doppler map of a backscattered return. This processing is usually realised by a bank of matched filters. Figure 6(b) shows a spectrogram of the same backscattered return. The spectrogram and other time-frequency distributions are thought to be useful in target classification. The time series used in these examples was obtained by using the impulse response of Fig. 5 and convolving it with a linear frequency modulated pulse.

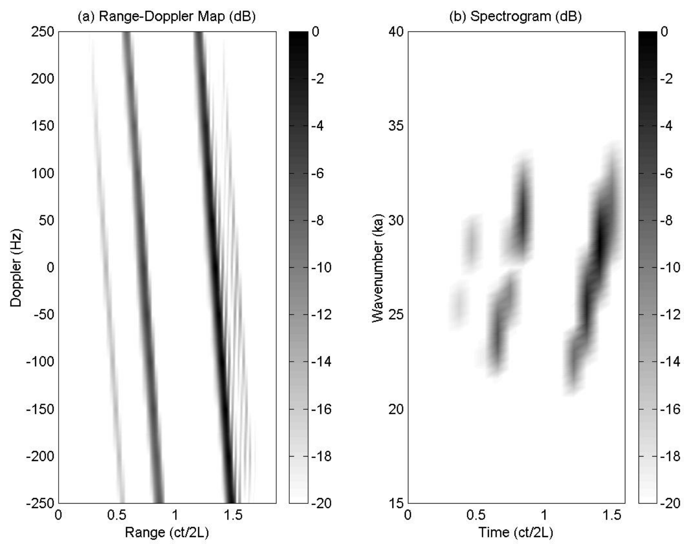

Fig. 6. (a) A range-Doppler map and (b) a spectrogram of a target echo at zero aspect.

Conclusions

The target transfer function, or its impulse response, contains all the intrinsic scattering information of that target. Once either of these functions is known, then it is relatively straightforward (at least in principle) to calculate the target response for any arbitrary input waveform. This is particularly useful when time series simulation of the scattered field is required.

Note that even though the transfer function and the impulse response contain the same information, sometimes certain aspects of the target response are better revealed by one representation over the other. This paper showed an example of a target complex in which the time domain target highlights gave a more intuitive interpretation of the results.

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Analysis of Active Sonar Reverberation Data

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Abstract
This paper presents an analysis of active sonar reverberation data collected in the Timor Sea. Various models for the reverberation as a function of time delay and Doppler frequency are compared. For the data analyzed, the K distribution was found to be the most appropriate model.

Introduction

In active sonar, a pulse is emitted from a source and then the returns due to the pulse from the many scatterers in the ocean are heard on a receiver. The received data is then passed through a narrowband correlator to measure the received amplitudes of the scatterers. In order to detect a louder than background return, say, from an air-filled object, knowledge of the background is needed. Background returns are echoes from various random scatterers and the sum of these returns is called reverberation. A study of the statistics of the narrowband correlation amplitude reverberation data should be able to give an idea of whether a return is a background return or a non-background return known as a signal.

This study of the statistics of the narrowband correlation amplitude data involves finding the distribution of the data and then finding an analytic distribution that best fits the distribution of the data. The analytic distribution can then be used to find the probability of any return being a background return.

This paper describes the processing of the data, gives the sampling intervals required for independent data samples and the groups of data that have the same distribution. Data of the same distributions will then be grouped and this grouping will collect enough data samples for a proper estimate of the distribution of the data. A test for the best fit of the analytic distributions to the amplitude data's distribution is then made. This paper tries to fit the grouped amplitude data to the Rayleigh, K [1, 2], Weibull [3] and Gamma distributions. The paper then examines the variations of the parameters of the best fitting distribution with time delay and Doppler frequency.

The data, the processing and some simple analysis

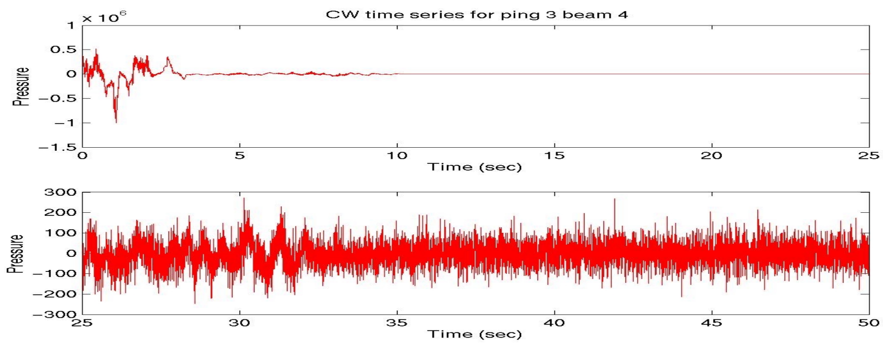

Figure 1: Beamformed Time series Data for Beam 4 Pulse 3

Reverberation data was collected from an active sonar system in the Timor Sea. This data was collected as beamformed pressure measurements. The pulse sent out was a half second continuous wave (CW) pulse. The recording of the returns from the pulse was for 50 seconds. The data comes from ten pulses and twenty-two beams. A sample of the data collected is shown in Figure 1.

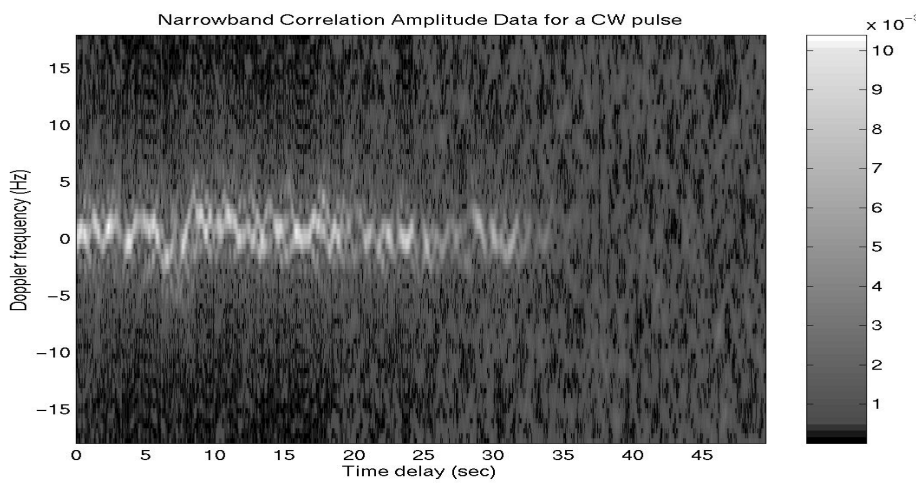

Figure 2: Amplitude data vs Doppler frequency and Time Delay for Beam 4 Pulse 3.

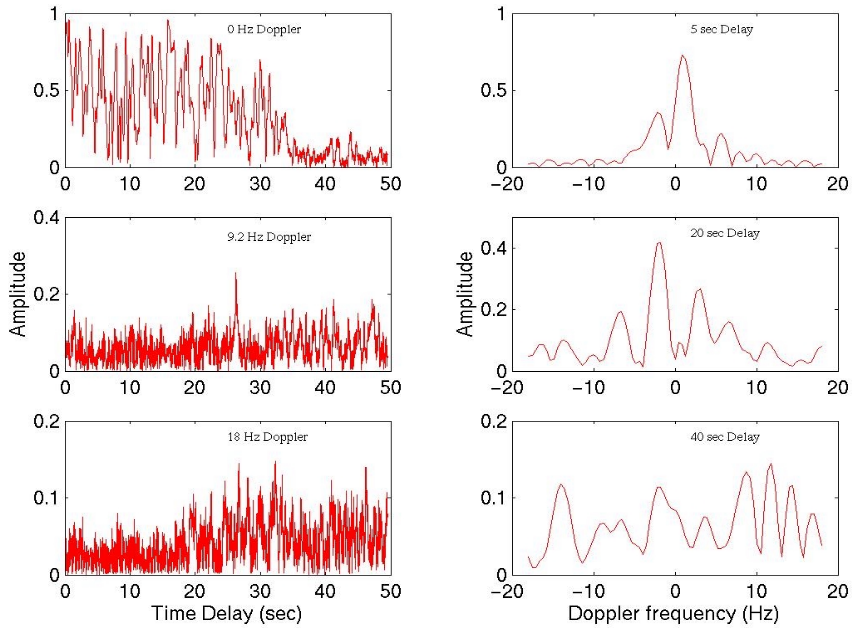

Figure 3: Various cross-sections of the Amplitude Data from Figure 2

This time series data was normalized by calculating the energy over fifty samples and then dividing the time series in that range of fifty points by the square root of the energy value. This normalized time series is then correlated with a replica of the transmitted pulse to produce narrowband correlation data at zero Doppler frequency. For other Doppler frequency data, the normalized time series data is correlated with a replica of the transmitted pulse with a specified Doppler frequency. The amplitude of the narrowband correlation data is to be used to detect a non-background return or a signal and this data is called amplitude data for this paper. An example of the amplitude data is shown in Figure 2, which uses the data in Figure 1.

Cross sections of Figure 2 are plotted in Figure 3. Figure 3, column 1 shows the amplitude data plotted against time delay for fixed Doppler frequencies. Figure 3, column 2 shows the amplitude data plotted against Doppler frequency for fixed time delay. Looking at the zero Doppler frequency plot in Figure 3 column 1, the distribution of the amplitudes changes abruptly at 35 seconds. This means the amplitude data is non-stationary with time delay. The 5-second time delay plot in Figure 3, column 2 shows higher amplitudes near the zero Doppler frequency than at the higher Doppler frequencies. This shows that the amplitude data is non-stationary with Doppler frequency.

For the distributions of the data to be shown, independence tests and homogeneity tests need to be done, so that the true data distributions can be shown.

Independence and Homogeneity tests

An independence test was done to find the sampling rate in time delay and Doppler frequency, so that the amplitude data collected for a dataset would be independent. Then the data, sampled at intervals to ensure independence, was placed into datasets that had small time delay ranges and had different Doppler frequencies. These datasets were then compared with each other with a homogeneity test to see which datasets could be placed together. Based upon these results, the datasets would be collected into groups. The independence test used was a correlation test. The homogeneity test was the Kolmogorov-Smirnov (K-S) test [4]. A summary of the results is discussed below.

The correlation test is an independence test if Gaussian statistics apply. For non-Gaussian data, dependent data may be uncorrelated but, for the most part, the correlation test is a good indicator of independence. The results from the autocorrelation in time delay domain showed that a half second CW pulse produces independent sampling after 0.25 seconds and the autocorrelation in the Doppler frequency domain showed that independent sampling after one Hertz. Independence was assumed to occur when the autocorrelation value was below 0.7. The data was also found to be independent with beam number and ping number.

The K-S test results showed that data from different ping numbers could be grouped together. The results showed that data could also be grouped together if the difference in time delay was no more than 6.25 seconds except at the transient periods, such as the thirty-five second mark. The transient periods were also grouped together in order to keep the grouping mechanism as simple as possible. Data that had the same absolute Doppler frequency could also be grouped together. Data that had absolute Doppler frequencies below 1.5 Hz could be grouped together and similarly data that had Doppler frequencies above 10 Hz could be grouped together [3].

Testing for the best fitting Distribution

The amplitude data from ten pulses was grouped into dataset. This produced eight time delay groups, each 6.25 seconds long, eight Doppler frequency groups and twenty-two beam number groups. This resulted 1408 data groups in all. There were two measures used to find which of the analytic distributions best fitted the data. The first measure was to see the percentage of datasets that had a K-S test results greater than 0.1. The second measure was the overall mean relative error (O.M.R.E.). The O.M.R.E. is the mean over the grouped datasets of the mean relative error. The mean relative error is the mean of the relative errors between an analytic distribution's and the data's survival functions, when the survival function of the data is less than 10^{-2}. The survival function is defined as the complement of the cumulative probability function. This relative error was only measured at points where the data existed. The relative error is the absolute difference between the survival functions of the grouped dataset and the analytic distribution's survival function divided by the grouped dataset's survival function. The O.M.R.E. was the best measure for our interest since we wanted to examine returns that had less than 0.01 probability of being a background return.

The analytic distributions were fitted to the data in order to estimate the distribution's parameters. These parameters were calculated from the moments of the sampled data, except for the Weibull distribution, where the parameters were calculated using Menon's method [3] and this method uses the moments of the logarithm of the data.

Table 1 shows the results of the measures and Figures 4, 5 & 6 show some of the analytic distributions with the grouped dataset's distributions.

Analytic Distribution	K-S Test	O.M.R.E.
Rayleigh	68.5%	0.2594
K Distribution	86.9%	0.1691
Weibull	94.3%	0.2935
Gamma	79.3%	0.2173

Table 1: Comparison of the Fit of Analytic distributions to the Data

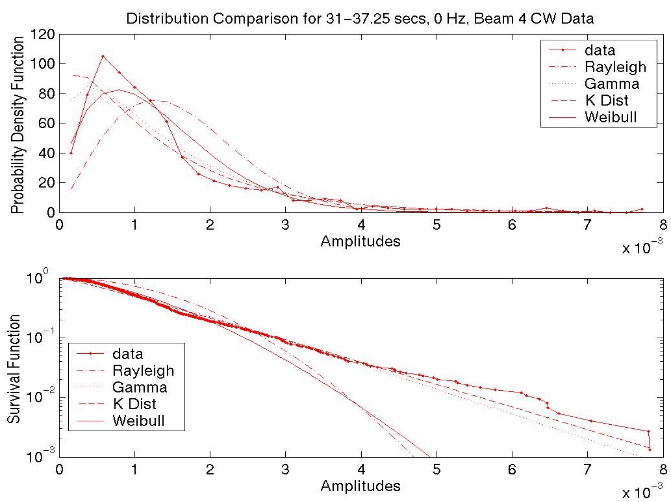

Figure 4: Comparison of Distributions for Beam 4 0Hz Doppler 31-37.25secs

With the exception of the data shown in Figure 4, which was transient data, all datasets had a reasonable agreement with at least one of the distributions.

The Table 1 results show that the Weibull gives the best description of the amplitude data's distribution according to the K-S test. The K distribution is also close to the results of the Weibull Distribution. Unfortunately the K-S test evaluates the fit at the bulk of the distribution and not at the low survival function values of the distribution. The O.M.R.E. results show this. The K Distribution has the best results for this test.

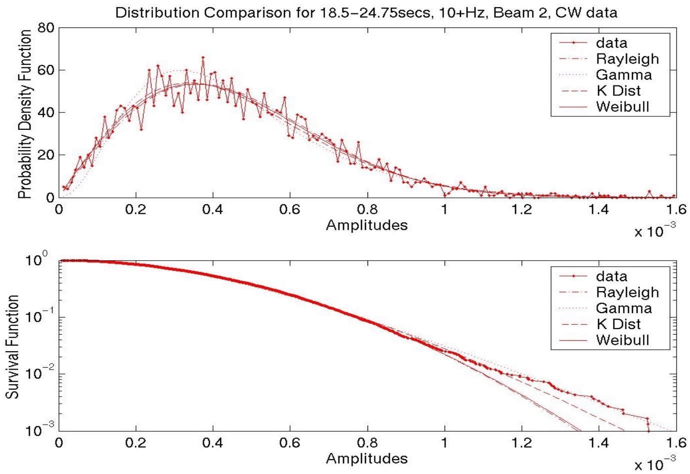

Figure 5: Distribution Comparison for 18.5-24.7 secs, >10 Hz Beam 2

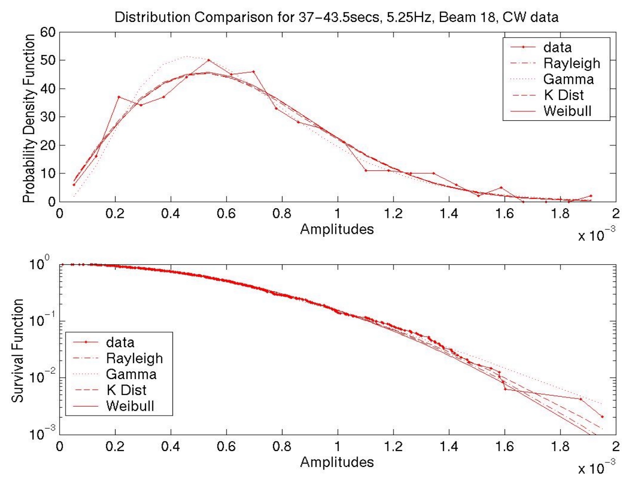

Figure 6:Distribution Comparison for 37-43secs, 5.25 Hz Beam 18

The K distribution as a function of the Narrowband Correlator's parameters

The K distribution has the probability density function

$P(x:\nu,b)=\dfrac{2b}{\Gamma(\nu+1)}\left(\dfrac{bx}{2}\right)^{\nu+1}K_\nu(bx)$, where $\Gamma(\nu)$ is the Gamma function and $K_\nu(x)$ is the modified Bessel Function of order ν. The parameter ν is the shape parameter. If ν is large the distribution approaches the Rayleigh distribution. Essentially the distribution is Rayleigh if ν is over 160. References [1] and [2] describe and derive the K Distribution. The fourth and second moment are used to calculate the parameter ν. The parameter b is the scale parameter and describes the Rayleigh parameter for large ν. The Rayleigh parameter is the second moment of the data and this is the Rayleigh distribution's only parameter. The Rayleigh distribution can be derived as the distribution of amplitudes from a complex Gaussian distribution that has a uniform phase distribution with a mean of zero. The Rayleigh parameter is the variance of the Gaussian distribution.

The K distribution is more skewed than the Rayleigh distribution as a Rayleigh distribution has a dependent fourth moment. This causes the K distribution to have a larger tail than the Rayleigh distribution, i.e., low values of ν yield longer tails. Figure 7 is a plot of the ν parameter versus Doppler frequency and time delay. This shows that the distributions for the amplitude data under 35 seconds will have more amplitudes above the most common amplitude than the distributions for the amplitude data after 35 seconds. Therefore the distribution has a smaller tail above 35 seconds and thus this Figure shows that the type of distribution is different below 35 seconds to that above 35 seconds.

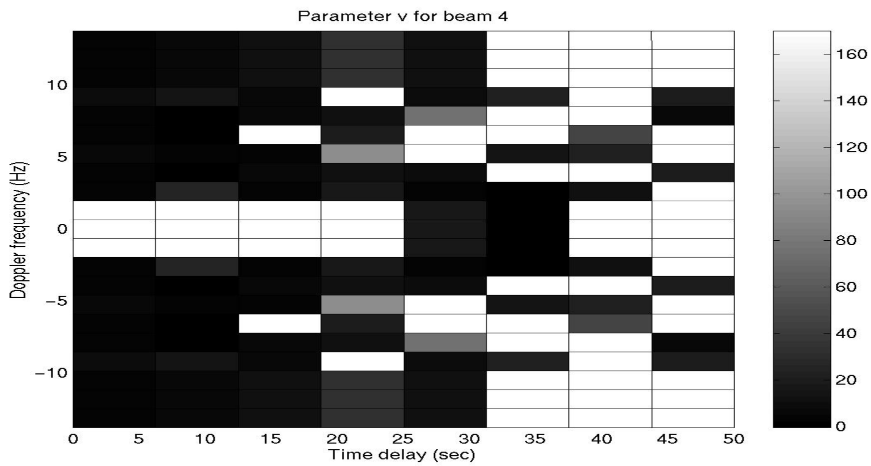

Figure 7: the ν Parameter as a function of Time Delay and Doppler for beam 4

Conclusion

This paper has summarised the results of the independence and homogeneity tests for returns from active CW sonar pulse. The paper models the distribution of the reverberation data and shows that the K distribution best fits the tail of the distribution. The paper also shows that the tail of the data's distribution becomes smaller with time delay.

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NOISE REDUCTION OF STEEL PIPE AND HOLLOW TUBES

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Abstract
This paper is an update on more recent work on the effectiveness of lining steel pipes and tubes with various polymer and ceramic materials to reduce impact noise emission. A paper was presented on this at the 1994 AAS conference in Canberra and described the effects of internal nylon lining of steel tubes used in steel plant run-out tables. Data was also presented at the conference of the effects of using ceramic material as a filler to dampen noise emission. Recent work has focussed on external polyurethane lining and internal plastic foam lining on similar pipes and tubes. The tubes are commonly used as conveyor rollers in steel and industrial production plants. The reduction in sound levels for each different application system will be presented.

Introduction

This work originally started in 1988 in the BHP Steel - Brisbane Market Mill, where impact noise of steel merchant reinforcing bar on the steel rolls of the final run-out table were causing high noise levels. This was a problem for both occupational exposures and environmental noise concerns. Following site testing, controls using high density nylon were implemented with success.

Further work then occurred in 1994 at the BHP Newcastle Bar Mill, where the main occupational noise issues were around the impact noise of the guillotine and the cut bars on the steel table rolls. Operational methods in Newcastle meant that high temperatures occurred in the guillotine rolls and polymer products were unsuitable because they would melt and possibly catch fire. Control methods for that installation involved ceramic materials pumped into the inside of the steel roll. Again, the site testing rig was used to evaluate the material prior to its implementation.

The most recent work has been in the Bisalloy steel plate mill at Unanderra, N.S.W. Temperatures in that application were low and so polymer materials were again considered. Polyurethane was applied externally and internally to steel rolls and the site testing method used to identify the most suitable material from a range of different grades. The final method selected was internal polyurethane foam.

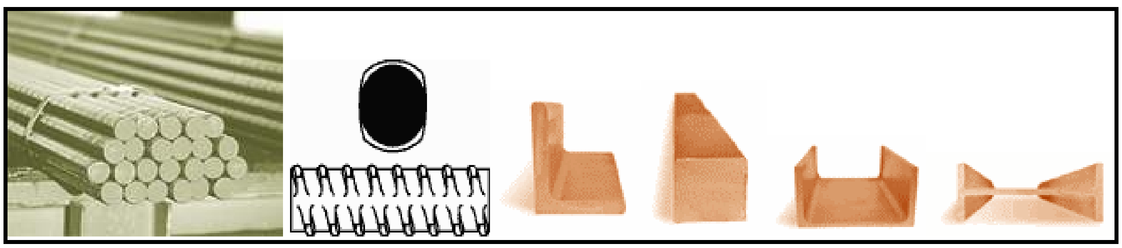
This paper describes the results of all tests and compares their effectiveness. Opportunities for similar approaches in reducing the impact and ringing noise of steel or aluminium conveyor rolls for both occupational and environmental noise management is discussed.

Steel Mills and Conveyor Rolls and noise

At the Product end of steel plants, bars, rod, flats, angle and plate of various shapes, grades and dimensions are produced. As they exit from the final shaping or straightening sections, they typically enter a run-out table, which is a series of steel rolls which act as a conveyor. The product can then be cooled and transported to other parts of the mill for grading, cutting, checking and packing for eventual delivery. The steel conveyor rolls are driven individually or in groups by belts or chains by small electric motors. By rolling they can move whatever material is placed on them.

Movement of steel on steel rolls creates noise from the impacts of either the front/leading edge of the product or material with the side of the roll. These impacts make the rolls and the product ring and emit noise. There can also be more frequent impacts from patterns of deformations in the product, such as the ridges on reinforcing steel bar, each striking the surface of the roll. The noise emitted depends on the speed of operation of the rolls and the number and rate of impacts. Examples of merchant bar products are shown in Figure 1 below:

Figure 1 Steel Reinforcing Products



Merchant Bar Processing

The merchant bar product is typically made from 12m long steel billets, which are reheated in a furnace to approximately 1200^{o}C and then rolled through a series of profiling rolls until they reach the final desired shape. when hot. As the billet passes through the rolling mill stands, the length of the product increases, depending on its cross-sectional area, but it may be cut when hot into lengths of 20m or thereabouts. After the last mill-stand, the product then passes along the run-out table to go to a cooling bed for air-cooling or directly to a guillotine for shearing to length suitable for later transport by truck or train. Movement along the run-out table and past the guillotine is by driven steel rolls.

Steel Plate Processing

Plate mills have a slightly different process, but steel slabs are reheated then rolled in a large mill stand until the desired thickness is achieved. It then passes through water spray cooling on the run-out table and on to air-cooling beds. Movement to the guillotines and beyond for dispatch is by powered steel rolls.

Specialty Steel Plate Processing

For specialty steel plate manufacturing, cold steel plate of the required grade is placed onto a feeder table and then into an annealing furnace for heat treatment to achieve the required metallurgical properties. After the furnace, the hot plate may be cooled by water sprays and air, then transported along powered steel rolls to checking and dispatch areas.

Temperature Range

As the above indicates, the product can be from cold to hot – above 200 °C after significant cooling, and so surfaces coming into contact with these temperatures must be able to withstand the likely range of temperatures occurring. Different parts of the plants require different approaches and treatment.

Brisbane Market Mill

The main problem for the Brisbane Mill was the high speed Tempcore® reinforcing bar running along the 405m long run-out table. Rolls were approximately 500mm apart and could transport the bar at up to 12.5 m/s, depending on diameter (the narrower bars traveling faster). Each rib deformation on the bar surface impacted the hollow steel rolls, with the resultant sound like a giant xylophone. This occurred for a period of 1 to 3 seconds, with a low sound level for a period of 4 to 8 seconds, depending on the status of production. The steel rolls were 215m diameter and 325mm long, had a wall thickness of 15mm and rang like a short tubular-bell. Because the bar traveled at high speed over the rolls, the temperature increase was not significant and so a polymer product was considered.

Newcastle Bar Mill

For the Newcastle Bar Mill, a similar but larger range of product is manufactured. The main noise issue was the impact of steel bars on the guillotine/shear table. At that time, from one to perhaps a dozen bars of sizes from 10mm to 63mm diameter are placed onto the shear table to a set length, then the bars clamped, the receiving table lowered and the shear is operated. At that time, the cut ends fall onto the receiving table rolls, while the upstream ends of the bars may shake around on their section of the table. At this time, there was a significant impact noise. As the reinforcing bars are moved along the rolls, they also cause the rolls to ring with each deformation impact. As the bars could be sitting at the shear table for some time, the surface temperature of the rolls can be relatively high. This meant that any system had to be stable at temperatures up to 500 °C.

Bisalloy Plate Mill

At the Bisalloy Steel plate mill, cold steel plate is loaded onto a steel roll entry table prior to entry to the annealing furnace. A batch of 10 or more plates on a feeder stand would be moved individually by a magnetic lift crane and lowered onto the entry table rolls. Depending on the skill of the crane operator, the plate could be dropped for a short distance to the rolls, causing impact noise. At the discharge from the furnace and after water cooling, as a magnetic crane lifts the plate off the run-out table, there can also be plates dropped onto another steel roll table for movement to the checking or dispatch area. This impact noise was primarily an occupational noise issue. The temperatures of the steel rolls were in zones and ranged from cold to hot, so different zones could be treated with appropriate materials. The cold zones were the locations where movement on and off the table occurred, so polymer products could again be considered. However, consideration also had to be given for times when a plate may need to be rolled backwards out of the furnace onto the inlet table. Roll dimensions were typically 150 or 194mm internal diameter and 3200 to 3500mm wide, with solid ends.

Roll Treatment

The treatment developed for the rolls was intended to dampen their "ringing" after contact with the steel sections. For the first project at the BHP Brisbane Market Mill, trials were made with a very lightweight two-part rigid polyurethane foam filling the interior of the roll, and a friction-fitted sleeve of high density nylon inserted into the inside of the roll. The temperature of the inside of the rolls was expected to remain low enough to allow effective use of the nylon without it losing its property or melting, because the bars only passed over the rolls momentarily. This work was reported in Tickell (1994). The reduction in sound level of a steel ball impact onto a treated roll compared to a bare roll were 8 dB(A) for the foam and 21 dB(A) for the nylon. The highest octave band reduction, of 22 dB, occurred at 4kHz, which also had the highest bare sound level.

For the BHP Newcastle Bar Mill work in 1994, polymer products were considered unsuitable because of the likely temperature of the passing bars. Also, the rolls were much wider, at around 1200mm, so a sleeve approach was not available. For this application, a pumpable ceramic paste was used and the test item to assess the reduction was a 140mm diameter water pipe. Reductions achieved in the test piece were 13 dB(A), 17 dB in the 500 Hz band and 13 to 15 dB in the 4k to 16k octave bands. Further measurements were done in 1996 prior to full implementation in the plant.

For the Bisalloy plant work in 1999 to 2000, the rolls were much wider again, at up to 3500mm, so filling them with a cement-like material would have had significant implications on the bed structural support. Also the roll temperatures could be controlled to be within a range potentially suitable for a polymer product. Trials were done with different types of internal and external flexible polyurethane lining, provided by M&S Engineering Supplies, who manufacture and prepare conveyor rolls of this type for Bisalloy and other industries. These types of external linings are typically used on belt driven conveyors as a form of tyre on the driving roll. Figure 2 shows some polyurethane coated rolls.

Figure 2 Typical Conveyor Rolls Lined with Polyurethane Coatings

Tests were initially done in the Environmental Health Laboratory at BHP Port Kembla, followed by workshop tests at M&S Engineering Supplies in Unanderra. Figure 3 shows the test rigs used for the impact test trials.

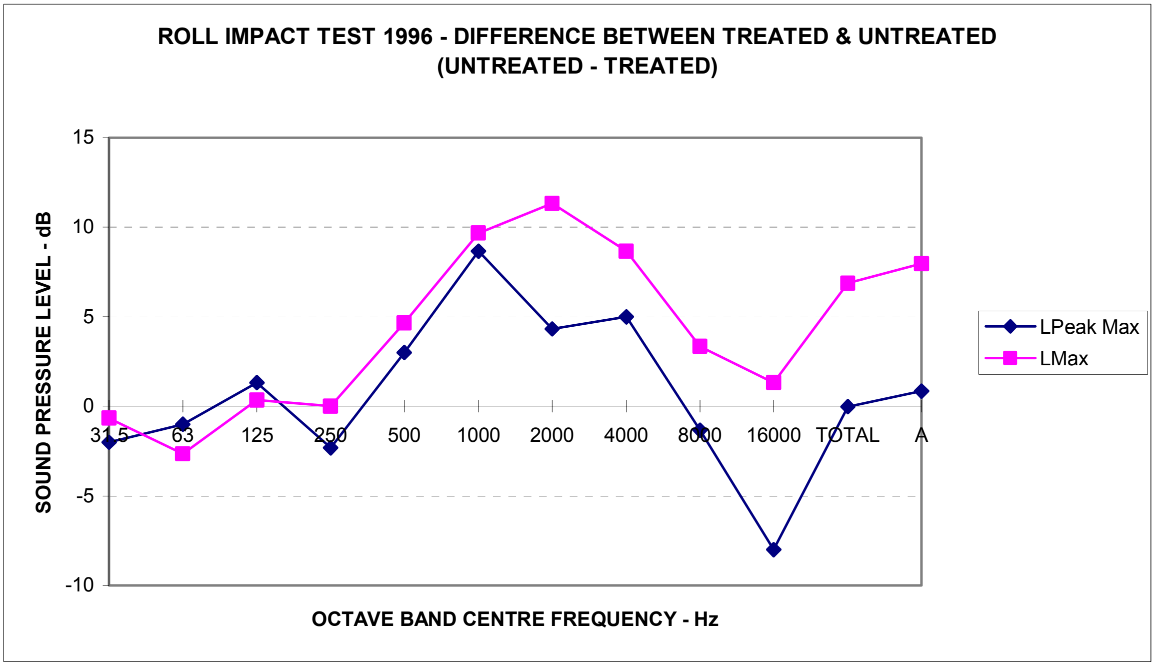
Figure 3 Impact Test Trials 1999-2000 for Polyurethane coated rolls

External treatment had the highest reductions because the impact of the steel on steel was avoided. However the operation of the rolls meant that they could be driven while the steel plate on top remains in a fixed position, causing potential for wear and ripping of the coating. Because of this, the approach of internal coating was preferred by the client, Bisalloy. The supplier of the polyurethane and fabricator of the rolls, M&S Engineering Supplies, then suggested a foam filling be used. This was because it could be applied in-situ by blowing the premixed foam into the rolls through an aperture in the end, whereas the internal lining required the rolls to be removed, end plates removed and then the coating applied. Testing was also requested for a case of sand-filled rolls, for comparison with other treatment. Sand had the lowest overall reduction of maximum impact sound level of 5 dB(A), with increasing attenuation from the internal polyurethane liners of 6 dB(A), then internal foam with 11 dB(A), to the external polyurethane liner with the highest reduction, 14 dB(A).

Results

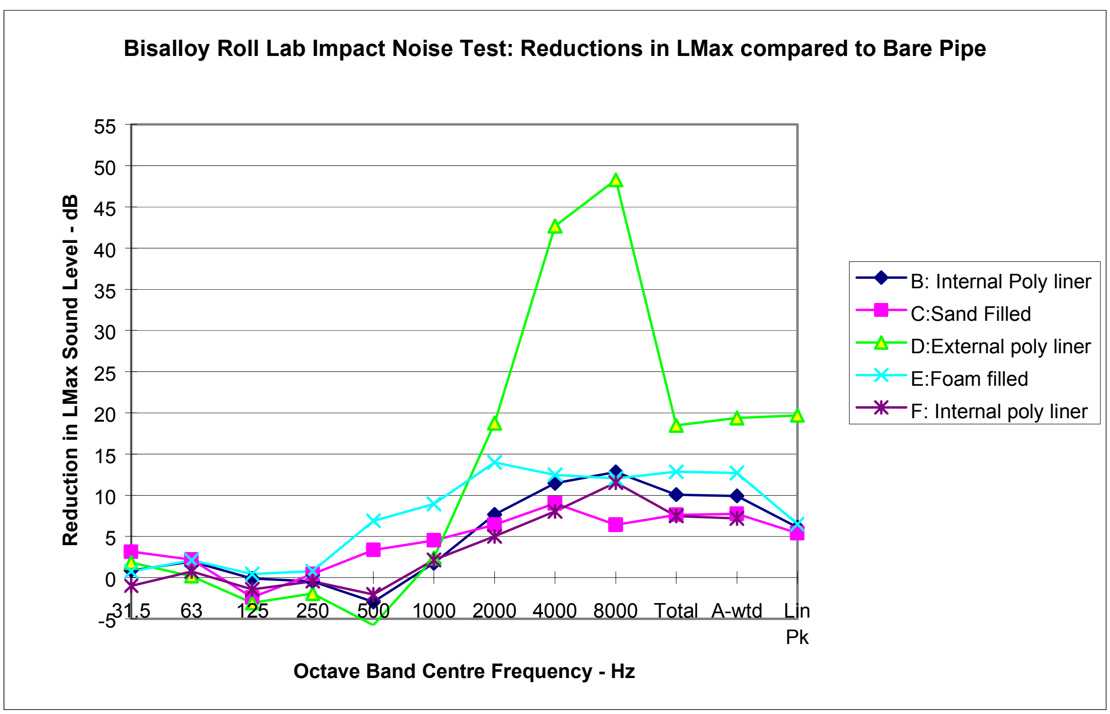
Measurements were taken for three consecutive impacts of the same force to get a consistent set of results. Results measured were maximum sound levels L_{OctMax} and LAE_{Oct} for a 10 second period including the impact – this was to assess the reduction in the ringing component of the noise. Results are shown below for 1996 and 1999 test work.

Figure 4 1996 Impact test results on 1200mm wide rolls with ceramic filling



Results for the tests shown in Figure 4, on the actual rolls in the shears area in-situ, showed a wider frequency range of reduction than those done with a 300mm long section of 140mm diameter water pipe, but a lower reduction. Water pipe tests had band reductions of 8 to 17 dB, compared to the maximum of 11 dB shown in Figure 4.

Figure 5 1999 – 2000 results on sand and polyurethane linings and foam filler



The results of Figure 5 show the external liner had a very significant reduction at 4kHz and 8 kHz compared to the internal treatments. However the internal treatments had around 8 to 13 dB(A) reduction overall and a relatively broad reduction between 1000 and 8000 Hz.

For all of the trials undertaken, there is a reasonable reduction in impact sound levels over the range 500 to 4000 Hz, which is of importance in occupational noise management – which was the reason for the work in most cases. Use of the types of materials shown above for both roll conveyor applications and even flat plates subject to impact would be expected to achieve a similar range of reductions. Ring frequency in rolls and pipes is an issue that would need to be considered in the further development of this application.

Acknowledgements

This work was undertaken for a number of clients, including BHP and Bisalloy, undertaken as part of consulting activities with BHP Engineering and its new owner Hatch. The permission of these organizations involved in allowing the work to be reported is gratefully acknowledged.. The assistance of M&S Engineering Supplies in providing the samples used for testing in the 1999 work and Pyrotek for the samples used in the 1994 work is also gratefully appreciated and acknowledged.

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STATISTICAL DETERMINATION OF OPTIMAL TRANSDUCERS PLACEMENT FOR MEASUREMENT OF POWER FLOW AND DYNAMIC PROPERTIES OF A VIBRATING TIMBER BEAM

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Abstract

Measuring the power flow and the dynamics properties in a timber beam requires a set of positions for the transducers used on the beam. By measuring the motion of the beam, we estimate a set of amplitudes for the propagating and evanescent waves and finally an accurate distribution giving an estimation of the dynamics properties of the medium. The shape of the distribution determines the quality of the estimation and leads to a set of positions for the transducers.

1. Introduction

The timber beams are the base of all the building industry in New Zealand for economical and timing reasons. However, the transmission of noise can be a real problem since the effect of such vibrating structures on humans is obvious, particularly in multi-residential buildings. Then the reduction of the noise seems crucial but can not be done accurately without a good knowledge of the vibrations. Reducing noise means reducing the energy flow which leads to the estimation of the dynamic properties of the beam closely linked to the energy propagated.

This work is part of a project to measure and model, in timber framed structures, the sound transmission. As simple beams, the timber elements of the structures are treated with the modal theory to obtain their dynamics properties which are the most important in vibrating structures. The present paper follows the process from the description of the phenomenon, to the estimation of the amplitudes of the waves and finally the dynamics properties as well as an optimum set of positions for the accelerometers.

2. Bending Waves in Beams

The derivation of the equation of motion for flexural vibration in beams is given by thin-beam theory which is based on the following assumptions :

i) There is no deformation of the middle plane (neutral) of the beam,
ii) There is no shear deformation,
iii) Normal stresses perpendicular to the neutral plane are negligible.

If *x* is the axis along the beam, *t* the denotes time, then the transverse displacement $\eta(x,t)$ is related to the applied pressure p(x,t) via [1] :

$$D \times \frac{\partial^4 \eta(x,t)}{\partial x^4} + m \times \frac{\partial^2 \eta(x,t)}{\partial t^2} = p(x,t)$$

Where D is the bending stiffness of the beam and m the mass per unit of length. The solution of such an equation of motion is given, at fixed radial frequency ω, by [3]:

$$\eta(x,t) = \left(a_1.\ e^{(i.k.x)} + a_2.\ e^{(-i.k.x)} + a_3.\ e^{(-k.x)} + a_4.\ e^{(k.x)}\right).\ e^{i.\omega.t}$$

The 4 amplitudes a_i describe the 4 different modes present in the beam :

- a_1 and a_2 are travelling waves toward $-\infty$ and $+\infty$ respectively
- a_3 and a_4 are evanescent waves decaying from the forcing point or joints in structures

Also k is the positive real allowable root depending on the pulsation ω and the ratio R, expression of the dynamics properties D/m.

3. Mathematical Model

3.1. Modal Amplitudes

The measurement of the displacement is most commonly done with accelerometers which measure the acceleration, second derivative of the displacement with respect to the time variable $\partial^2/\partial t^2\ \eta(x,t)$. We will denote y(x,t) this acceleration measured at the position *x* and the time *t*.

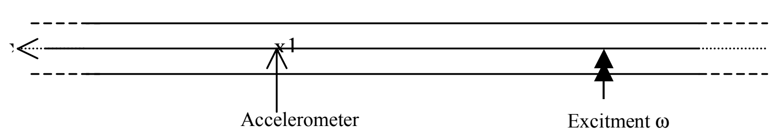

figure 1 : measurement of the acceleration

Then $y(x,t) = -\omega^2.\ \eta(x,t)$

$$= A_1.\ e^{(i.k.x)} + A_2.\ e^{(-i.k.x)} + A_3.\ e^{(-k.x)} + A_4.\ e^{(k.x)} + \text{noise}$$

Since the probability to have a single value y_i is $(1/ 2\pi)^{N/2}.\exp\left[- 1/2 . y_i(A,R)^2\right]$, then the probability function to measure an *y* vector with an *A* and a *R* given, is then

$$P_y(A,R) = (1/ 2\pi)^{N/2} . \exp\left[- 1/2 . \sum_{i=1}^{N} y_i(A,R)^2\right].$$

If the *noise* is chosen with a Gaussian distribution, then all the statistical properties are well known and the level of noise is independent of the position *x*, we assume that the noise comes from the measurement process and not from the medium itself. If now we denote the set of modal amplitudes as a four dimensioned vector $A = \{ A_1, A_2, A_3, A_4 \}$ where $A_i = - \omega^2. a_i$, then we can denote the set of accelerations measured $y = \{ y_1, y_2, ..., y_N \}$ with y_n the acceleration at the point x_n.

For convenience, we will denote the previous equation $y = E \times A + noise$ where E is a $N\times4$ matrix containing the exponential terms of η.

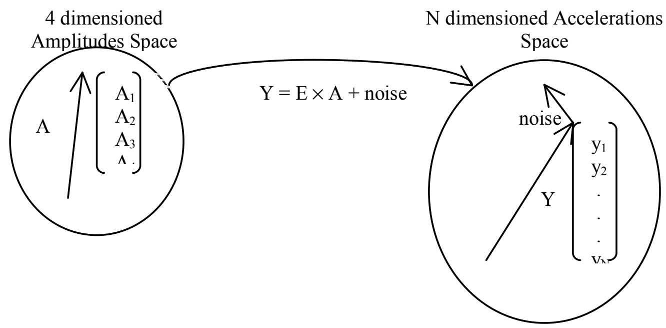

figure 2 : principle of the measurment

Then finding the coefficients *A* requires solutions of the matrix equation. It is known that the accuracy of estimation is improved by using the most possible measurement locations. So since the rank of *E* is 4, the rank of *y* , N, has to be greater than 4. Then the matrix *E* is not a square matrix and consequently non invertible. In these conditions, by using the maximum likelihood method [4], we can obtain the estimated vector $\hat{A}$.

Let's denote $\zeta(y_1...y_5|\theta)$ the probability that the observed set of data $\{y_1, ... y_5 \}$ will occur. Then, θ is a parameter in this function which is contained in the 4 dimensions Euclidean space denoted Ω. ζ is a continuous variable, it reflects the relative likelihood that the set $\{y_1, ... y_5 \}$ occurs and depends on the true value of the θ. For a set $\{y_1, ... y_5 \}$ given, ζ is a variable of θ. The estimate $\hat{\theta}$ is a value of θ which satisfies $\zeta(y_1...y_5|\hat{\theta}) = \max_{\theta\in\Omega} \zeta(y_1...y_5|\theta)$ then we say that the likelihood is maximum.

According to the fact that Ω is an open interval and that $\zeta(y_1...y_5|\theta)$ is differentiable and assumes a maximum in Ω, the MLE solution $\hat{\theta}$ is the set of solutions of the simultaneous equations $\partial/\partial\theta_i \left[\text{Ln}\, \zeta(y_1...y_5|\theta) \right] = 0$ with $i \in [\![1,4]\!]$. We obtain then the estimator $\hat{A}$ by solving the system formed by the simultaneous equations :

$$\sum_{i=1}^{N} \frac{\partial}{\partial A_j} y_i\,(A,R)\; .\; y_i(A,R) = 0 \text{ for a R constant.}$$

3.2. Estimation of the Dynamics Properties

Using the ratio *D/m* and not the Young's modulus *E* and Poisson's ratio ν doesn't really matter in this area. Since the ratio *R*, *E* and ν are closely linked by the relation $D = \frac{E.h^3}{12.(1-\nu^2)}$ where *h* is the thickness of the beam which is not really easy to manipulate is a such general process. Having an estimation of the acceleration at this point gives us information about the appreciation of the ratio R = D/m. The closest $\hat{y}$ is from the measured acceleration, the best is the estimation of R.

Then $\hat{y}_k = \sum_{i=1}^{4} E_{ki}.\, \hat{A}_i$. The estimator becomes then $\|d\|^2 = \| \hat{y} - y \|^2 = \sum_{i=1}^{N} \| \hat{y}_i - y_i \|$.By minimizing this term, we may find a good estimate $\hat{R}$ for the coefficient R by adjusting the value of *k*.

4. Positioning the Accelerometers

The estimate $\hat{A}$ is now a function of the set of positions $\{x_1, x_2, ..., x_N\}$ and of the ration *D/m*. Consequently, the probability that a set of data $\{y_1, y_2, ..., y_N\}$ occurs is also a function of these 2 variables. Measuring the set of accelerations means assuming a true value of *R*, and processing the calculation of $\hat{A}$ and $\hat{y}$ gives us an estimation of $\hat{R}$. Then assuming that the measurement geometry is given and fixed, we can get the distribution of the estimate $\hat{R}$ for a R and a pulsation ω given. For such an unbiased estimator, a lower bound for the standard deviation σ of the estimator can be established by the Cramer-Rao lower bound relationship [6]:

$$\text{VAR}\left(\hat{\theta}\right) \geq \frac{E[\hat{\theta}]^2}{n.E\left[\frac{\partial}{\partial\theta} \text{Ln}\left(\zeta(y_1...y_5|\theta)\right)\right]^2}$$

Finding the measurement geometry which minimises the variance is giving us the optimum set of positions for the transducers along the beam.

5. Experimental Results

The measurement of the bending waves has been done with 5 accelerometers then it fixed N to 5. For a 2.8 meters length of 100mm × 50 mm beam of pinus radiata, supported by sand traps on each extremity, and centrally excited, the optimum measurement geometry found was x = {x_1 = 280 mm, x_2 = 560 mm, x_3 = 700 mm, x_4 = 840 mm, x_5 = 1120 mm } for a frequency of 100 Hz with the origin of the x-axis at the point source. The modal amplitudes are expectedly very low after the first reflection in the sand trap.

Conclusion

We have been working on this process mainly to find the optimum measurement geometry to measure the most accurate dynamics properties of a timber beam. Such a process may need more work to extend to a T structure and then an I structure. The dynamics properties depend linearly on the frequency, then the accuracy of such a method is obviously better than any static measurement. The possible extension to more complex structure would need an heavier theory and would need to care about boundary conditions and quality of each joints in the structure.

Acknowledgements

The authors is grateful to Colin Fox, George Dodd and Keith Ballagh for supporting this work under grant and for their advices.

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ACOUSTICS OF ANCIENT CHINESE MUSIC BELLS

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Abstract
The ancient Chinese music bells, which have oval-like cross sections, possess a unique feature of short sound decay time that is specifically suitable for the music with fast tempo. Although having been recorded in the literature nearly 1000 years ago, this feature was never truly understood. Recent damping measurement of oval pipes with different flatness suggested a challenging task for acousticians as the increase of the modal damping with the pipe's flatness is only significant when pipe is measured in air but not in vacuum. In this paper, the decrease of the sound-decay-time of Chinese music bells and oval pipes with the increased cross-section flatness is investigated. It is for the first time that such short sound decay feature is explained in terms of the rich sound radiation characteristics of the symmetrical modes of the music bells/flatten pipes. The finite element and boundary element methods are employed to illustrate how the flatness significantly affects the normal velocity distribution, radiation efficiency and directivity of the modes.

Introduction

The history of Chinese bells can be traced up to the Shang dynasty (1600-1100 B.C.) [1]. Different from all Western bells, ancient Chinese music bells have oval-like (eyelet shape) cross-sections. The unique acoustical features of the ancient Chinese music bells include two different strike notes, and short sound decay time which is specifically suitable for the music with fast tempo. The interval between the two strike notes was often designed to be major or minor third. The two-tone property of Chinese music bells has been studied and mechanisms are understood [2]. Changing from a circular cross section to a shape of flattened oval, the degenerated modes of a bell with the same natural frequency become split. Two different natural frequencies corresponding to the same modal indices but with symmetrical and anti-symmetrical mode shapes (with respect to the major axis) are thus possible. Depending upon if the bell is stroked at the normal or side strike position, symmetrical or anti-symmetrical mode is exited and corresponding tone is then generated.

Around 1090, Sheng Kuo documented the short decay time of the music bells by comparing it with the long decay time of the bells with circular cross sections [3]. However, the mechanisms of short sound decay of Chinese music bells were never understood. A significant progress has been made towards such understanding by the experimental work by Wang et al. [4] in 1991. In their experiment, 4 identical steel pipes (14.4cm long, 0.4cm thick and 10.5cm in external diameter) with circular cross section were used to simulate the vibration of the music bells. Three of the pipes were flattened to different flatness ($\alpha = a/b$, where a and b are respectively the major and minor axes of the oval) and one remains the original circular cross section. The time decay of the structural vibration of these four pipes was measured in vacuum and in air separately after an initial impact excitation at the normal strike position. The measured damping constants are summarized in Table 1. It was concluded that the material damping is not related to the flatness of the pipe, but air damping increases as flatness of the pipe increases.

Table 1 Damping constants of four pipes measured in vacuum and in air.

$\alpha = a/b$	1	1.177	1.333	1.639
β_v (Vacuum)	0.601	0.746	0.933	0.705
β_a (Air)	0.710	1.285	2.631	4.817

Sound Radiation from Flatten Pipes

Vibrating pipes loss their energy in air through sound radiation. The analysis of sound radiation characteristics will shed light on the air damping of flatten pipes and the mechanisms of short decay time of ancient Chinese music bells.

Given the length, thickness and circumference, the resonance frequencies, mode shapes and modal radiation efficiencies of flatten steel pipes can be calculated as a function of the pipe flatness. In this analysis, steel pipes have 14.4cm in length, 0.4cm thickness and 33.0cm external circumference, and are free on both ends. Finite element and boundary element methods are used to investigate the vibro-acoustical properties of the first two modes.

Structural mode shapes

The first non-rigid mode pair of the free-free pipe has modal index $(n,m)=(2,0)$ representing 2 complete nodal meridians (4 anti-nodes in the circumference direction) and rigid body translation in the axial direction. As the pipe flatness increases, the resonance frequency of the symmetrical mode (the one with a node at the spine) $(2,0)_a$ in the pair decreases, while that the anti-symmetrical mode $(2,0)_b$ increases as shown in Figure 1.

The out-off plane displacement of the symmetrical mode $(2,0)_a$ along the circumference is shown in Figure 2, where l/L is the ratio of the arc length to the circumference. As α increases the amplitude and area of the in-phase vibration on the normal-strike-surfaces increase. We observe a significant increase in the volume velocity of the pipe. Thus an increased efficiency of sound radiation is expected. On the other hand, the out-off plane displacement of the anti-symmetrical mode $(2,0)_b$ remains unchanged. The variation of the energy loss of this anti-symmetrical mode due to sound radiation with α is only indirectly related to the pipe flatness due to the corresponding increase of the nature frequency.

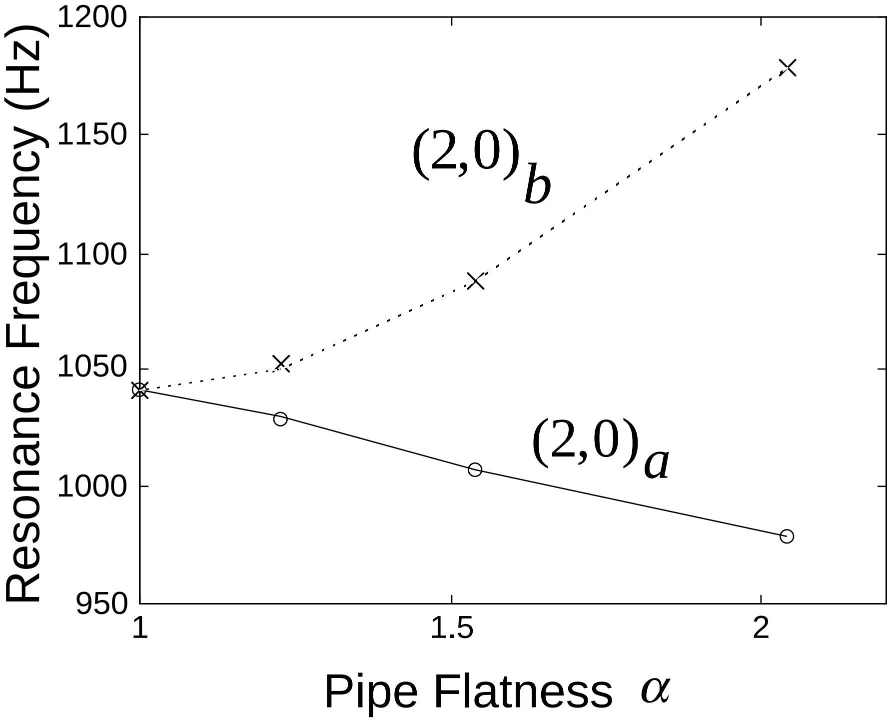


Figure 1. Resonance frequencies of the symmetrical mode $(2,0)_a$ and anti-symmetrical mode $(2,0)_b$.

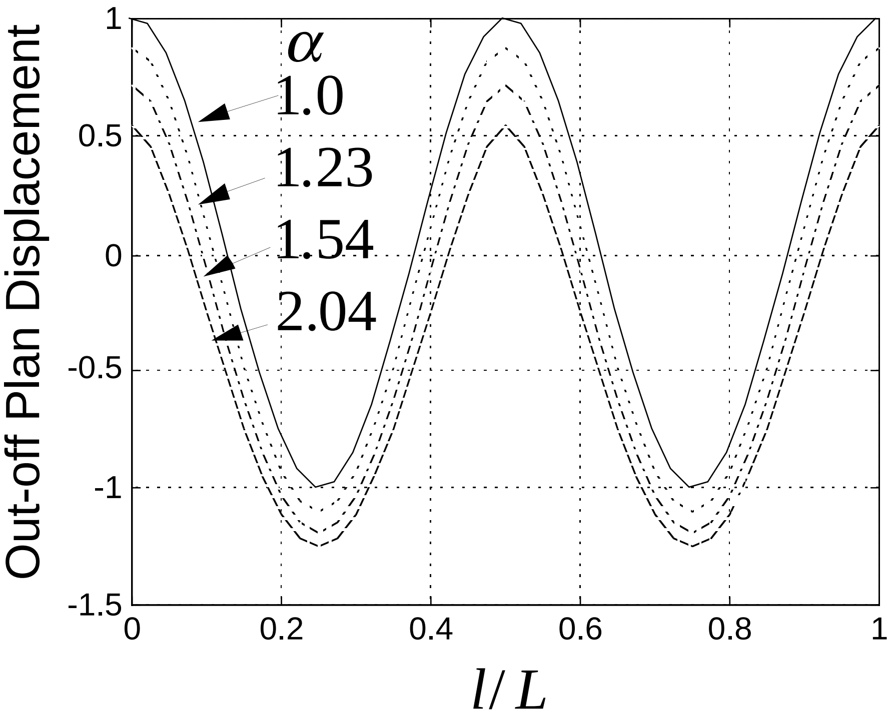


Figure 2. The out-off plan displacement of the symmetrical mode $(2,0)_a$ along the circumference direction.

Sound radiation efficiency

The energy loss of the ith pipe mode due to sound radiation is described in terms of radiation efficiency defined as:

$$\sigma_i = \frac{\int_S \mathrm{Re}(p v_n^*) ds}{\rho_o c_o \int_S v_n^2 ds} \tag{1}$$

where p and v_n are respectively the sound pressure and normal velocity on the vibrating surface. $\rho_o c_o$ is the characteristic impedance of the air. The damping constant β_{ia} describing the decay of the pipe mode in air ($\phi_i = \phi_{io} e^{-\beta_{ia} t}$, where ϕ_{io} is the modal amplitude) is related to the sound radiation and material internal damping by

$$\beta_{ia} = (\sigma_i \rho_o c_o / \rho h) + \beta_{iv} \tag{2}$$

where β_{iv} is the material damping constant, ρ and h are the mass density and thickness of the pipe wall.

The radiation efficiencies of the symmetrical $(2,0)_a$ and anti-symmetrical $(2,0)_b$ modes (shown in Figure 3) increase with the increase of pipe flatness. The significant increase in the radiation efficiency of mode $(2,0)_a$ is due to the dramatic change of the mode shape, while the small increase in σ of mode $(2,0)_b$ is merely due to the increase of resonance frequency.

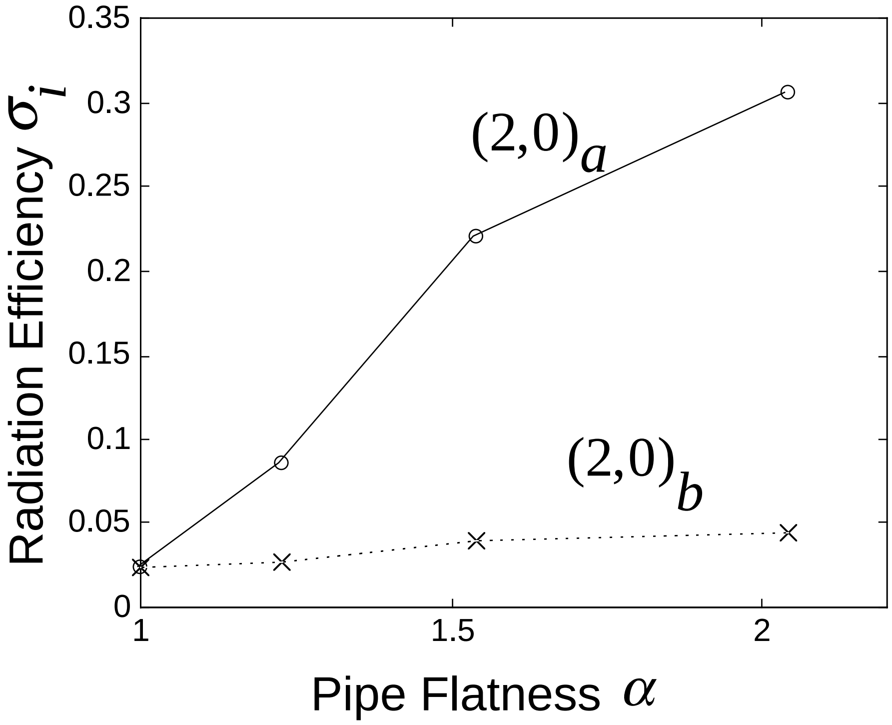


Figure 3. The radiation efficiencies of the symmetrical mode $(2,0)_a$ and anti-symmetrical mode $(2,0)_b$.

The damping constant of mode $(2,0)_a$ as a function of α is predicted using Equation (2), and an average experimental value for the material-damping constant $\eta_{(2,0)v} = 0.762$ based on Table 1. A reasonable agreement between the predicted and the measured damping constants shown in Figure 4 brings a conclusion that the decrease of decay time of an oval pipe is caused by the increase of the radiation efficiency of the symmetrical mode $(2,0)_a$ while flatness of pipe cross section is increased. However such significant decrease of decay time only occurs to those modes with a significant increase in volume velocities. For example, the damping constant of $(2,0)_b$ mode is not affected significantly by the pipe flatness because a small increase of radiation efficiency is involved in this case.

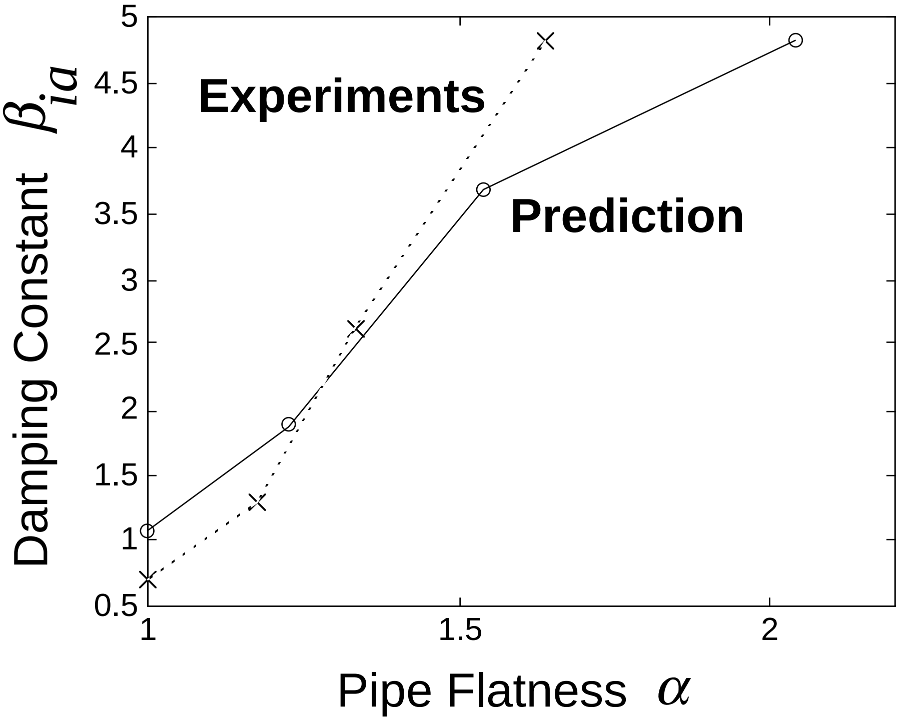


Figure 4. The damping constant of the symmetrical mode $(2,0)_a$.

Model radiation of sound

The significant change of $(2,0)_a$ mode shape with α (see Figure 2) gives rise to a dramatic change in the sound radiation efficiency (see Figure 3) and directivity of the mode. Presented in Figure 5, the radiation directivity of mode $(2,0)_a$ as a function of α explains the mechanisms associated with the dramatic increase of the modal radiation efficiency. At its resonance frequency, the $(2,0)_a$ mode of circular pipe ($\alpha = 1$) radiates sound as a quadrupole with its lobes oriented in the major and minor axes directions. The modal radiation directivity becomes a dipole as $\alpha = 1.23$. As α further increases, the modal radiation takes the doughnut-shape.

Conclusions

Among many acoustical innovations in Chinese history, the short decay time feature of the ancient Chinese music bells stands out as a fine example of ancient wisdom and technology. However the explanation of the physics behind this feature has been waited for nearly 1000 years since Sheng Kuo. In this paper, the long lasting question about the short sound decay of ancient Chinese music bells has received a satisfactory reply through the analysis of sound radiation characteristics of the first couple of modes in flatten pipes.

As the flatness of a pipe increases, the resonance frequencies and mode shapes of the originally degenerated modes in the pipe with circular cross section change significantly. The change in the resonance frequencies between the symmetrical and anti-symmetrical modes is responsible to the two-tone quality of the music bells, while that in the mode shapes is the source for the increased sound radiation and therefore the decreased sound decay time. However, only the symmetrical mode $(2,0)_a$ out off the first couple of modes, experiences the significant change in mode shape and thus the increase in the radiation efficiency. A dramatic evolution of sound radiation directivity of this mode was observed as flatness of a pipe increases. Starting as a quadrupole sound source for $\alpha = 1$, the directivity gradually changes into dipole and eventually into a doughnut-shape as α increases. In summary, the short sound decay time of the ancient Chinese music bells can be explained using an interesting sound radiation phenomenon of a flatten pipe, which is a transformation from a weak to strong sound radiator of the symmetrical mode $(2,0)_a$ as the flatness of the bell/pipe increases.

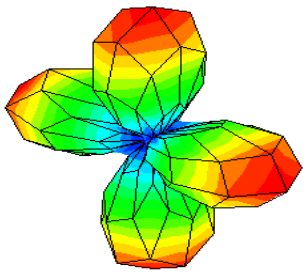
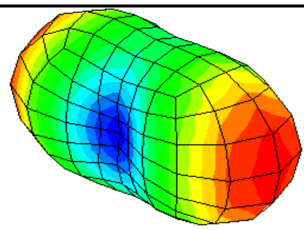
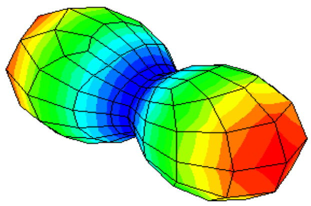
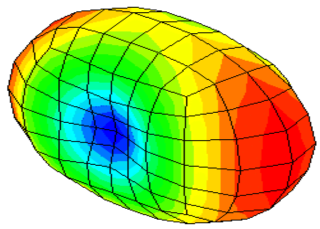
Pipe Flatness α	Radiation Directivity $(2,0)_a$ Mode	Pipe Flatness α	Radiation Directivity $(2,0)_a$ Mode
$\alpha = 1$		$\alpha = 1.54$	
$\alpha = 1.23$		$\alpha = 1.23$	

Figure 5: The radiation directivity of mode $(2,0)_a$ as a function of α.

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BANDICOOT - A NOVEL APPROACH TO USING A PITCH-CATCH ACOUSTIC PROBE FOR FIELD NON-DESTRUCTIVE TESTING

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Abstract
The acoustic Pitch-Catch probe is commonplace in the world of aerospace non-destructive testing, however the usefulness of the technique is lacking in many respects, being cumbersome to use and generally very costly. Building on several years of experience, a new approach has been taken by CSIRO to produce a simple and versatile system that incorporates an optimised Pitch-Catch probe within an optical computer mouse and combined with a notebook computer, to provide a fully featured scanning system for a fraction of the cost of systems currently available. This paper describes the approach taken and some of the underlying research in developing the Bandicoot.

Introduction

The testing of composites consisting of a honeycomb core sandwiched between skins of various fibre composite mixtures presents some problems to the use of conventional ultrasonic methods. The impedance mismatch between the skin and core and the thickness of many of these constructions attenuates the ultrasound too much for good transmission or reflection results. Thus it has become common to use alternative methods and, in particular, vibrational methods with frequencies less than 100 kHz. A range of such 'acoustic' NDT systems are commercially available and include the use of Pitch-Catch and Mechanical Impedance (MIA) techniques. Using existing commercial systems for in-service damage to aircraft can be complicated and very costly. In many circumstances quantitative NDT cannot be carried out in the field due to the lack of skilled personnel and equipment, with the aircraft having to return to a service centre for inspection.

Traditionally acoustic probes have been used as hand pick-and-place devices. However, recently systems have become available where the probe can be attached to a 'C Scan' system. An example is the MAUS system built by Boeing where a track is attached to the structure by suction cups and the sensor is moved, by hand or automation along the track, allowing positional information to be encoded.

Pitch-Catch Acoustic Probes

The Pitch-Catch principle is quite simple and widely used in acoustic, ultrasonic and many other wave propagation applications. The concept in its simplest form normally incorporates two transducers, one configured as a dedicated drive and the other as a dedicated receive channel (Hence the terms "Pitch" and "Catch").

The type of pitch-catch probe shown in Figure 1 is typical of an acoustic frequency NDT device. In popular commercial systems the transducers are generally strengthened polarised ceramic bimorphs, consisting of bonded sandwiches of opposing polarised piezo-ceramic disks with a thin metal or ceramic shim between. When a voltage is applied to the transducers, one ceramic element will attempt to expand and the other element contract. This action couples through the adhesive bond to create a bending or flexing mode that achieves a much greater displacement amplitude than could be expected from thickness expansion of the ceramic elements by themselves. The bimorph ceramic disks are normally mounted with their edges free and mechanical coupled to the test specimen via a centrally located contact pin.

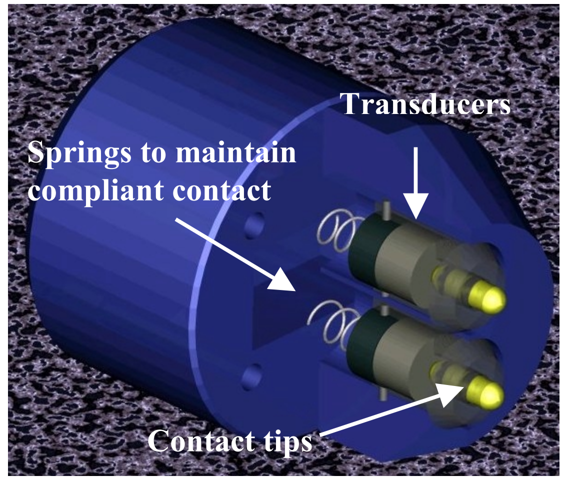

Figure 1 – A typical Pitch-Catch probe configuration

Excitation in various commercially available devices is usually a short tone burst or a swept sine "chirp" within the frequency ranges 2 to 70 kHz. Various forms of often quite complex detection and analysis have been used to process the result and produce an output indicative of damage. In general these methods work quite well in that they are sensitive to the defects sought but in fact they are difficult to set up and to calibrate. Whilst this may not be a problem for skilled engineering personnel, it is very difficult to set up a system so that relatively unskilled operators can use it to make pass/fail decisions.

The CSIRO method for NDT using a Pitch-Catch probe

In recent years CSIRO has been researching the use of a common acoustic Pitch-Catch probe for detection of soft impact damage to Nomex cored (paper resin honeycomb), carbon fibre reinforced polymer (CFRP) sandwich panels. This work [1] provided some very useful techniques for analysing the returned waveforms. In particular, analysis methods were developed that can isolate particular features within a test panel such as impact damage, background diffraction effects, and even the core itself. Examples of some relevant images are shown in Figure 2 to Figure 4.

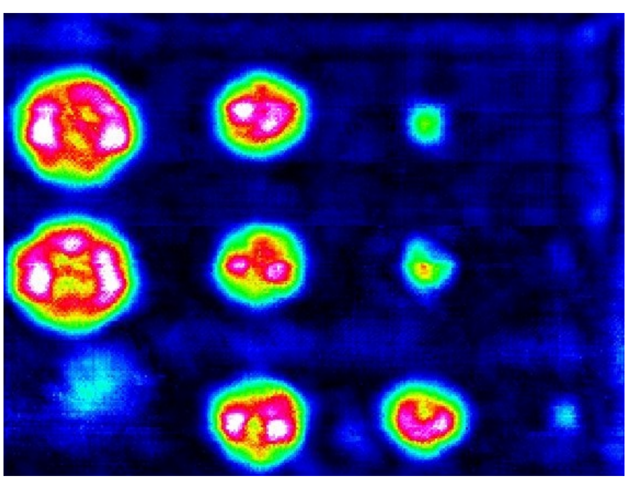
Figure 2 – Pitch-Catch "C-Scan" of an impact damage test panel

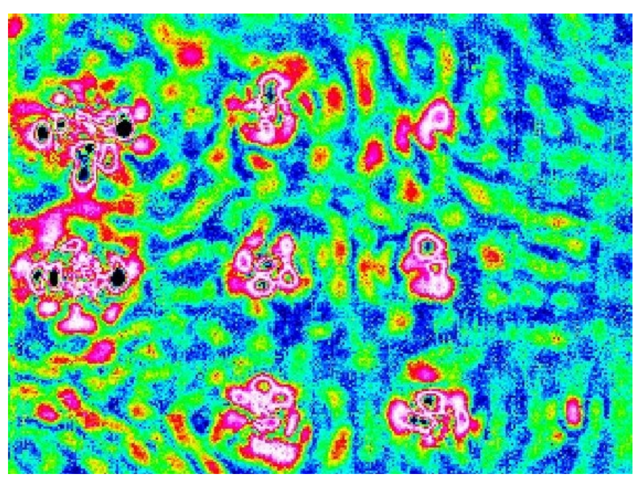
Figure 3 – Same scan as shown in Figure 2 above, but this time the data was processed to highlight background scattering effects

The Bandicoot hand-held scanner

During the course of the study into soft impact damage in Nomex cored CFRP sandwich panels, the idea evolved that a practical outcome of the study could be the development of an improved Pitch-Catch probe, bundled with analysis software developed at CSIRO, and incorporated within its own low cost positioning system. The intended purpose of the design is to produce a simple and cheap NDT system.

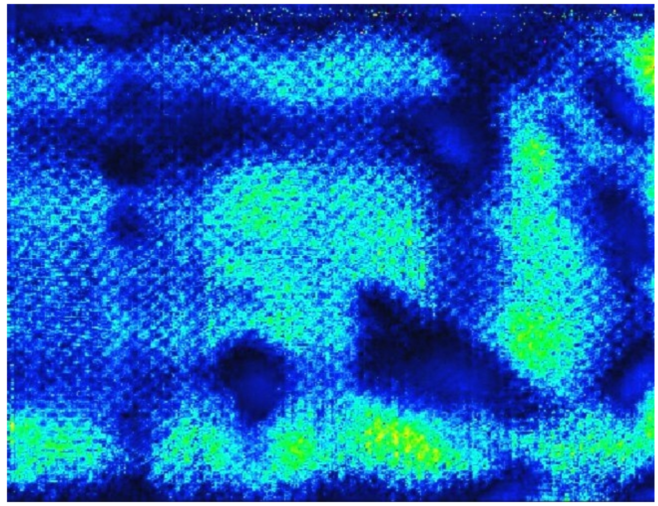

Figure 4 – A scan of a panel analysed to highlight the honeycomb core.

The resultant demonstrator consisted of a Pitch-Catch probe housed with a dual optical positioning system, a PCMCIA digitisation card and a notebook PC. The system was given the name of Bandicoot after a distinctly Australian mouse-like marsupial.

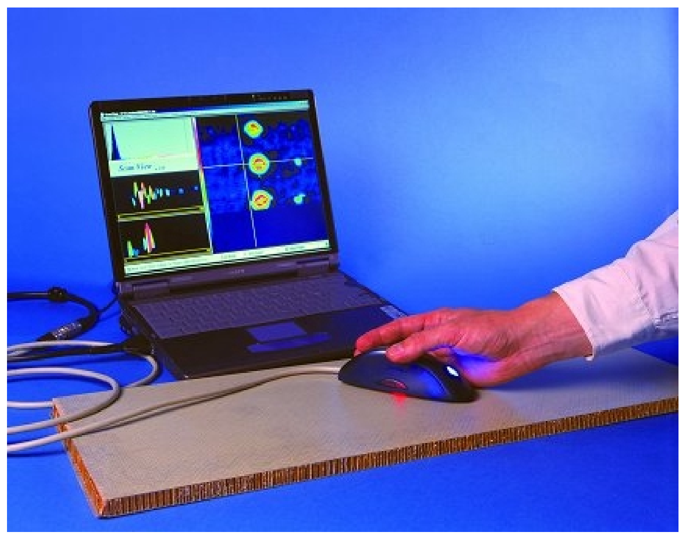

Figure 5 - The Bandicoot demonstrator system examining a Nomex cored test panel.

The hand-held probe

A typical implementation of the Bandicoot design can be seen in Figure 5. The handpiece contains the dual tipped Pitch-Catch sensors and two optical position detection units as well as several user defined contact switches. Also included within the probe are electronics for exciting the transmit sensor, and impedance matching and filters for the receiving channel.

The optical position detection units use light emitting diodes to illuminate a small area of surface that is imaged by a receiver. The two dimensional cross correlation between successive images is calculated giving x and y distances for any movement. As the two distance values are in the coordinate system of the unit, rotational motion cannot be detected and could cause positional errors. The approach taken in the Bandicoot to overcome this problem is to use two optical position units where the correction into the user coordinate system can be calculated knowing the distance between the optical detectors. All positional information is communicated back to a notebook PC via a standard USB port.

The base of the probe has 4 soft slides. These are distributed outside the area of the Pitch-Catch NDT sensors and the optical detectors so that the entire unit is held level with the test piece.

Micro switches are also set into the base of the probe to detect lift-off. This is necessary because if the probe is lifted off the panel the reference coordinate system is lost. A number of strategies are incorporated into the software to handle this contingency. The contact detection sensors are situated at the edge of the base in order to allow maximum sensitivity to lift-off.

Excitation in typical commercial Pitch-Catch systems

In most existing commercial instruments the user selects the operating points by looking for the parameters that give the greatest difference between 'good' and 'bad' sections of panel. This is one of the major contributory factors to the perceived unreliability of the method. Common pitfalls are:

- Selection of the wrong mode (eg. impulse, swept, other).
- Selection of the wrong frequency or frequency range.
- Selection of the optimal display mode. Data from the returned signal can often be displayed in a number of ways.
- Interpretation of the display.

Only some of these parameters will be controlled by the user and their uses are dealt with in the instructions accompanying a system. Even so experience is required to implement them to the best advantage.

The Bandicoot excitation strategy

The Bandicoot system does not use any of the conventional excitation signals. Generally the excitation is quite broadband. In fact versions have been built where the excitation is a step function. However the optimum excitation, being a compromise between narrow and broadband excitation methods, is a burst of only two or three cycles of a sine wave.

A narrow band excitation gives a better detection in principle because most defects in sandwich panels have natural frequencies, determined by their size and type. In the past the reasoning behind the use of Pitch-Catch probes has been based on the idea that propagating Lamb waves are excited in the panel and detected as they pass the receive tip. Where there is a defect, the mechanical impedance of the panel is changed yielding both a delay, ie a phase shift, and an amplitude change between 'good' and 'defective' regions.

A 'lumped element' model of a defect has been found to be most useful. The propagation velocity of flexural waves in sandwich panels are generally in the range 400 to 600 $m.s^{-1}$ and is non-dispersive [2]. Over much of the frequency range used for these probes this gives wavelengths larger than the defects, making propagation models problematic due to the small ratio of defect size to wavelength and the small tip separation.

If more energy is supplied at or around the frequency where the panel best responds to, then there is a much better probability of detection and a more accurate estimate of defect boundaries. Where this frequency is known this is obviously a better choice. In fact it is not as difficult as has been traditionally thought to estimate this frequency to within a kHz or so, in some cases, on the basis of other known data [1].

On the other hand, if an appropriate frequency is not known, then a broadband excitation maybe more suitable. The main problem in using broadband excitation is that unwanted resonances, which often have a higher Q than the defect response, are also excited. These may come from the probe or from the test structure. All commercial probes have this problem. If this response falls at or near the defect frequency the functioning of the probe is seriously compromised. If it is sufficiently distant in frequency, band pass filtering will solve the problem but the filter needs to be of a very high Q itself to attenuate these resonances without attenuating the desirable part of the response.

Signal digitisation and processing

On board the Bandicoot probe, the received waveform is passed through a low pass filter for anti-aliasing, and a high pass filter to reduce mechanical, sliding and handling noise. Then it is digitised with a PCMCIA data acquisition card in a notebook PC. The current acquisition card has a maximum sample rate of 300 kHz and a 14-bit A/D converter.

The system is configured by the user in a set-up window, in which the digitised, windowed waveform and the FFT are displayed with the probe in a free running mode. Sampling rate, sample size, trigger delay and windowing function are all selectable but defaults are also included. The user can nominate a result to be the reference result or one may be retrieved from memory.

The frequency spectrum thus obtained is used for the defect detection. The time waveform is not used for the analysis because it is much less robust to handling noise or other interfering signals.

The spectrum usually contains data up to 50 kHz that appears quite complex and without further processing will not give a good result. It is necessary for the user to decide which parts of the spectrum are useful and which parts are artefacts of the equipment and test piece dimensions. On the basis of this knowledge a band of the spectrum can be selected for further analysis.

A selection can be made by viewing the spectrum collected over a ‘good’ piece of panel. This reveals the frequency structure not introduced by the defect. Knowledge of the likeliest frequency band for defect response allows a range to be chosen where the effects of the defect are maximised compared to other structures, such as those introduced by the probe itself. A small number of ‘built-in’ ranges are available for some popular sandwich constructions.

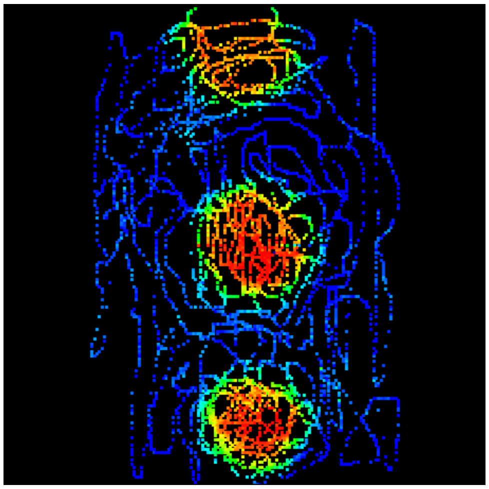

Figure 6 – A typical Bandicoot scan

Scanning

As mentioned above, the analysis is done in the frequency domain. A band of frequencies may have been selected, either by the user during set up or as the default or the complete spectrum can be used. The frequency data is compared to the reference data and a ‘damage index’ calculated. This number is used to create a colour display of the scan area in the display graticule. An example scan is shown in Figure 6 and Figure 7.

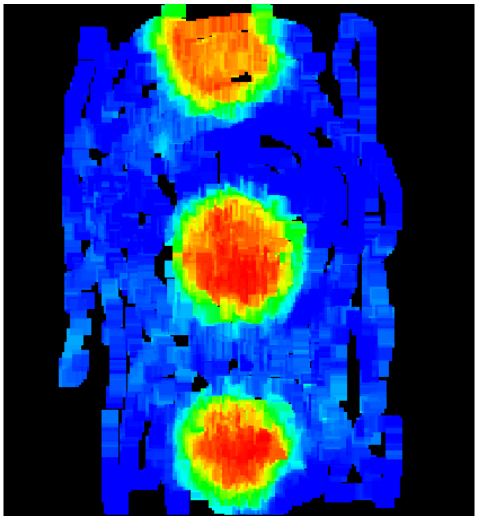

Figure 7 – An enhanced image of the scan in Figure 6

Once a scan has been completed the data can be retrieved and the display recreated. Because the original waveforms have been stored, the software also allows the user to re-analyse them using a different frequency band or re-display the data using different colouring schemes. Areas and traverses of the image may be selected for dimensional measurements and a “B Scan” option is also available. In this mode the waveforms are displayed continuously in the data window as the mouse is moved over the display graticule.

The next generation of the Bandicoot

Due to the favourable response to the demonstrator, the Bandicoot is to be developed into a fully functional prototype. It is intended that this new design include some of the DSP technology that CSIRO has been at the forefront in developing. The new Bandicoot will contain within itself all electronics and processing required for comprehensive NDT without the need for expensive PCMCIA data acquisition cards. This leaves the notebook PC serving only as a data storage and display device. The new design structure is shown in Figure 8.

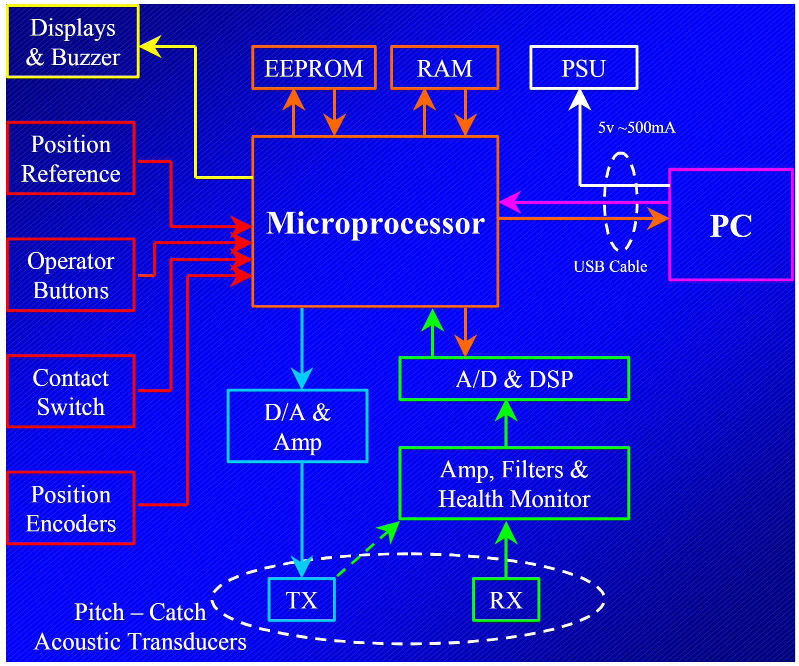

Figure 8 – A schematic representation of the intended new Bandicoot design. All components to the left of the PC will be housed in a computer mouse-sized handheld probe.

By utilising existing CSIRO technology within the Bandicoot, development costs will be kept at a minimum while providing a capable unit that is simple to operate. The design also permits complete reconfiguration via downloadable software to enable the Bandicoot to adapt to new applications.

Conclusions

The Bandicoot is a novel [3] implementation of the acoustic Pitch-Catch probe technique. It uses new analysis algorithms designed to maximise reliability and increase sensitivity at the same time. The probe is housed in a computer mouse-like structure, which improves the reliability and reproducibility of the results. The probe interfaces with a PC in the conventional manner so a 'C Scan' can be created on the display as the data is collected. Apart from the mouse, the only other hardware requirement is a suitable notebook computer.

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Acknowledgments

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MULTI-CHANNEL CONTROL OF FLUID-BORNE AND STRUCTURE-BORNE NOISE IN A PIPE-PUMP SYSTEM

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Abstract

The preliminary investigation of active multi-channel control of fluid-borne and structure-borne noise propagated in a pipe-pump system using fluid and wall-radial wave control actuators is described. The model considered is a long pipe, with one end excited by a pump and the other end connected to a water tank. Acoustic control is achieved using a piezoelectric ceramic (PZT) fluid-wave actuator located on the inside of the pipe wall and downstream of the pump, and structural control is achieved using three PZT stack actuators positioned in a ring outside the pipe wall and further downstream from the acoustic actuator. It is demonstrated that active control gives noise reductions up to 14 dB 1 m upstream of an error hydrophone (downstream of control source), 21 dB at the error hydrophone and 15 dB 1 m downstream of the error hydrophone; and structural reductions up to 7 dB at the pump's blade-passage frequencies.

Introduction

Examining the control of fluid-borne and structure-borne noise in pipe-pump systems is important for controlling the underwater noise radiation of naval vessels. Previously, Pan and Hansen [1-2] have studied active control of vibration transmission in a cylindrical shell using circumferential arrays of vibration control forces and error sensors.

To date there has only been a limited amount of work carried out into the active control of fluids in pipes. Brevart and Fuller [3] conducted a theoretical study of active control of wave propagation in fluid-filled elastic cylindrical shells using radial line forces to minimise radial shell vibration. Fuller and Brevart [4] carried out an analytical and experimental investigation into the potential of actively controlling the total power flow in fluid-filled elastic pipes using structurally mounted actuators and sensors. Brennan et al. [5] studied the active control of fluid waves in a perspex pipe using a fluid wave actuator and a fluid-wave sensor, and reported that during their control experiment the wall-radial acceleration increased when the fluid-wave actuator was applied. This indicated that the fluid-borne and structure-borne noises were coupled. They recommended that two actuators (one fluid-wave and one structural-wave actuator) be used so that fluid waves could be controlled over a wide range of frequencies. Note that the work presented in [4-5] was performed on perspex pipes which, when compared to steel pipes used on naval vessels, are more amenable to deformation by external forces. Also the disturbance sources were fluid-type or structural-type incident wave in [3], and harmonic point force excitation using a shaker in [4-5], which when compared to pump noise used on industrial and naval vessels, are more stable and controllable. Juniper et al. [6] developed a polyvinylidene fluoride (PVDF) noise source, and carried out an experimental and theoretical investigation of characteristics of the PVDF noise source attached to a water-filled steel pipe. Podlesak [7] examined active control of noise transmission in a water-filled steel pipe excited by a tonal noise source, using the PVDF noise source in [6] as a control actuator at very low frequencies (below 50 Hz), where structural waves could not be easily excited by applying the fluid-wave control source.

The work outlined here is a preliminary experimental investigation into the control of fluid-borne and structure-borne noise transmission along a water-filled steel pipe using fluid-wave and structural-wave actuators simultaneously, at frequencies where structural waves are strongly coupled with acoustic waves to produce total noise transmission. To the authors' knowledge this has not been conducted previously.

Experimental Arrangement

A schematic diagram of the pipe-pump model is shown in Figure 1. The pump had a seven-bladed impeller driven by an electric motor that was controlled by a variable speed drive. The pump pumped water from a holding tank of dimensions 6x6x4 m through a composite PVC pipe, then into a steel transmission pipe. The steel transmission pipe had a length of 12 m, inner diameter of 100 mm and wall thickness of 6 mm. The output of the steel transmission pipe was connected to the fluid-wave control source, attached to the structural-wave control source and fixed to the structural sensing section. The sensing section was attached to a steel-terminating pipe of length 3 m, which connected back to the water tank. In all measurements, the various pipe sections were horizontally supported by resilient mounts above three tri-pods (see Figure 1).

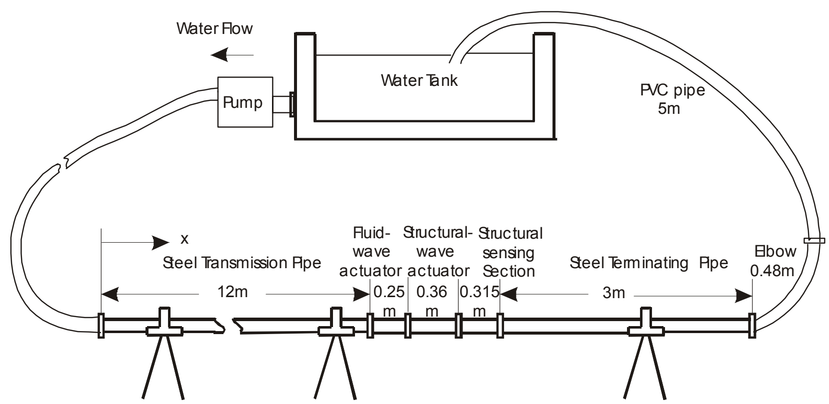

Figure 1. Schematic diagram of pipe-pump model.

Refer to Figure 2. The test pipe was excited by the pump, and acoustical control was implemented using the PZT fluid-wave actuator, which was operated to minimize sound pressure level (SPL) at the error hydrophone. Wall-axial wave control was carried out by driving the six PZT patches in phase with each other. This was necessary due to the limited number of piezo-amplifiers available, as independent control requires one amplifier for each actuator. Wall-radial wave control was demonstrated using the three PZT stack actuators. The PZT stack actuators were driven independently to minimise the sum of squared outputs of the radial accelerometers. One error hydrophone, one axial accelerometer and three radial accelerometers were used as experimental and numerical analysis indicated that these numbers were sufficient.

A block diagram of the noise and vibrating control system is shown in Figure 3. Distance between hydrophones was 1 m. A source signal from the pump (as reference) and error signals from the error sensors were fed via amplifiers to a feed-forward controller. The controller generated five control signals: one was used to drive the PZT fluid-wave actuator, another to drive the in-phase PZT patches, and three to drive the three PZT stack actuators.

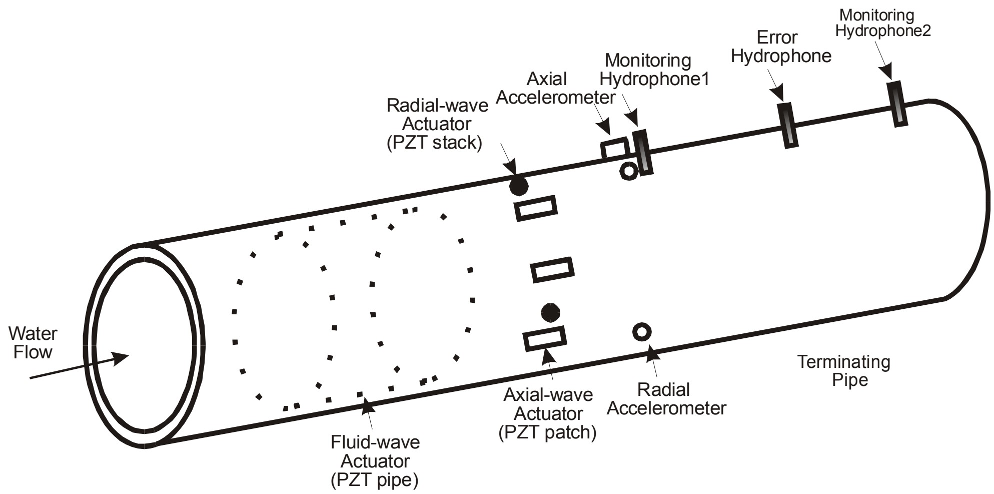

Figure 2. Acoustics and vibration control system physical layout.

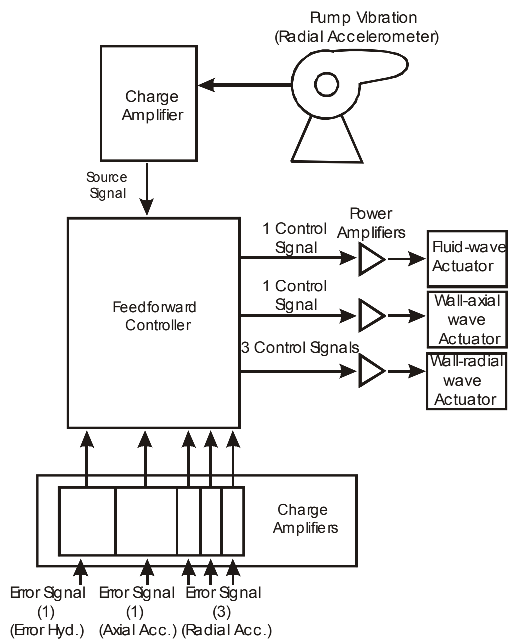

Figure 3. Block diagram of the noise and vibration control system.

Experimental Results and Discussions

Uncontrolled acoustical response

In general, it was found that the SPL measured at the error hydrophone was due to several frequency components from fluid and structural excitations, in which the blade-passage frequency produced the dominant response for sound pressure. A typical result for frequencies over the range from 0 to 200 Hz is shown in Figure 4, which has a blade-passage frequency of 126 Hz, where dB are relative to a SPL of 1 μPa. The similar results to that of Figure 4 were produced for the system had blade-passage frequencies from 26 to 171 Hz, which were corresponding to the allowed speeds of the pump. Therefore, the control of SPL due to a blade-passage frequency is the major issue of this research.

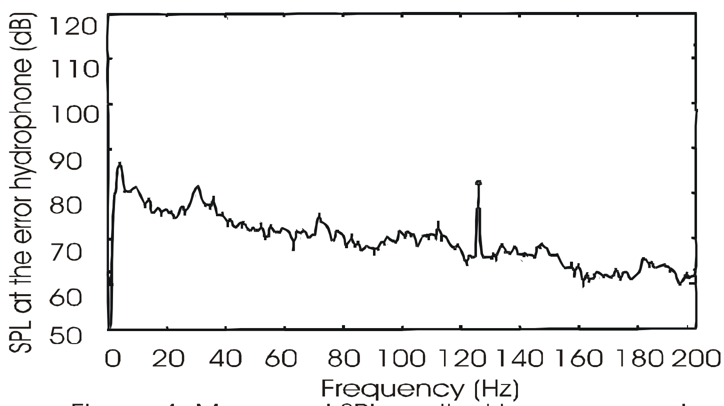

Figure 4. Measured SPL excited by a pump at a blade-passage frequency of 126 Hz.

For the allowed speed range of the pump, the measured SPL at the error hydrophone as a function of blade-passage frequency is presented in Figure 5. The SPLs at 116 Hz, 121 Hz and 126 Hz were significant from Figure 5, and at these frequencies the coherences between the reference sensor and error sensor were high (greater than 0.9). Consequently, these three blade-passage frequencies were selected for experimental investigation.

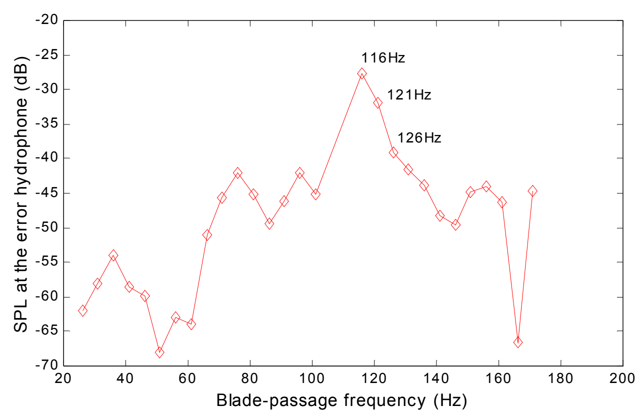

Figure 5. Measured uncontrolled SPL with pump excitation.

Uncontrolled structural response

For a blade-passage frequency of 126 Hz, the respective contributions of axial and radial acceleration along the transmission pipe to the terminating pipe are shown in Figure 6, where dB are relative to an acceleration of $1 m/s^2$. The distance x is defined in Figure 1. From Figure 6, it can be seen that the major structural response was due to wall-radial acceleration, and similar results were obtained at frequencies of 116 and 121 Hz. This is primarily due to the following two reasons. One is the first axial mode frequency was measured to be 140 Hz, below which the observed axial acceleration was due to the axial components of the bending strain arising from the radial motion of the pipe. The other is that there were considerable radial mode frequencies below 140 Hz, which resulted in a large wall-radial acceleration distribution.

Minimisation of SPL with a fluid-wave actuator

For the pump excitation at the blade-passage frequency of 126 Hz, the spectra of the uncontrolled SPL from Figure 4 and the controlled SPL using the PZT fluid-wave actuator only, are compared in Figure 7. It can be seen that a 21 dB reduction was achieved at the blade-passage frequency, and the SPL control did not result in undesirable modes called control spill over. Similar results were obtained at the blade-passage frequencies of 116 and 121 Hz.

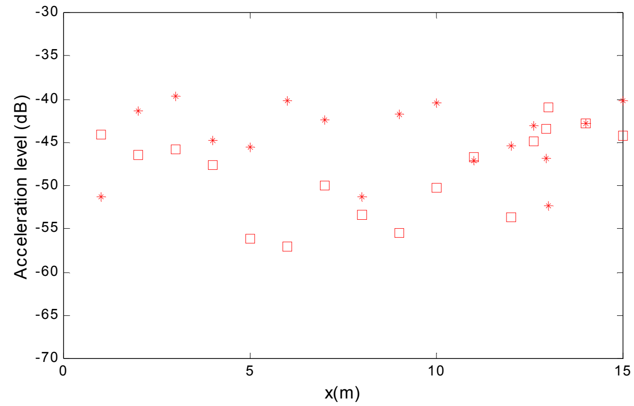

Figure 6. Measured uncontrolled acceleration distribution excited by the pump at a blade-passage frequency of 126 Hz; axial acceleration; * * * radial acceleration.

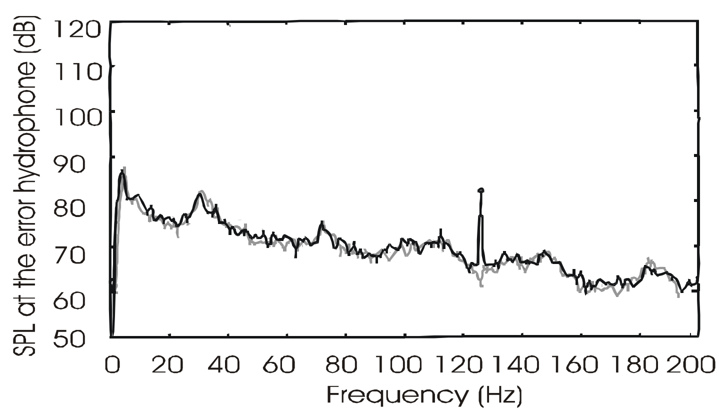

Figure 7. Measured SPLs excited by a pump at a blade-passage frequency of 126 Hz; uncontrolled; controlled.

Figure 8 shows the measured reductions, using the PZT fluid-wave actuator only, as a function of blade-passage frequency. The acoustical reductions were measured at the error hydrophone and two monitoring hydrophones as shown in Figure 2. The wall-axial and wall-radial acceleration reductions were measured at axial and radial accelerometers respectively (see Figure 2). Figure 8 indicates that the whole pipe-pump system can be made quieter by applying the acoustic control actuator. Figure 8 demonstrates 7 to14 dB reduction at the monitoring hydrophone 1, 17 to 20 dB reductions at the error hydrophone, and 8 to15 dB reductions at the monitory hydrophone 2. Figure 8 also shows that noise control gives a reduction of up to 3 dB in the axial acceleration but an increase of up to 5 dB in the radial acceleration. Such behaviour indicates that control of the wall-radial acceleration may supplement the reduction obtained by the fluid-wave control source.

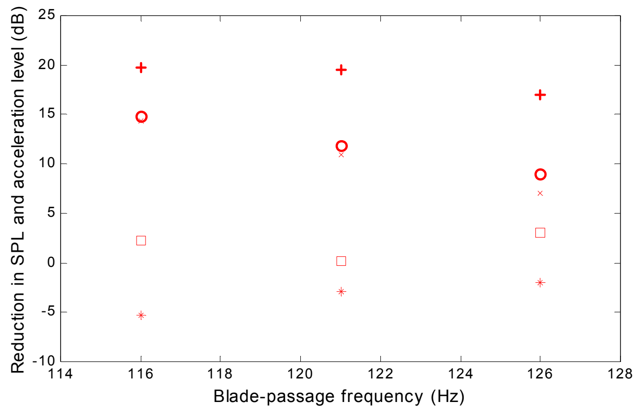

Figure 8. Measured reductions using PZT fluid-wave actuator only; × × × reduction of SPL upstream of the error hydrophone; + + + reduction of SPL at the error hydrophone; o o o reduction of SPL downstream of the error hydrophone; reduction of axial acceleration; * * * reduction of radial acceleration.

Minimization of wall acceleration with structural wave actuators

As previously indicated there was no axial mode frequency below 140 Hz. Thus, there is no advantage in controlling wall-axial waves at the investigated frequencies (116 Hz, 121 Hz and126 Hz).

Experimental tests were also carried out by using the three PZT stack actuators to control the wall-radial acceleration. It is emphasized that only one power amplifier was available to drive the stack actuators, and resulted in up to 7 dB achievable reduction of radial acceleration.

Multi-channel control of fluid-borne and structure-borne noise

Based on experience with the effect of minimization of wall acceleration on the acoustical reduction described above, control of SPL and wall-radial acceleration simultaneously were expected to give better acoustical reduction than using a single fluid-wave actuator.

By way of example, the blade-passage frequency of 126 Hz was selected. Table 1 shows the measured reductions using multi-channel control, and the reductions due to a single acoustical actuator (from Figure 8). Table 1 shows that by a reduction in the radial acceleration of 6 dB, gave an increase of 3 dB (refer to hydrophone 3) in SPL reduction downstream of the error hydrophone and 2 dB (refer to hydrophone 1) in SPL reduction upstream of the error hydrophone. Note that the reductions were small due to the limited capability of the amplifiers as described above. The results demonstrate operational multi-channel control. Controlling the radial acceleration increased the SPL reduction for the blade-passage frequency below the first axial mode frequency, which indicated that active control of noise-borne and vibration-borne noise in the pipe-pump system is feasible. This approach demonstrated that it is possible to develop an active system to control fluid-borne and structure-borne noise in pipe-pump systems, which is important for reducing the underwater noise radiated from naval vessels.

Table 1 Acoustic and structural reductions (dB)

	Hydrophone 1	Hydrophone 2	Hydrophone 3	Radial acceleration
SPL control only	7	17	9	-2
SPL and structural control	9	16	12	6

Results for 116 Hz and 121 Hz are not presented here as the acoustical responses at those frequencies were larger than that at 126 Hz (see Figure 5). Therefore, control at those frequencies required even more powerful amplifiers to drive the control actuators. However, the reductions shown in Figure 8 would be minimal reductions for multi-channel control by simply switching the structural actuators off.

Conclusions

Fluid-borne and structure-borne noise in the pipe-pump system can be reduced by using fluid-wave and structural-wave actuators driven by a multi-channel controller. For the pipe-pump system studied with one fluid-wave and three wall-radial wave actuators, it is possible to achieve noise reductions of up to 14 dB 1m upstream of an error hydrophone, 21 dB at the error hydrophone and 15 dB 1m downstream of the error hydrophone; and structural reductions of up to 7 dB at the pump's blade-passage frequencies.

Acknowledgments

The authors wish to thank Mr Ted Symes for providing rubber mounts, Mr Peter Climas for helping to design the wall-radial actuators, Mr Ross Juniper and Dr Mike Podlesak for their questions and suggestions, and Mr Michael O'Reilly and Mr Peter Climas for experimental support.

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REAL-TIME FEEDFORWARD CONTROL USING VIRTUAL ERROR SENSORS IN A LONG NARROW DUCT

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Abstract
Active Noise Control (ANC) using a pressure squared cost function, within a highly damped and modally dense enclosure results in small zones of attenuation in the immediate vicinity of the error sensors. Consequently, an observer, who may be only a few centimeters away, may not notice any noise level attenuation as a result of the active noise control. "Virtual" error sensors use a forward-difference algorithm to predict and hence minimise the sound at a location remote to the error sensors. In previous work, control using a virtual error sensor was synthesised using a model of a long narrow duct, which was then validated using post-processed experimental data. Here, the results of the more practical scenario of "real-time" active noise control with virtual error sensors and a feedforward controller, are presented. Tonal noise is controlled at frequencies that are both on and off resonance in a rigid, long, narrow duct and the effect of active control on the dominant mode is observed.

Introduction

The use of a local active noise control system within a highly damped and modally dense enclosure can result in small "zones of quiet" around the error sensor. Therefore, for the observer to perceive any reduction in noise level, the error sensor must be placed in very close proximity to the observer's head, which in many cases is impractical. The concept of "virtual" sensing, an active noise control technique where a local zone of quiet is created at a location remote from the error sensor was first introduced by Garcia-Bonito *et al.* (1996). Their theory was based upon a known measured acoustic transfer function between a permanent remote microphone and a microphone temporarily placed at the observer location. The sound pressure level at the observer location was estimated and minimised through the modification of the permanently placed microphone signal with the previously measured transfer function. However, this assumes that the transfer function between the physical microphone and the virtual microphone does not alter with time and hence large estimation errors may occur if there is any environmental or physical system changes. Cazzolato (1999) introduced a novel forward-difference extrapolation virtual sensing technique designed to adapt to any physical system changes. Two virtual error sensing algorithms were developed to predict the sound pressure at the observer location. The techniques were applied to control tonal noise in a long narrow duct model and the results were validated with experimental data. However, in both cases control was evaluated by a post-processed quadratic optimisation of the data. This paper will compare and analyse the results of real-time active noise control using a feedforward controller with hard-wired virtual error sensors.

Theory

At low frequencies, when the distance between the transducers making up the virtual sensor is much less than a wavelength, the spatial rate of change of sound pressure is low and therefore predictable (Kestell, 2000). Hence, by fitting a straight or curved line between the pressures measured, p_1, p_2 and p_3 at fixed locations, the pressure, p_v at a remote location can be estimated (Figure 1). The two forward-difference virtual microphone algorithms are summarised below.

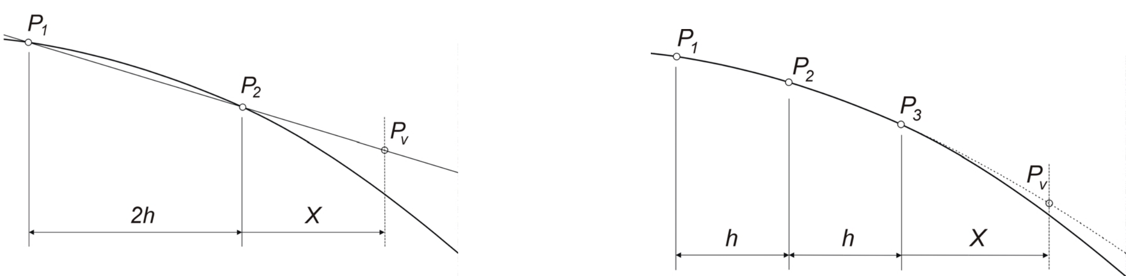
1. Two microphone, first-order prediction:

$$p_v = \frac{(p_2 - p_1)}{2h} x + p_2 \tag{1}$$

2. Three microphone, second-order prediction:

$$p_v = \frac{x(x+h)}{2h^2} p_1 + \frac{x(x+2h)}{h^2} p_2 + \frac{(x+2h)(x+h)}{2h^2} p_3 \tag{2}$$

where p_v is the pressure at the observer location, x is the distance between the observer and the nearest sensor, p_1, p_2 and p_3 are the measured pressures and h is the separation distances between the transducers for the second-order prediction and the separation distance between the two microphones in the first-order prediction is $2h$.



(a) First-order (b) Second-order

Figure 1 Forward-difference extrapolation

Method

Results for real-time control in the duct were compared to results obtained using both the analytical model and post-processed experimental data. A primary noise source was positioned at one end of the duct with a control source located 0.5m from the opposite end (Figure 2). The sound pressure profile around the virtual sensors was observed over a 0.5m length with 21 equally spaced measurement locations. With the duct rigidly terminated the resonance quality factor (Q) was approximately 50. The duct was modelled using the ANSYS FEA (Finite Element Analysis) package and transfer functions between the primary and secondary source and the 21 measurement locations were calculated using a modal superposition technique in which the first 25 modes were considered.

For the post-processed results, transfer functions were measured experimentally between the two sources and the 21 measurement locations. Loud speaker sources were excited with random noise over a frequency range of 0-400 Hz. The data obtained was then post processed and the cost function minimised using quadratic optimisation, which incorporated a 1% error (40 dB control limit) to simulate more realistic experimental results.

The real-time experiments discussed here were conducted using the feedforward EZ-ANCII controller developed by Causal Systems.

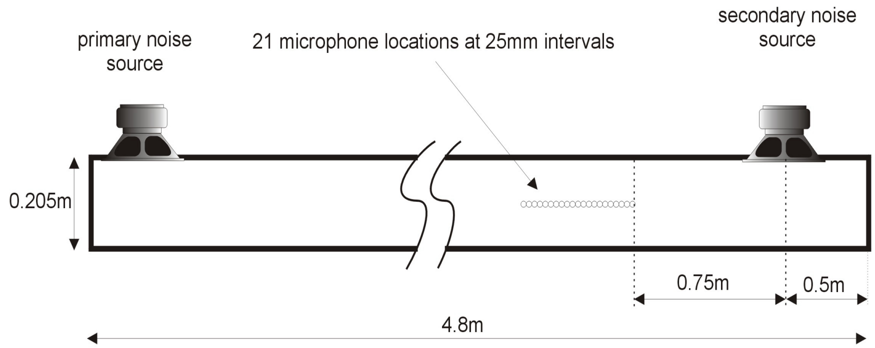


Figure 2 Schematic system representation of the long narrow duct

Results for rigidly terminated duct

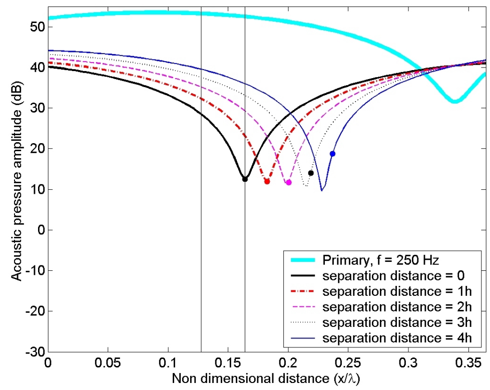
Real-time control, on-resonance example

Figure 3 shows the results obtained when controlling an acoustic resonance in a long, narrow, rigidly terminated duct. The vertical lines represent the sensor locations and filled circle represents the observer location. The curves show the controlled sound field corresponding to increasing separation distances between the observer and the sensors. Figures 3(a), (c) and (e) show a comparison of the performance of the three control evaluation methods using the first-order virtual microphone. Numerical control shows an attenuation of 40 dB at all separation distances. The post-processed and real-time control results show a decrease in attenuation as the separation distance between the transducers and the observer location increases to 4*h*. These results indicate that real-time control out-performs post-processed control with 19 dB attenuation at 4*h* using post-processed control compared to 25 dB at 4*h* using the real-time controller. The performance of the post-processed control is affected by inherent FFT errors in taking frequency response measurements. These errors are greatest when the coherence is low, occurring at resonances and anti-resonances. The poor coherence at anti-resonances is a result of low signal to noise ratio. The low coherence at resonance is due to spectral leakage. On the other hand, sensitivity and phase mismatch between the predicting transducers limits the performance in the real-time control example.

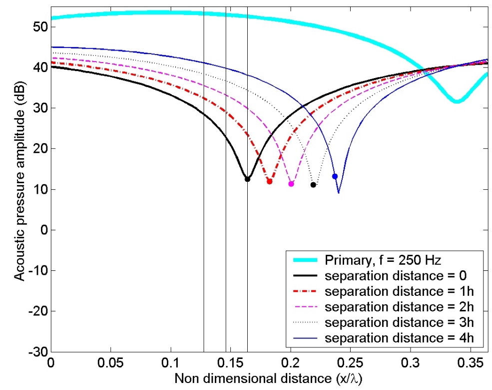
Figures 3(b), (d) and (f) show the performance of the second-order virtual microphone for the three control strategies. The numerical simulation shows an attenuation of 40 dB for all separation distances. The real-time control example again achieves greater attenuation than the post-processed control for all separation distances. However, the accuracy of the second-order virtual algorithm is affected by small spatial variations as suggested by Kestell (2000) (see Figure 4) and proves to be a less accurate prediction method when using physical data.

Real-time control, anti-resonance example

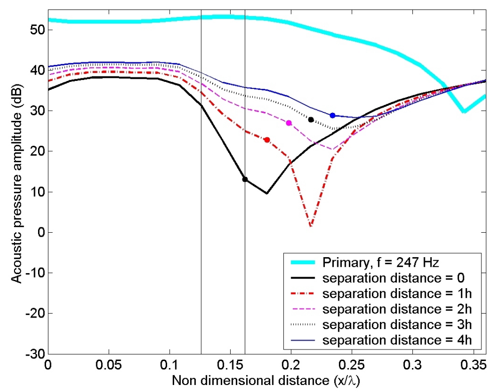
Figure 5 displays the results obtained when controlling an anti-resonance, at 265 Hz in the same rigidly terminated long narrow duct. Figures 5(a), (c) and (e) show the results using the first-order virtual algorithm. At an off-resonance condition, the level of control is significantly reduced because several modes dominate the response. In this case, the post-processed experimental control out performs the real-time control because the frequency response data is less affected by leakage at this anti-resonance frequency.



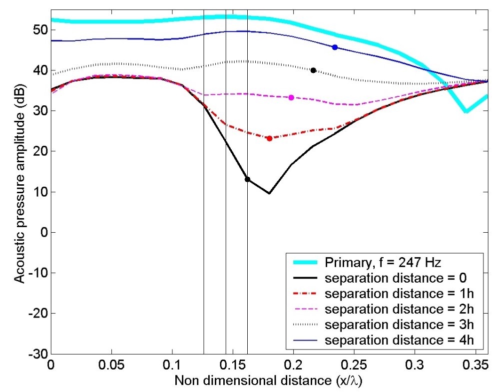
(a) Numerical simulation – first-order



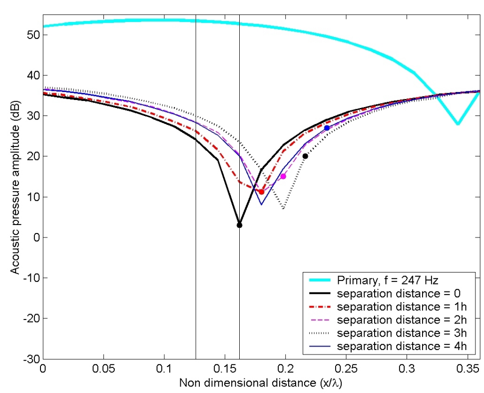
(b) Numerical simulation – second-order



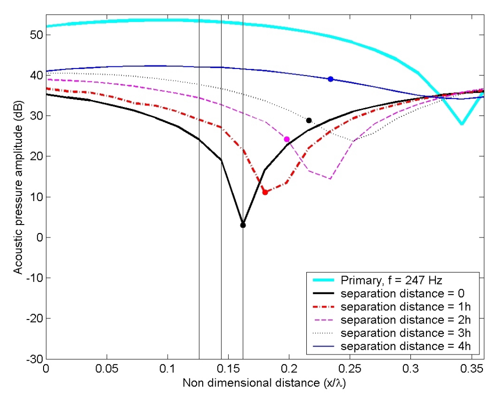
(c) Post-processed experimental control - first-order



(d) Post-processed experimental control - second-order



(e) Real-time control – first-order



(f) Real-time control – second-order

Figure 3 Uncontrolled and controlled sound pressure amplitudes along a rigidly terminated duct at an acoustic resonance using first and second order virtual microphones. Actual transducer locations are marked by vertical lines and the observer location by a circle.

Figures 5(d) and (f) show the results for the second-order virtual microphone using post-processed data and real-time control respectively. Again, post-processed experimental control out-performed real-time control, achieving 10 dB attenuation at 4*h* compared to a gain of 5 dB at 4*h*. At the anti-resonance the real-time control performance is limited by the strength of the signal, as there is a lower signal to noise ratio (compared to the resonance example) at this frequency. It is also limited by sensitivity and phase mismatch between the transducers, which affects the accuracy of the prediction algorithm, unlike the post-processed data which used the same microphone to take all the measurements. The first-order prediction algorithm out performs the second-order algorithm in the post-processed control and real-time control examples, confirming that the second-order prediction algorithm is prone to corruption from short wavelength extraneous noise.

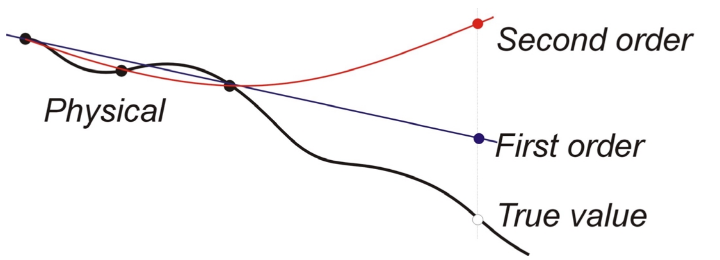


Figure 4 Prediction errors in the presence of short wavelength spatial pressure variations

Conclusions

The performance of two forward-difference prediction virtual algorithms using real-time control in a long narrow rigid walled duct has been evaluated. The results are in agreement with those of Kestell *et al* (2000) and suggest that these forward-difference virtual microphones can be successfully implemented in a real-time feedforward control situation. The post-processed control results indicate that the data were significantly affected by inherent errors that exist when taking frequency response measurements with a FFT and broadband noise. On the other hand, the performance of the real-time control is influenced by phase and sensitivity mismatch between the prediction transducers. In both cases, on and off-resonance, the first-order prediction algorithm out performed the second-order prediction algorithm, which confirms that the second-order algorithm is more sensitive to short wavelength spatial variations. Work to improve the prediction algorithm and reduce the effect of short wavelength extraneous noise has begun and involves using higher order microphone arrays, which involves the use of redundant microphones.

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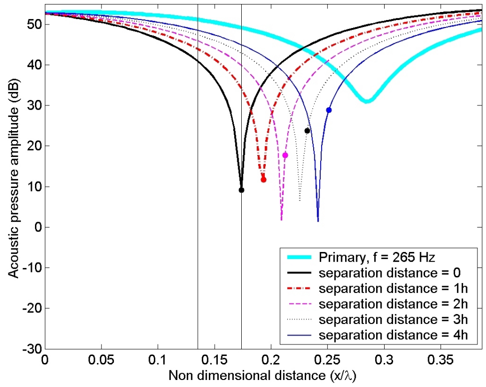
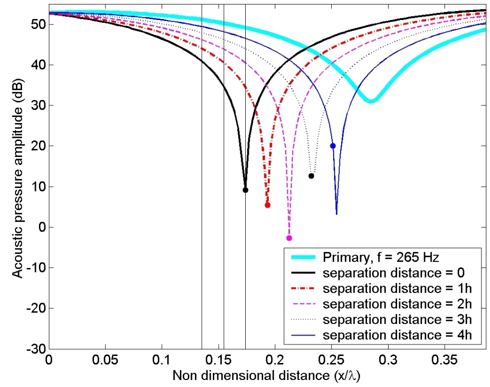
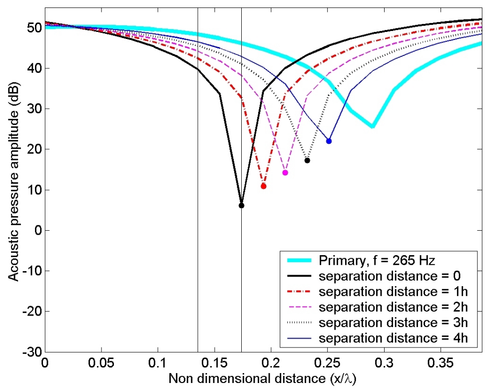
3. Kestell, C.D., Cazzolato, B.S., Hansen, C.H, Active noise control in a free field with virtual sensors, J. Acost. Soc. Am., 95(5), 232-243 (2001).



(a) Numerical simulation – first-order



(b) Numerical simulation – second-order



(c) Post-processed experimental control -
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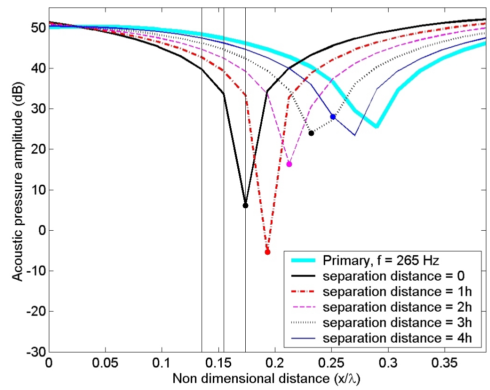
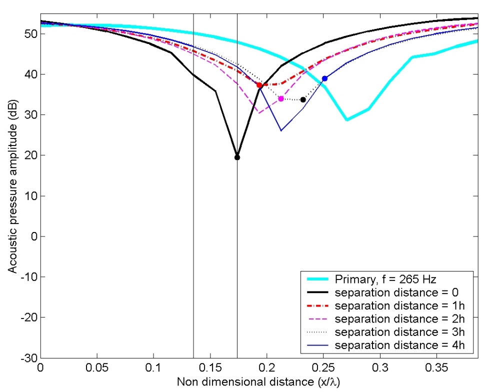
first-order

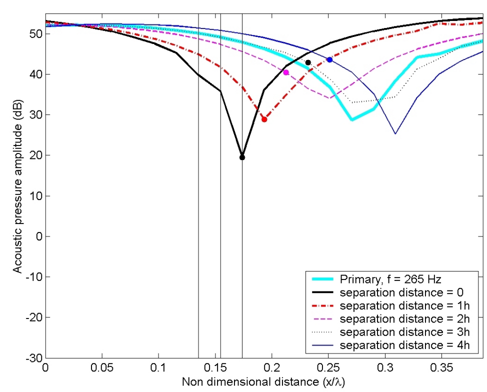


(d) Post-processed experimental control

second-order



(e) Real-time control – first-order



(f) Real-time – second-order

Figure 5 Uncontrolled and controlled sound pressure amplitudes along a rigidly terminated duct at an acoustic anti-resonance using first and second order virtual microphones. Actual transducer locations are marked by vertical lines and the observer location by a circle.

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SOUND LEVEL METER STANDARDS FOR THE 21ST CENTURY.

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Abstract

The Australian standards AS1259-1990 parts 1 and 2 describe performance specifications for Sound Level Meters. These standards are derived from and are technically equivalent to the IEC standards now re-numbered as IEC60651–1979 and IEC60804-1985. The basic specifications set out in IEC60651 and the additional characteristics for Integrating/Averaging meters added in IEC 60804 have remained essentially unchanged for over 20 years except for minor amendments and more recent amendments dealing with EMC requirements.

The IEC working group 4 (Sound Level Meters) of the IEC Technical Committee 29 (Electroacoustics) has been engaged for some years in the task of writing a new standard that will replace, update and combine the original IEC standards. It is reasonable to expect that in due course this new standard IEC61672 will become accepted as an Australian standard and will replace AS1259-1990 parts 1 & 2. As most new Sound Level Meters now coming onto the market have anticipated the new standard due to be published in 2002 it is timely to investigate the differences.

1. Introduction

The first International Electrotechnical Commission standard for sound level meters was published in 1961 as IEC123. There has been a number of versions of an Australian standard for sound level meters; the earliest was AS Z37-1967, which, after several revisions, was re-published as AS1259-1976 culminating in AS1259-1990 Parts 1,2 [1,2]. These were to follow closely the standards IEC60651 and IEC60804 [3,4]. However, by the time that IEC60804 was published in 1985, it and IEC60651 were regarded as technically obsolete as the construction of sound level meters had advanced rapidly with the use of digital technology including the use of digital rather than analogue displays. This is even truer today, as modern designs have become completely digital from the preamplifier with functions now built in as "firmware". There is no longer reliance on hardware components and the dynamics of analogue pointer displays, rather the skill of a programmer to emulate a design goal.

The new standard IEC61672-200X to replace 60651 and 60804 was begun in the early 1990's and is to be published in parts; Part 1 (Specifications) and Part 2 (Pattern Evaluation Tests) are expected to be published in 2002. Part 3 (Periodic Verification) is currently at working draft stage. Part 4 will cover detailed format for reporting tests to Part 2, and Part 5 will provide procedures for the estimation of measurement uncertainties during tests due to the presence of the sound level meter in various acoustical environments [5].

2 Australian Context.

The new series of standards embodied in 61672 are significant for the Australian acoustical community which is no longer represented only by equipment users. There is at least one successful Australian manufacturer and exporter of airport noise monitoring equipment who will in future work with this new standard to enable pattern evaluation to be carried out successfully in whatever part of the world market sales are made. There are also several other manufacturers of noise logging equipment for Australian domestic consumption, at least one with limited export experience.

There are a number of changes in design goals in 61672 that will result in different performance and facilities in instruments which must be taken into account when framing local ordinances and statutes.

In the Australian market there is currently a void as regards local pattern evaluation and the National Measurement Act [6] and its regulations do not list equipment for the measurement of sound in Certified Measuring Equipment. Most if not all of the sound level meters imported at the cheaper end of the market (Type 2) may be non-compliant or marginal and there is in general only the manufacturer's assurance that the equipment complies with the standard. Further,it appears that none of the equipment manufactured for domestic consumption in Australia has been subjected to a rigorous pattern evaluation as defined by the OIML in OIML R88-1998 [7]. Australia subscribes to the OIML (Organisationale Internationale Metrology Legale) via the National Standards Commission which is responsible for legal metrology in Australia. There is consequently little protection for the user unless the equipment being sold in Australia has a demonstrated pattern evaluation from a recognized overseas authority.

The new IEC61672 parts 2 and 3 have been formulated in co-operation with the OIML to have regard for the provisions of legal metrology. The coming of the new standard IEC61672 affords an excellent opportunity for the Australian situation to be clarified by encouraging equipment to be pattern approved. With the increased protection afforded by pattern evaluation there will unfortunately be some increased cost to the user and this may make many of the cheaper instruments suitable only for survey purposes.

Some statutory authorities or services engaged in sound level testing, for example motor vehicle muffler testing, are requiring the provision of a "Regulation 13" [6] certificate that verifies proof of traceability to National Standards for veracity during court proceedings. It is not feasible to issue such a certificate for non-type approved equipment; this hiatus knocks out the present Type 2 equipment thus increasing the cost to the authority at least 5 fold.

In the following sections the technical differences between the current and new standards will be explored.

3. Changes

3.1 Measurement Uncertainty. In line with accepted metrological practice, the estimated uncertainty of the measurements must be taken into account when making judgments of pass or fail to a design goal with tolerances. Without taking uncertainties into account when framing the tolerances around design goals in standards, this leads to an effective reduction in the tolerances. The new standard has “loaded” the tolerances with “typical” uncertainties and they are tabulated in the standard for guidance to the test house. This effectively removes the effect of the uncertainties during the judgment process providing the actual test uncertainties are no greater than the tabulated uncertainty. For the purposes of comparison between 60651/60804 and 61672 in this paper, the uncertainties are not included in any tolerances quoted. The “loaded” tolerances may be found in the new standard.

3.2 Change from Type to Class. The old standards 60651 and 60804 allowed for 4 performance types from Type 3 to Type 0 with increasingly tighter tolerances. The new standard 61672 will allow 2 performance categories designated as Classes 1 and 2 with the same design goals but with Class 2 having, in general, wider tolerances. The descriptor “Type” has been changed to avoid confusion with types of instrument in the context of facilities fitted. The older Type 0 and Type 3 have not been included. Type 0 represented a laboratory level seldom used and Type 3 is seen to be unnecessary, as modern manufacturing techniques should ensure improved performance. In practice Types 2 and 3 were seldom subjected to type approval so performance could not be substantiated.

The effect of environmental conditions has been rationalised to allow more realistic ranges of environmental effects such as temperature; Class 2 (0°C to 40°C) as distinct from the higher performance expectation of Class 1(-10°C to 50°C). In 60651 all types were required to demonstrate performance from -10°C to 50°C albeit with different tolerances and this prohibited most manufacturers taking the risk of pattern approval for their Type 2 instruments. In addition reference conditions have been changed from 20°C/65% RH to 23°C/50% RH which brings the equipment into line with most electrical metrology.

3.3 Directional Response. The tolerance limits in 61672 have been extended to include an incidence angle of 150° and have been tightened at higher frequencies. These changes are shown in Table 1 below, where the existing 60651 tolerances are shown in parenthesis.

Table 1
Directional response tolerance limits for Class 1 and 2 sound level meters as required by 61672 and compared to 60651 (in parenthesis)

Frequency kHz	Maximum absolute difference in displayed sound levels at any two sound-incidence angles within ± θ degrees from the reference direction dB					
	θ = 30°		θ = 90°		θ = 150° (not in 60651)	
	Class/Type					
	1	2	1	2	1	2
0.25 to 1 (0.035 to 1)	1 (1)	2 (2)	1.5 (1.5)	3 (3)	2	5
>1 to 2	1 (1)	2 (2)	2 (2)	4 (5)	4	7
>2 to 4	1.5 (1.5)	4 (4)	4 (4)	7 (8)	6	12
>4 to 8	2.5 (2.5)	6 (8)	7 (8)	12 (14)	10	16
>8 to 12,5	4 (4)	…	10 (16)	…	14	…

The implication of this change will impact equipment with larger diameter microphones which probably will not meet these specifications, Marsh [5].

3.4 Weighting Networks. The design goals for A and C have not changed and a Z (Zero) or "Flat" weighting has been introduced. There is however no specification for unweighted Peak, see below. In line with greater expectations of performance, the tolerances around the design goals (including Z) have been tightened for Class 1 instruments below 80 Hz and above 6.3 kHz. This is intended to ensure a minimum microphone response at 16 Hz and 16 kHz (20 Hz and 8 kHz for Class 2), this was previously +3/-∞ dB in IEC60651, that is, no specific requirement for response. These differences were summarized in [5] and are reproduced below in Table 2 for emphasis.

Table 2
Frequency weightings and tolerance limits, IEC60651 compared to IEC 61672

Nominal frequency [a] Hz	Tolerance limits (dB)					
	Class 1 (Type 1)		Change	Class 2 (Type 2)		Change
	60651	61672-1		60651	61672-1	
10	+3;-∞	+3; -∞		+5; -∞	+5; -∞	
12,5	+3;-∞	+2.5; -∞	*	+5; -∞	+5; -∞	
16	+3;-∞	+2; -4.5	*	+5; -∞	+5; -∞	
20	±3	±2	*	±3	±3	
25	±2	+2; -1.5	*	±3	±3	
31,5	±1.5	±1.5		±3	±3	
40	±1.5	±1	*	±2	±2	
50	±1.5	±1	*	±2	±2	
63	±1.5	±1	*	±2	±2	
80	±1.5	±1	*	±2	±2	
100	±1	±1		±1.5	±1.5	
125	±1	±1		±1.5	±1.5	
800	±1	±1		±1.5	±1.5	
1 000	0 [b]	±0.7 [c]	*	0 [b]	±1 [c]	*
1 250	±1	±1		±1.5	±1.5	
4 000	±1	±1		±3	±3	
5 000	±1.5	±1.5		±3.5	±3.5	
6 300	+1.5; -2	+1.5; -2		±4.5	±4.5	
8 000	+1.5; -3	+1.5; -2.5	*	±5	±5	
10 000	+2; -4	+2; -3	*	+5; -∞	+5; -∞	
12 500	+3; -6	+2; -5	*	+5; -∞	+5; -∞	
16 000	+3;-∞	+2.5; -16	*	+5; -∞	+5; -∞	
20 000	+3;-∞	+3;-∞		+5; -∞	+5; -∞	

a) The tolerances from 160 Hz to 630 Hz and from 1600 Hz to 3150 Hz have not changed from 60651 to 61672

b) Tolerance limits were 0 dB at the reference frequency as the design goal was in terms of sound levels relative to the sound level at the reference frequency, assumed to be 1 kHz for this purpose.

c) In 61672 the tolerance limits are nonzero as the design goal frequency weightings are relative to the unweighted sound pressure level at the position of the microphone on the sound level meter, but in the absence of the meter.

3.5 Display Linearity. In IEC60651 linearity requirements were based on the available technology of the time and included provision for range changing. Display linearity errors arise from the inability of the detector/squaring circuit or the display circuit to provide a linear display of the sound pressure level at the microphone. The requirement in 60651 was for an indicator range of at least 15 dB with at least 10 dB specified as a “primary” display range. Within those ranges 2 sets of tolerances applied, firstly for increments between 1 and 10 dB within the primary range, (±0.2 dB to ±0.4 dB for Type 1) and secondly, outside the primary range for any signal the tolerances were increased (±1.0 dB for Type 1). Where any range changing, automatic or manual occurred, the tolerance was ±0.7dB within the primary range.

In IEC 61672 these requirements have been clarified by a requirement for a defined reference range with linear operating span of at least 60 dB at 1 kHz for either class of instrument. These requirements are intended to apply from 16 Hz to 16 kHz for Class 1 sound level meters and from 20 Hz to 8 kHz for Class 2. A maximum error of ±0.8 dB (±1.1 dB for Class 2) applies to any range and includes errors introduced by range controls. On a linear operating range, errors for changes in input signal of from 1 dB to 10 dB must not exceed ±0.3 dB for Class 1 or ±0.5 dB for Class 2.

3.6 Time Weighting and Tone Burst Response. There was a clear separation between Time Weighting and Integrating/Averaging functions in IEC 60651 and IEC 60804 with L_{Aeq} (equivalent continuous) as the prime metric and S_{EL} (dose) derived from L_{Aeq} in terms of time. Specifications for Time Weighting and Integrating have been brought together in IEC61672 under the title "Toneburst Response" and the Table 3 is reproduced below. The terminology has been clarified and L_{AE} (S_{EL}) has now become the prime metric.

The quantity L_{AT} (L_{Aeq}) is specified under the heading "Response to repeated tonebursts" in terms of the difference δ_{ref} between the theoretical time-average sound level of a sequence of N tonebursts extracted from a steady signal and the time-average sound level of the steady signal as: $\delta_{ref} = 10 \lg(NT_b/T_m)$ where
T_b is the toneburst duration and
T_m is the total measurement duration, both in seconds.

For L_{AT} the tolerances from the Table 3 above are used. Thus the emphasis has changed to be time independent for L_{AE}. This does not, as has been feared, remove L_{AT} (L_{Aeq}) from the specifications in 61672 which apply for an electrical signal at toneburst durations from 0.25 ms to 1 s. IEC 60804 as amended required a minimum toneburst duration of 1 ms.

Table 3

Reference 4 kHz toneburst responses and tolerance limits including maximum expanded uncertainty of measurement

Toneburst duration, T_b ms	**Reference 4 kHz toneburst response, δ_{ref}, relative to the steady sound level** dB		**Tolerance limits** dB	
			Class	
	$L_{AFmax} - L_A$ $L_{CFmax} - L_C$ **and** $L_{ZFmax} - L_Z$**; Eq. (15)**	$L_{AE} - L_A$ $L_{CE} - L_C$ **and** $L_{ZE} - L_Z$**; Eq. (16)**	**1**	**2**
1 000	0.0	0.0	±0,5	±1.0
500	-0.1	-3.0	±0.5	±1.0
200	-1.0	-7.0	±0.5	±1.0
100	-2.6	-10.0	±1.0	±1.0
50	-4.8	-13.0	±1.0	+1.0-1.5
20	-8.3	-17.0	±1.0	+1.0-2.0
10	-11.1	-20.0	±1.0	+1.0-2.0
5	-14.1	-23.0	±1.0	+1.0-2.0
2	-18.0	-27.0	+1.0-1.5	+1.0-2.5
1	-21.0	-30.0	+1.0-2.0	+1.0-3.0
0,5	-24.0	-33.0	+1.0-2.5	+1.0-4.0
0,25	-27.0	-36.0	+1.0-3.0	+1.5-5.0
	$L_{ASmax} - L_A$ $L_{CSmax} - L_C$ **and** $L_{ZSmax} - L_Z$**; Eq. (15)**			
1 000	-2.0		±0.5	±1.0
500	-4.1		±0.5	±1.0
200	-7.4		±0.5	±1.0
100	-10.2		±1.0	±1.0
50	-13.1		±1.0	+1.0-1.0
20	-17.0		+1.0-1.5	+1.0-2.0
10	-20.0		+1.0-2.0	+1.0-3.0
5	-23.0		+1.0-2.5	+1.0-4.0
2	-27.0		+1.0-3.0	+1.0-5.0

NOTE 1 For the purpose of this standard and for conventional sound level meters, reference 4 kHz toneburst response δ_{ref} for maximum time-weighted sound levels shall be determined from the following approximation

$$\delta_{ref} = 10 \lg\left(1 - e^{-T_b/\tau}\right) \quad (15)$$

where T_b is a specified duration of a toneburst in seconds,
τ is a standard exponential time constant specified in 5.7.1, and
e is the base of the natural logarithm.
Equation (15) applies for isolated 4 kHz tonebursts.

NOTE 2 For the purpose of this standard and for integrating and integrating-averaging sound level meters, reference 4 kHz toneburst response δ_{ref} for frequency-weighted sound exposure levels is determined from the following approximation

$$\delta_{ref} = 10 \lg\left(T_b / T_0\right) \quad (16)$$

where T_b is a specified duration of a toneburst in seconds, and
T_0 = 1 s is the sound-exposure reference duration.

NOTE 3 Reference 4 kHz toneburst responses in table 3 are valid for the A, C, and Z weightings. Other frequency weightings may have other reference toneburst responses.

3.7 Peak C Sound Level. In 60651 the performance specification was for a test of the onset time (charging time) of the peak detector (unweighted) and which was specified to be less than 100 µs for Type 1. In practice the actual onset time varies from meter to meter from 10 µs to over 50 µs and the unweighted peak response to an acoustic event using unweighted Peak (Flat) may vary widely between individual sound level meters meeting Type 1 specifications in the presence of infrasound or high audio frequencies. IEC 61672 has adopted C weighting for the Peak design goal which is demonstrated by response to a single cycle input signal at 31.5 Hz, 500Hz and 8 kHz with additional tests using positive and negative ½ cycles of 500 Hz. The response in these cases is compared to the steady signal from which the single or ½ cycle signals are extracted. This approach will lead to consistent measurement of common events with individual instruments meeting the design goal.

It could be claimed that this will not allow correct measurement of events such as blasting overpressure or highly impulsive noises; this was always a potential problem with 60651.

3.8 Time weighting I (impulse). It has been found by the working group that time weighting I is not suitable for rating impulsive sound with respect to loudness hence it is not recommended for use in assessing the risk of hearing impairment. The design goal for time weighting I has been placed in the standard as an informative Annex since I weighting is still referenced in many documents.

4. Conclusion

The new IEC61672 standard will ensure that sound level meters built to its design goals will have enhanced and more consistent performance than under the older standards. If the Australian community adopts IEC61672 as an Australian standard then an ideal opportunity will arise to resolve the present hiatus involving pattern approval of noise measuring equipment.

5. References

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PROFILING LISTENERS

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Abstract

Our policies concerning noise depend on how we understand our populations of exposed persons to react to noise. Similarly our criteria with respect to other aspects of acoustics - e.g. auditorium and hall design - depend upon what we believe our audiences to want. However, humankind is likely to be in continuous evolution with respect to its tastes, preferences and sensitivities. Consequently our policies and criteria need to be constantly under revision based on continuing research. At the same time the validity of basic premises with respect to sound and noise need to be regularly reviewed.

In our work we have questioned why policy makers have felt no need to establish a formal and scientific definition for NOISE. Similarly we have questioned whether teaching and research in Concert Hall design is acknowledging the continuously evolving nature of both "popular" and classical music and music making.

With the aims of (1) establishing the needs of modern day public performance venues, and (2) proposing a more scientific basis for noise policies, we have carried out surveys and experiments on listeners designed gather data on the listening habits and preferences of music consumers, and to investigate possible links between attention and noise sensitivity and the physiological responses of persons exposed to sound. Findings from this work will be presented.

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LOW FREQUENCY NOISE ANNOYANCE – WHY?

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Abstract
In some situations, people complain about annoyance due to a noise and it is found that the A-weighted SPL does not correlate with the perceived annoyance. Why is this? We know that, in general, the A-weighted SPL does correlate with Loudness. But with respect to Annoyance, at low frequencies (ie below 100 Hz), that relationship breaks down. This implies that other factors are at play. What are these factors? What do we know about these? Some recent research into the assessment of rumble due to HVAC noise does provide some clues. The current results will be discussed

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Low frequency noise control - the next step for noise control and management?

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Abstract
Low frequency noise problem has largely been ignored or avoided because of the extensive use of the dBA weighting in noise measurement and assessment, as well as the difficulties in reducing it by the traditional noise control methods. As a result, low frequency noise becomes an environmental and industrial pollutant of increasing importance. Recent studies revealed that the low frequency noise could be as harmful and annoying as high frequency noise, and should not be underestimated. This problem has already attracted the attention from World Health Organisation (WHO) and other important occupational and environmental organisations, where the research and control of low frequency noise have been recommended. Furthermore, a new technology of active noise control has been developed very fast recently, which is very effective at reducing the low frequency noise. The management and control of low frequency noise are very likely the next major step in the area of noise control. The recent development on the research of the low frequency noise and the active noise control will be addressed in this paper.

Introduction

Low frequency noise (LFN) is commonly defined as the noise with frequencies below 500Hz. It has posed serious problems to occupation health and safety, and environment protection, but has not been addressed properly. Traditionally, the A-weighted sound pressure level (or sound power level) is used to qualify the noise emission from noise sources and to assess the noise impact on human. The adoption of the A-weighting scale is originally due to that the effect of the noise on human is entirely focused on the hearing-loss and the A-weighting filter network matches well with the equal loudness contour of human ears. However, the A-weighting measurement significantly weights down the level of low frequency noise. For example, 100 dB noise at 30 Hz is weighted down to 60 dBA. As a result, the LFN and its effect have largely been underestimated and ignored.

On the other hand, the control of LFN is extremely difficult. It is well known that the traditional noise control measures, such as noise absorption, noise insulation, and noise barriers, are all very ineffective to LFN. In addition, LFN attenuates much slower in the transmission than high frequency noise does. For instance, the transmission attenuation due to atmospheric absorption is over10 dB per 1000 m for the noise of 2000 Hz. However, it is only about 0.1 dB/1000 m for the noise of 63 Hz. The low frequency noise is much more penetrating, and travels much farther than the high frequency noise. This is why noise complaints from LFN are increasing.

More and more evidences have shown that low-frequency noise can be as harmful as high-frequency noise, and its effect on human is not limited to the resultant of hearing loss. Recent research has shown that LFN has a significant impact on both physical and mental health issues of human and should not be underestimated. There are many cases with LFN, in which even though the A-weighted noise levels comply with the relevant noise regulations, the noise complaints still exist. It is reasonable to conclude that A-weighting scale may not be a good indicator for the LFN impact. WHO and other major occupational and environmental hygiene organisations have recommended the research on the LFN - its impacts and its assessments.

Meanwhile, a new technology of active noise control has been developed very fast recently, which is most effective at controlling the LFN. The occupational and environmental requirement and the new technology of active noise control have made the LFN control and management necessary and practical. It is very likely that the LFN control and management will become a major area of noise control in the near future.

This paper reviews the recent development on the research and management of the LFN, and the authors' experiences with LFN problem in their active and passive noise control researches.

Low Frequency Noise Impact

Many sources in the industrial and living environment radiate noise with a dominant proportion of low-frequency components, such as ventilation systems, fans, heat pumps, diesel engines, pumps and compressors. Other major low frequency noise sources in daily life include road vehicles, subways, rail traffic, and aircraft. The booming musical entertainment at nightclubs and taverns also contributes to the low frequency pollution. Due to its efficient propagation and reduced efficiency with traditional control techniques, LFN is becoming the major noise pollution in both living and occupational environments. It has been found the complaints of LFN comprise over 70% of the total number of complaints of noise in an urban environment[1].

Most of the machinery engine noise in industries is also predominantly LFN. For instance, noise emissions from the machinery and equipment in Western Australia's mining industry are mostly low frequency in nature or at least having strong low frequency components. Similar conclusion is also reported in US's mining industry[2] and Canada's energy industry[3].

More and more evidence has shown that LFN can be as harmful as high-frequency noise. It has both physiological and psychological influences on human. Berglund et al. reports that intense LFN appears to cause symptoms like respiratory impairment and aural pain[4]. Branco et al. studied a systemic disease developed as a result of long-term exposure to intense LFN, namely vibroacoustic disease, using small mammals and humans[5]. Their conclusions strongly suggest that long-term exposure to high level noise at a frequency spectrum below 500Hz (conditions prevalent in many industrial settings) is likely to lead to pathological sequelae to the cardiorespiratory system and the central nervous system, as well as to the immune system. Branco also studied the LFN impact on the respiratory system using human and animal models, and found the evidence of the respiratory pathologies in LFN exposed workers[6]. Yamada et al. investigated the physiological and psychological influences of LFN on human. Their findings clearly showed that the low-frequency exposure increased heart and respiration rates[7]. There are reports that LFN produces even higher hearing losses than medium or high frequency noises[8].

Psychological influences of LFN have mostly been reported by the prevalence of annoyance, which results in the disturbance of sleep, rest and concentration, as well as headaches[1]. It has found that it took longer time to fall asleep and it was easier to be irritated in the morning when the LFN was present[9]. The reduced work performance and quality due to LFN was reported by Waye et al. when they studied the effect of low frequency ventilation noise[10]. They also reported the tiredness caused by the LFN exposure at work[11]. Studies also showed that speech intelligibility might be reduced more by LFN than other noises expect those in the frequency range of speech itself[1].

Low Frequency Noise Evaluation and Management

The management of LFN is based on the adequate evaluation of low frequency noise impact. As mentioned previously, one of the major reasons that the LFN problem has long been ignored is the extensive use of A-weighted noise level to assess the noise impact, which weighs down much of the low-frequency components. More and more evidences show that the A-weighted noise level is not a good indicator of noise pollution, especially when prominent low-frequency components are present. Take the noise from a primary crusher at a Western Australia's mining site as an example. The noise is dominated by very strong low frequency components, as shown in Fig. 1. The overall sound pressure level can be reduced by about 30 dB if the noise components lower than 125 Hz are removed. However, the A-weighting scale keeps almost unchanged, as indicated in Fig. 1. It is hard to imagine that the annoyance of these two noises is the same!

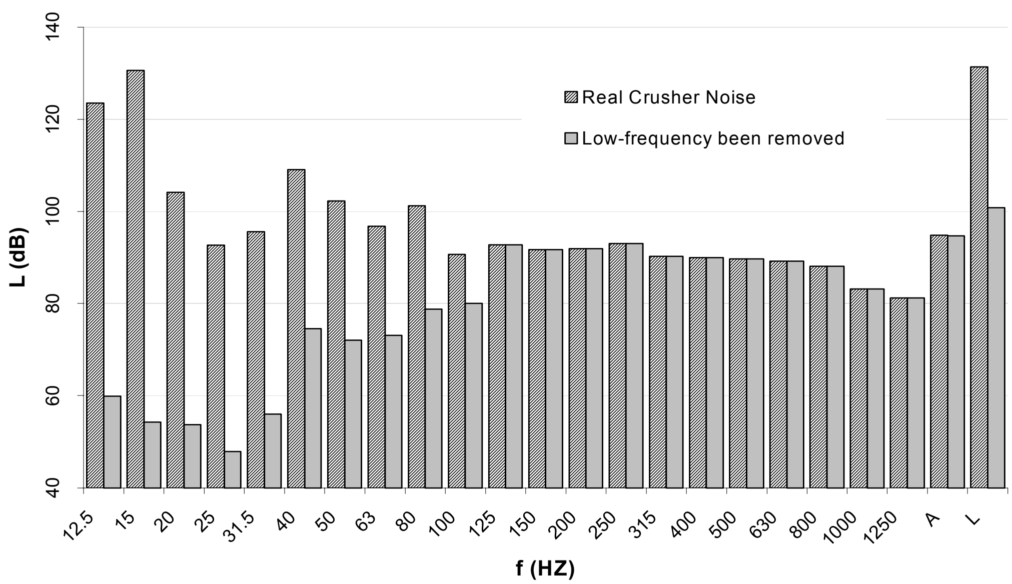

Figure 1. A primary crusher noise before and after LFN removal.

In fact, there are more and more reports that the loudness judgments and annoyance reactions are sometimes greater for LFN than other noises for equal sound pressure level[4]. Sometimes, a decrease in dBA level even produces an increase in loudness – due to low frequency components[12]. In many environments with LFN, even though the noise levels in dBA are within noise limits for the residents, the complaints still occur[1]. A very recent study in Hong Kong found that low-frequency music noise caused numerous complaints even when its contribution made the overall background noise level increased by 1 dBA[13]. It has been found that A-weighting can not correctly assess the aircraft noise impact, where the noise at low frequencies (<100 Hz) plays important role. The evaluations using C-weighting or 1/3 octave low frequency bands have been proposed[14-16]. Some other recent studies indicated that A-weighting is also not appropriate to reflect the annoyance caused by the road traffic noise[17], or the impact of the industrial noise on the adjacent residents[3].

It has been concluded that noise control, building and rebuilding of new acceptable environments, or other types of measures against the LFN problems cannot be based only on evaluations of the dBA or other simple rating alternatives[18]. When the noise is dominated by LFN, an alternate measurement method to A-weighting is required[15-19]. Although the LFN evaluation has already been extensively studied, further efforts to set up the appropriate evaluators for LFN in different noise conditions are still necessary[20].

There is a tendency of inclusion of LFN in noise management and the relevant guidance and regulations. World Health Organisation and some major US occupational hygiene organisations (NIOSH and MSHA) recommended the research on the health effects of low-frequency components in noise and vibration[2,19]. Some industries, such as Alberta Energy & Utilities Board in Canada, have started to regulate the LFN in their Noise Control Directives[3]. Some local authorities have also started to regulate the LFN in their environments[21]. A model community noise ordinance standard governing the LFN is also under development by the American National Standards Institute[22]. It is expected that the LFN management will be a must in all areas of industrial and environmental noise control in the near future.

Low Frequency Noise Control

Recently, a new technique of noise control, active noise control (ANC), has been developed and is attracting more and more research and application. This technique involves using noise to cancel existing noise, and is becoming another useful option of noise control. A very important advantage of this new technology is that it is particularly effective for LFN, which is very difficult to be controlled by traditional engineering control methods. This character of ANC provides a very good tool in controlling the LFN that is increasingly polluting our living and working environments.

Although the principles of active noise control have been known and intensively explored for several decades, its practical applications have become possible by the recent progress in control theory, the invention of adaptive signal processing, and the sufficient insight into the properties of sound fields. Some of the practical applications of this technique were summarized recently by Tichy[23]. They include: (1) noise control in ducts and pipes - such as active silencer for the noise of power plants and combustion engines, high temperature gas silencer, locomotive silencer, etc; (2) noise control in enclosures - such as active noise control in aircraft cabins, in helicopter cabins, in automobile cabins, etc; (3) noise control in open space - such as active control of transformer noise and airport run-up noise, and active noise barriers; (4) noise insulation - such as the reduction of transmission loss of the lightweight partitions, double-glazed windows, and fuselage structures using ANC techniques; and (5) active headsets. It can be expected that there will be more and more practical applications of ANC to LFN problems.

However, the promotion of ANC application depends on the appropriate assessment of LFN impact, as well as the relevant criteria and regulations governing the LFN. Although the subjective benefits of ANC have been revealed[24], the efficiency of ANC becomes very insignificant if only judged by the A-weighted noise level. One example is the active control of propeller aircraft run-up noise at Vancouver Airport. The noise contains strong low frequency tonal components, with the fundamental frequency of 110 Hz and its harmonics, as shown in Fig. 2. Our three-channel ANC system was able to tremendously reduce the first three tonal peaks in the experiments - from 15 to 20 dB[25]. The significant difference was perceived when the ANC system removed the annoying low frequency components. However, if measured with A-weighting scale, the overall level was reduced by only one dBA - the difference that should hardly be detected by human ear.

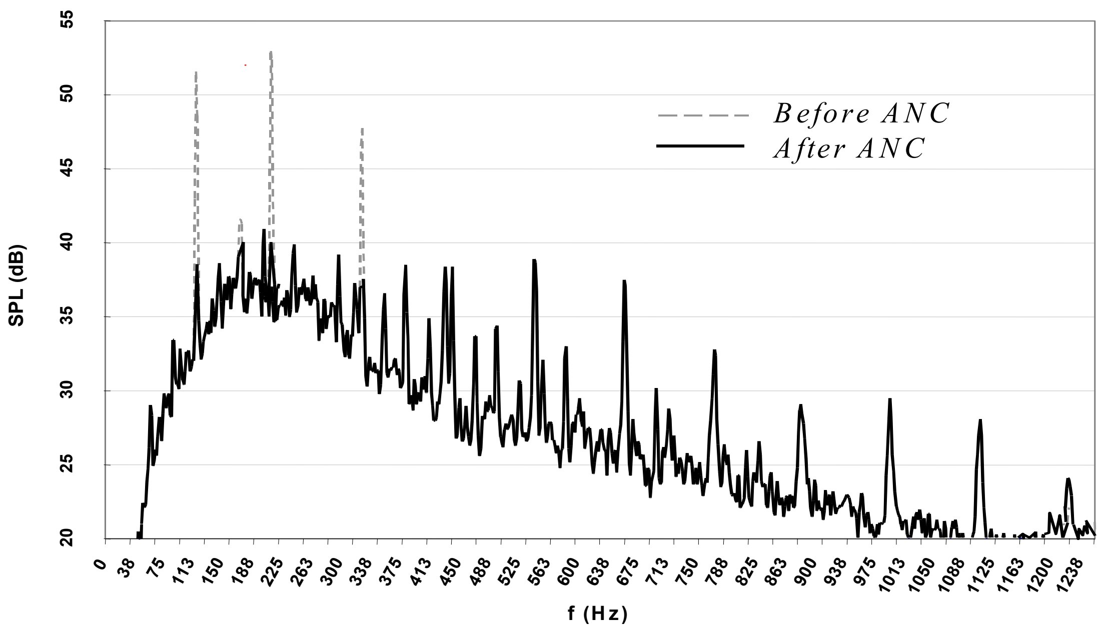

Figure 2. Propeller aircraft run-up noise before and after ANC.

A similar situation occurred when we applied an ANC system to reduce the truck cabin noise of Western Australia's mining industry[26]. The noise was also dominated by low-frequency components, in which most of the noise energy was in the frequency range lower than 200 Hz. The ANC system successfully attenuated the tonal noise at frequencies lower than 200 Hz, which made the overall sound level reduced by over 10 dB and the cabin environment much less annoying. However, when assessed with A-weighted level, the difference was only about 2-3 dBA!

Conclusions

The problem of LFN has become more and more apparent, and needs to be managed. A new technique for controlling LFN – active noise control – is getting into the stage of practical application. It is expected that the study of LFN impact, its evaluation, management measures and control, will become the frontier area of noise control and management in the near future.

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Brake Related Noise &Vibration: Review

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Abstract
A vehicle brake system has to meet the customer's requirement for performance, durability and comfort. In recent years, brake related noise and vibration has become an issue of growing concern to the automotive industry, especially to the brake and friction material suppliers and has become a significant source of customer dissatisfaction and of warranty cost. Brake N&V comfort issues may arise from actuation system or base brake system and the most common ones are low frequency shudder, hum, groan, moan and squeal etc.

Brake shudder (roughness) is a forced vibration phenomenon excited by braking torque variation. The excitation frequency is an integral multiple of the disc rotation speed and the effect is amplified by the resonances of suspension and steering system. The torque variation is caused by the variations in rotor thickness, interface friction level and clamping force. Drivers sense shudder through brake pedal (pulsation), steering wheel, seat assembly, floorboards as well as through visual inputs. In addition to these, some irritating hum noises can also be generated. Groan is a semi-resonant vibration with frequency typically less than 100Hz as results of stick-slip or instability due to a decreasing friction with speed. The predominant vibration modes are caliper rigid body rotation and local suspension parts. Hum and moan noises are similar to groan noise as discussed above and has a frequency typically in the range of 200 to 500 Hz. It also involves rigid caliper and some local suspension modes of vibration. It is associated uneven pressure distribution between pad and rotor as results of installation, tapper wear etc and occurs mostly under brake-off.

Brake squeal is a tonal noise generated by the self-excited, unstable and resonant vibration of the brake system. This unstable vibration is triggered by the rubbing action of friction pads on the rotor during braking and is a phenomena related to a noisy irritant created by stick-slip similar to the noise associated with a piece of chalk scratching a blackboard. Squeal frequency may be as low as 1kHz and as high as far above human hearing range. The noise is transient and chaotic and may last through the whole stop or may just be a chirp at the beginning and the end of stop. Squelch is a type of high frequency squeal, but is characterised by amplitude-modulated waveform. When the amplitude modulation is not constant, the noise sounds subjectively like "wire brush" and looks like a non-resonant vibration.

Thus, it is the aims of this paper to:
(a) Introduce various types of brake related N&V Australian N&V researchers and engineers
(b) Explain some of the difficulties in tackling brake N&V
(c) Review some of analytical, experimental and numerical methods used to solve some of the issues.

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Vibration Analysis of a Disc Brake System

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Abstract

Brake squeal is a major concern associated with the disc brake systems currently used on motor vehicles. During squeal, the brake system is in a resonant and unstable vibration mode. Brake squeal characterisation and understanding is complicated by the fact that it is a transient phenomenon, and that the system is also assembled from many components with complex and varying interface conditions.

Research is currently being undertaken at ADFA in order to understand the vibro-acoustic behaviour of brake squeal. Experimental modal testing and finite element analysis (FEA) techniques have been applied to a brake system. The paper discusses the effects of coupling between brake components and presents the steps involved in developing a validated FEA model of an assembled brake system. This validated finite element model will be used in the next phase of research to study the effects of friction coupling and the prediction of squeal propensity.

1. Introduction

A major problem for automotive N&V (noise and vibration) engineers is brake squeal. Many decades of research have failed to provide a complete understanding of the problem or the methods to predict it completely [1-3].

This paper outlines a structured approach to understanding the modal vibration characteristics of disc brake components and assembly. Modal testing has been conducted on the individual components at free conditions and also on the assembly to determine the modal properties. The following component and assembly modal characterisations are presented in this paper:

(1) free-free modal analysis of rotor, pad, anchor and caliper,

(2) the rotor mounted on the hub without the brake caliper,

(3) the complete brake assembly without any line pressure, and

(4) the complete brake assembly with 2 MPa brake line pressure applied.

By varying the boundary conditions in this way, the effect of coupling between various components on modal frequencies and damping can be assessed. With the aid of experimental modal testing, a FEA model of the assembled brake was developed. This validated finite element model will be used in the next phase of the project to study the effects of friction coupling and the prediction of squeal propensity for an entire brake system.

2. Brake System Description

The "drum in disc" rear brake assembly being studied is typical of many modern disc brake assemblies featuring a "fist" type caliper as shown in Figure 1. Figure 2 shows the six components of the brake assembly, comprising the rotor, anchor bracket, caliper, pins, piston and pads. The rotor is a drum-in-disc type with the friction surface for the park brake incorporated on the inner section of the disc. When hydraulic pressure is applied to the piston the inner pad is forced against the brake rotor. The caliper itself "floats" on the pins and moves away from the rotor due to the reaction force. Fingers on the caliper force the outer pad into contact with the other side of the rotor clamping it between the pads and causing a braking torque.

3. Modal Testing

3.1 Experimental Set-up

The first step of modal analysis is to obtain Frequency Response Function (FRF) measurements for the test component. FRF measurements were made with a Brüel & Kjær type 2032 FFT analyser using a Brüel & Kjær type 4374 uni-axial accelerometer, Brüel & Kjær type 8001 impedance head and Brüel & Kjær type 2635 charge amplifiers. The excitation was provided with a Brüel & Kjær type 4810 shaker with a random noise signal generated by the FFT analyser. The signal was amplified with a Brüel & Kjær type 2706 power amplifier. A Hanning window with 50 averages was used for each FRF. A detailed description of modal testing procedures is given by Ewins [4].

To improve the frequency resolution available from the FFT analyser, baseband random noise excitation was used between 0 and 6.4 kHz, and zoom random noise excitation between 6.4 and 12.8 kHz. This resulted in a resolution of 8 Hz for 800 samples in each frequency band.

Testing of the individual components required free boundary conditions. This was implemented by placing the components on a sheet of foam insulation during the testing. The natural frequency of the foam mat was much lower than the lowest natural frequencies of the components, so coupling between the test component and base support was negligible. FRF measurements were made for the major components; the rotor, brake pads, caliper housing and anchor bracket.

Analysis of the experimental data was conducted with STAR Modal v 5.23, a commercial modal analysis software package [5]. STAR Modal uses a curve-fitting process to determine the modal parameters for the modes contained within FRF data. Five curve-fitting methods are available - Coincident, Quadrature, Peak, Polynomial and Global. The Global method was most commonly used, but often several methods were used to check reliability of the fit method.

3.2 Component Grids

The grid for the rotor consisted of 384 points arranged along 48 lines of 8 points each radiating from the centre of the rotor at an angular spacing of 7.5° as shown in Figure 3. Measurements were taken in the r and z directions. Grids were generated over the surface of the other components. These consisted of 25, 65 and 36 grid points on the brake pad, caliper housing and anchor bracket respectively. Measurements for the other components were taken in all three spatial directions where possible.

3.3 Assembled Brake System

In an effort to try and simulate the conditions experienced by an operating brake, the complete brake assembly was tested. The four previously mentioned configurations were used. The assembly was mounted on small feet and was isolated during testing by a foam mat. Again, the frequency range of interest was 0 to 12.8 kHz.

4. Modal Testing Results

4.1 Individual Components

Modal testing of the individual components was conducted for the frequency range from 0 to 12.8 kHz. Table 1 is a summary of the modal frequencies for the pad, anchor bracket and caliper housing. Each of these frequencies corresponds to a vibration mode for the component. Coupling between components can arise when two or more components have the same or similar modal frequencies. For example, the caliper housing and the anchor bracket have individual vibration modes at 3120 and 3170 Hz respectively. These modes increase the likelihood of the assembled brake system having a vibration mode close to this frequency.

Table 1: Modal frequencies for the individual brake system components.

Modal Frequencies (Hz)						
Pad	Caliper Housing		Anchor Bracket			
2340	2810	8580	890	3260	7280	9970
5180	3120	9170	1020	4340	8020	10510
6190	3790	10240	1200	5290	8180	10870
7450	4420	10900	1710	5940	8670	11230
7760	6310	11580	2810	6610	8920	12370
10080	7500	12710	3170	6830	9170	12460
	8330					

4.2 Assembled Brake System

Table 2 shows a summary of the important bending and in-plane modes for the rotor in four experimental configurations. For each mode, the modal frequency, damping factor and normalised log magnitude are listed as determined using STAR Modal. The magnitude for each mode is the magnitude of the summed FRF data at the respective modal frequency. The values are shown as log values due the range of the data and are normalised to the first bending mode (2,0) of the free-free rotor.

The mode shapes are largely classified as either out-of-plane or radial in-plane. A pair of numbers (m, n) denotes the out-of-plane modes, where m and n indicate the number of nodal diameters and number of nodal circumferences respectively. Figure 4 shows a (3,0) out-of-plane mode shape. The radial in-plane mode shapes are denoted by the number of in-plane nodal diameters.

Three main trends can be seen as components were added to the test assembly: damping and frequency increased and the magnitude of the modal peaks decreased. The application of line pressure to the assembly had the strongest effect as all of the modes are damped significantly and the assembly did not vibrate in some of the modes present in the no pressure configuration. The odd order bending modes ((3,0), (5,0) and (7,0)) were found to be the most affected by the application of pressure. This effect is most likely due to an antinode located near the pads on the rotor surface. The 7^{th} bending mode (8,0) had the highest modal peaks for free-free condition, whilst he 6^{th} bending mode (7,0) was the strongest for rotor mounted on hub case and the 5^{th} (6,0) for both of the completely assembled configurations.

A comparison of the modal frequencies between the assembled brake system and the individual components is shown in Table 3. It can be seen that the modal frequency of the assembled system is largely governed by the vibration modes of the rotor. The modal frequencies of the individual components do not appear to greatly affect the assembled brake system. Measurements have not been taken on components other than the rotor in the assembled conditions, but it is suspected their modes are modified by the coupling due to the assembly.

Table 2: Summary of modal frequencies, modal damping and normalised log magnitude for the free rotor and the assembled brake system. The log magnitude (10log{mag}) is the summation of the FRF data at the modal frequency normalised to the first bending mode of the free rotor.

	Rotor free-free			Rotor mounted on hub		
Mode shape	Freq (Hz)	Damp factor (%)	log mag normalised dB	Freq (Hz)	Damp factor (%)	log mag normalised dB
2,0	994	0.37	0.00	1030	0.74	3.99
3,0	2430	0.18	11.83	2460	0.6	9.87
0,2	2550	0.22	3.38	2680	0.74	-9.14
1,1				3070	0.28	3.41
in-plane(2 nodal dia.)	2900	0.15	4.33	3150	0.36	5.32
4,0	3800	0.14	16.57	3810	0.15	16.93
2,2						
in-plane(3 nodal dia.)	4630	0.22	2.49	4680	0.21	2.27
5,0	5290	0.13	16.56	5280	0.16	20.33
6,0	6990	0.11	20.43	6980	0.091	21.29
in-plane(4 nodal dia.)	7120	0.12	-1.01	7170	0.14	-6.5
in-plane(side to side)	7840	0.17	-2.50	7840	0.26	-12.85
3,2				8480	0.28	-8.25
7,0	8900	0.11	25.45	8890	0.086	23
in-plane(5 nodal dia.)	10050	0.4	5.69	10120	0.15	1.34
3,2				10320	0.52	-12.9
8,0	10990	0.11	29.61	11010	0.23	16.46
in-plane with 2 dia				12040	0.1	-5.36
	Complete assembly - no pressure			Complete assembly - 2 MPa		
Mode shape	Freq (Hz)	Damp factor (%)	log mag normalised dB	Freq (Hz)	Damp factor (%)	log mag normalised dB
2,0	1060	1	-0.91	860	4.3	-11.01
3,0	2480	0.44	6.47	2690	1.7	-2.66
0,2	2680	1.6	-13.43			
1,1	3100	0.69	-5.07	3120	1.1	-11.56
in-plane(2 nodal dia.)	3160	0.63	0.9	3220	1.5	-13.24
4,0	3870	0.63	7.41	4050	1.6	0.34
2,2	4660	0.43	-5.38	4680	0.48	-4.87
in-plane(3 nodal dia.)	4720	0.45	-3.64	4810	1	-13.89
5,0	5330	0.36	11.25	5350	1.5	-1.19
6,0	7020	0.16	15.31	7020	0.61	5.03
in-plane(4 nodal dia.)	7180	0.2	-14.95			
in-plane(side to side)	7830	0.35	-18.8			
3,2	8490	0.35	-15.031	8460	0.82	-13.65
7,0	8910	0.14	14.33	9020	1.3	2.17
in-plane(5 nodal dia.)	10130	0.19	-7	10210	0.6	-11.65
3,2	10340	0.44	-18.42			
8,0	11050	0.28	10.62	11410	0.91	0.01
in-plane with 2 dia	12080	0.13	-12.02			

Table 3: Summary of the individual modal frequencies in comparison to those of the assembled brake system.

			Modal Frequencies (Hz)			
rotor mode shape	assembled no pressure	assembled 20 bar	rotor free-free	pad	caliper housing	anchor bracket
2,0	1060	860	994			890/1020
						1200
						1710
				2340		
3,0	2480	2690	2430			
0,2	2680		2550			
					2810	2810
1,1	3100	3120				
in-plane(2 nodal dia)	3160	3220	2900		3120	3170
						3260
4,0	3870	4050	3800		3790	
					4420	4340
2,2	4660	4680				
in-plane(3 nodal dia)	4720	4810	4630			
				5180		
5,0	5330	5350	5290			5290
						5940
				6190		
					6310	
						6610
						6830
6,0	7020	7020	6990			
in-plane(4 nodal dia)	7180		7120			7280
				7450	7500	
in-plane(side to side)	7830		7840	7760		
						8020
					8330	8180
3,2	8490	8460				
					8580	8670
7,0	8910	9020	8900			8920
					9170	9170
						9970
in-plane(5 nodal dia)	10130	10210	10050	10080	10240	
3,2	10340					10510
						10870
8,0	11050	11410	10990		10900	11230
					11580	
in-plane with 2 dia	12080					
						12370
					12710	12460

5. Finite Element Analysis

5.1 Simulation Approach

The commercial finite element analysis (FEA) program ANSYS 5.7 [6] has been used to model the entire brake system. However, rather than develop a complete model of the assembly in one step, individual components were initially modelled separately. This allowed the individual models to be validated or "tuned" without the complication of coupling between the components. The modal testing results were used in this validation process. Material properties including density, Young's modulus and Poisson's ratio were adjusted until results from the FEA simulation were in agreement with the experimental results.

The manufacturer of the components supplied the geometry of the components to ensure accuracy. The mesh for each of the components was refined to a level that provided a good balance between accuracy and computational cost.

5.2 Individual Components

The brake pad used in the brake system consists of moulded friction material bonded to a steel backing plate. Material properties of the steel were well known, but those of the friction material were largely unknown. Experimental results were used to "tune" the material properties of the friction material until there was agreement between the experimental and simulated modal frequencies (see Table 4).

Table 4: Summary of material properties for "tuned" FEA models.

Component	Material	Young Modulus, E (GPa)	Density, ρ (kg/m^3)	Poisson's Ratio, ν
Rotor	cast iron	118	7046	0.32
Anchor bracket	cast iron	170	7300	0.3
Caliper housing	aluminium	65	2550	0.3
Pad backing plate	steel	207	7860	0.3
Pad friction material		5	2550	0.3

Modelling of the caliper housing, anchor bracket and rotor was simpler in that they consisted of only one type of material. Models for these components were also "tuned" in the same way as the pad with the material properties shown in Table 4. Solid95 (20 node brick) elements were used for these components with 960 elements used for the caliper housing, 778 elements used for the anchor bracket, and 936 elements used for the rotor (Figure 5).

A comparison between the experimental and FEA modal frequencies for the rotor is shown in Table 5 and the mode shape for the 2nd bending mode is shown in Figure 6. It can be seen that modal frequencies fall within 3% of the experimentally determined values. Since the rotor modes dominate the vibration characteristics of the assembled brake system, it is important that the dynamics of the rotor be modelled accurately. Similar results were obtained for the other components, with a good level of agreement found between the FEA and experimental results.

Table 5: Comparison between experimental and FEA modal frequencies for the important rotor modes.

Modal Frequencies (Hz)					
Experiment	FEA	% error	Experiment	FEA	% error
994	977	-1.7	6990	6827	-2.3
2430	2381	-2.0	7120	7115	-0.1
2550	2603	+2.1	7840	7853	+0.2
2900	2981	+2.8	8900	8730	-1.9
3800	3712	-2.3	10050	10079	+0.3
4630	4666	+0.8	10990	10850	-1.3
5290	5157	-2.5			

6. Conclusion

As part of research into the vibro-acoustic behaviour of brake squeal, the vibration characteristics of a brake system have been investigated. Modal testing and finite element analysis techniques have been applied to the individual components of a brake system as well as the assembled system. It was found that modal characteristics of the brake rotor have the major affect on the assembled brake system in comparison to the other components. When additional components were included in the assembly both the modal frequencies and damping tended to increase. Significant damping and a reduction in modal peaks were observed when a typical braking pressure (2 MPa) was applied, with the effects being greatest on odd order bending modes.

Acknowledgment

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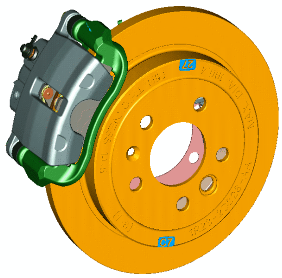

Figure 1: Rear brake assembly

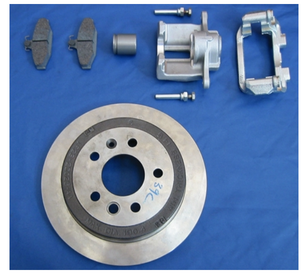

Figure 2: Brake system individual parts: (clockwise from top left) pads, piston, pins, caliper housing, anchor bracket and rotor

Figure 3: Rotor modal testing grid geometry (384 points).

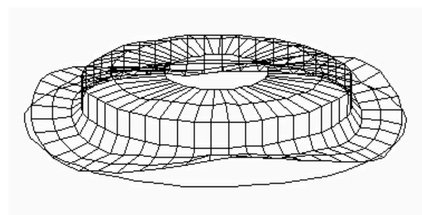

Figure 4: 2nd bending mode, (3,0) out-of-plane, of brake rotor

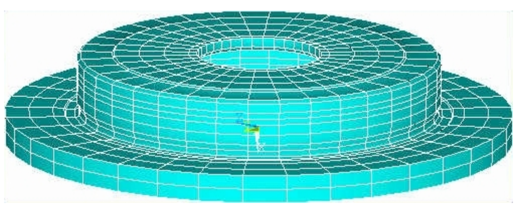

Figure 5: Rotor FEA geometry (936 elements).

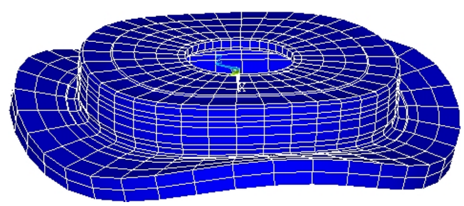

Figure 6: FEA 2^{nd} bending mode, (3,0) out-of-plane

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SUBJECTIVE AND OBJECTIVE EVALUATION OF BRAKE RELATED NOISE AND VIBRATION

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Abstract
Common brake Noise and Vibration (N&V) issues are shudder, groan, moan, squeal etc. Customer expectations of brake N&V is difficult to quantify. Therefore, the evaluation of the brake N&V quality of a vehicle has been very subjective and is a task which brake and vehicle makers have been heavily relying on trained test drivers. This is time and cost intensive, is limited in repeatability and is a subjective process. This paper will first review some of subjective practices commonly used by brake and vehicle manufacturers and then proposes an objective approach using psycho-acoustic parameters to objectively evaluate brake squeal noise.

1. Introduction

A vehicle brake system has to meet customer's requirements for performance, durability and comfort. In recent years, brake related N&V concerns have become an issue of growing concern to the automotive industry through increased customer dissatisfaction and warranty cost. Brake N&V comfort issues may originate from the actuation system and base brake system with the most common ones being shudder, groan, moan, rattle, squeal etc. Drivers hear the noises such as squeal, moan etc and sense vibrations such as shudder through the brake pedal (pulsation), steering wheel, seat assembly, floorboards as well as through visual inputs.

The most common brake N&V issue is brake squeal, which is a tonal noise generated by the self-excited, unstable and resonant vibration of the brake system. Squeal frequency may be as low as 1kHz and as high as above human hearing range. The noise is transient and chaotic and may last through the whole stop or may just be a chirp at the beginning and at the end of stop.

Customer expectations of brake N&V are difficult to quantify. Typical feedback from customers are statements such as "the brake feels rough", "the brake became noisy after I came back from a trip up to a mountain" etc. Obviously, these alone are not enough to develop objective metrics. In addition, the situation is further complicated in that different people have different perceptions or different tolerances to different noises. Human perception is as much about what we think we hear or feel, as it is about what we actually hear or feel. Thus, evaluating the brake N&V quality of a vehicle is a task which brake and vehicle makers have been relying on trained drivers. This process is time and cost intensive, limited in repeatability and is very subjective. There isn't a satisfactory method currently available to serve as a basis for comfort quality definition during the development of brake system. Furthermore, brake N&V also depends on operating conditions, history of usage and driver technique. Different drivers use brakes differently and may experience different N&V issues on the same car.

To overcome the repeatability and cost problems associated with the vehicle testing, the noise Dynamometer with environmental control capability has been developed and has proved to be a very useful tool to screen and develop countermeasures for brake squeal noise. However, developing a test matrix or sequence to be fully representative of typical customer usage and projecting the results to the customer's expectations has not been straight forward. It is complicated by the fact that the noise measured on the Dynamometer is not the same as perceived as in-situ due to masking effects of other noises in the car. Thus, it is not always possible to confidently tell the difference between two packages or two different countermeasures unless they are dramatically different in noise performance.

Most of the applied knowledge currently used in industries today is semi-empirical and based on results from years of experimental trial and-error studies. There is, therefore, an urgent need to develop a more precise and objective brake noise quality map for effective countermeasure development. This paper will firstly review some of the commonly used subjective and objective practices and secondly to propose a new objective approach based on human perception and brake usage conditions.

2. Brake N&V Testing and Subjective & Objective Noise Evaluation

2.1 Brake N&V durability test and subjective rating

Brake N&V depends on vehicle system set-up, environmental conditions and usage. Despite some advances that have been made in analytical techniques to predict brake squeal noise, it is still well short of being a predicative tool. Therefore, N&V validation is still conducted later in a development program after production intent hardware becomes available.

It has been common practice within the brake industry to use trained drivers to conduct brake system durability and N&V testing along pre-defined circuits such as in Los Angeles, Detroit, Mojacar, etc. These circuits are proprietary to each individual vehicle manufacturer, brake supplier and friction material supplier. Normally, the driver rates the brake N&V in the traffic as well as during evaluation along "quiet routes" based on his or her perception. Sometimes, instrumentation can also provide some objective measurements. Brake N&V design targets and acceptance criteria are often specified as in-vehicle subjective ratings. These rating scales are also proprietary to each company. Table 1 summaries some of the proprietary scales.

Table 1 Subjective N&V Rating Scale

	UNACCEPTABLE				BORDERLINE		ACCEPTABLE			
	1	2	3	4	5	6	7	8	9	10
Evaluation	POOR			CUSTOMER COMPLAINT	BORDERLINE	BARELY ACCEPTABLE	FAIR	GOOD	VERY GOOD	EXCELLENT
NVH Rating	NOT ACCEPTABLE			OBJECTIONABLE	REQUIRES IMPROVEMENT	MEDIUM	LIGHT	VERY LIGHT	TRACE	NO TRACE
Condition Noted By	ALL CUSTOMERS	AVERAGE CUSTOMERS			CRITICAL CUSTOMERS				TRAINED OBSERVER	NOT PERCEIVED
Procedure	REQUIRES ACTION				REQUIRES INVESTIGATION		ACCEPT			CHECK RESULTS

Using this scale, a typical design target for brake N&V performance on a vehicle is: "Brake N&V whilst evaluated on the Brake Durability Schedule shall have an average rating of at least xx during the standard portion of the test. No more than x% of ratings shall be less than x.x".

This approach has the following distinctive advantages:

- It is the actual "driver" who rates the noise based on his/her perception.
- The brake system is evaluated under in-traffic conditions.

The disadvantages are:

- It is a cost and time intensive process.
- The test is not repeatable (even the same driver along the same route).
- It is subjective and requires consistency from the driver.
- It is difficult to achieve consistency between different drivers and thus, the results may be disputable.

The other concern with this practice is that it is possible to mistakenly attribute the noise, which is actually coming from a nearby vehicle to the test vehicle. To overcome this, accelerometers can be placed on each caliper and a microphone within the cabin. Transfer function analysis or correlation analysis between the accelerometers and microphone can detect which brake generated the noise.

2.2 In-vehicle and Dyno testing and objective measurement

To overcome some issues with the above approach, an in-vehicle noise matrix following predefined speed, pressure and temperature pattern was initially developed to conduct repeatable noise screening at the proving ground.

However this test can only be conducted when representative vehicles become available. Therefore, noise dynamometers with climate control have been commonly used to screen squeal noise at a early stage of the development. Almost all vehicle manufacturers, brake suppliers and friction material suppliers use their own proprietary matrix. The two common ones are:

(1) AK matrix developed by the European brake working group
(2) SAE2521 matrix developed by the US brake working group

The results from a Dynamometer testing can be represented as:

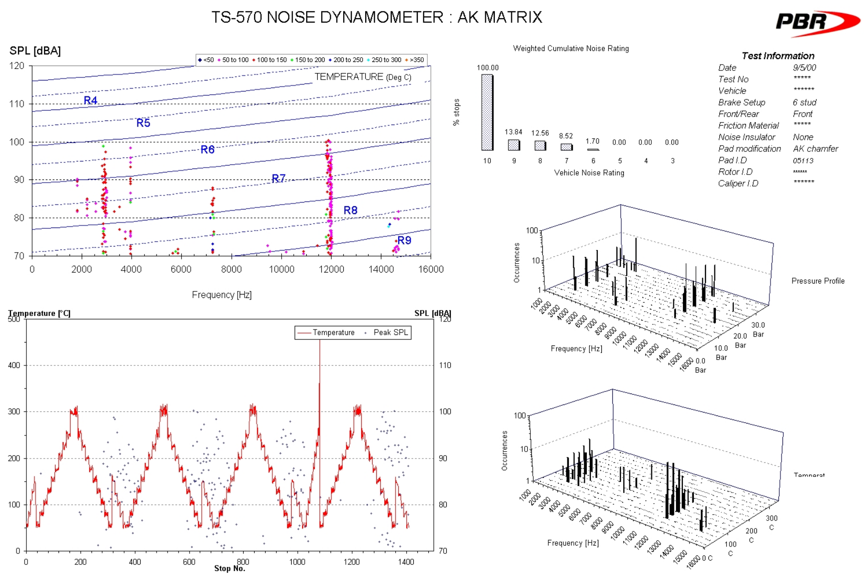


Figure 1 A typical test result from noise dynamometer

From these results, the following information can be obtained:

- SPL Vs frequency
- SPL & frequency vs temperature
- SPL & frequency vs pressure
- When the squeal noise occurred

On the one hand, this approach has the following advantages:

- The test environment and operating condition can be controlled very well so it is repeatable.
- The results are objective and less easily disputed.
- It only takes 24 hours to conduct one test, which is equivalent to about 10 days durability test.
- Only major suspension components are required.

On the other hand, this approach also has the following limitations:

- N&V issues, that are sensitive to vehicle setup such as shudder, groan etc are difficult to be evaluated.
- The test matrix normally does not represent the real usage and usage history (although some effort has been made to digitize some of the durability tests).
- The results are objective and it is difficult for a noise engineer to be confident that the system meets the subjective target.

3. Subjective vs Objective Evaluations

Many companies are making effort to convert the output from Dynamometer into some sort of noise indexes for comparative study. These indexes are then related to the subjective rating scale. Table 2 shows an example by grouping the noise into four levels based on the SPL. Different types of noise are then weighted differently when calculating the noise index.

Table 2: Noise Classification

Level	**Weight**	**Definition**	**SPL at 0.5m from rotor**
A	**W-1**	**Painful Noise**	**>Level-1 dBA**
B	**W-2**	**Unpleasant noise**	**Level-2 to Level-1 dBA**
C	**W-3**	**Bothering noise**	**Level-3 to –Level-2 dBA**
D	**W-4**	**Not-Bothering noise**	**<Level-3 dBA**

A noise index is then calculated by using the following formula:

$$\text{Noise Index} = \frac{\begin{array}{l}\text{No. of Level A noise x W-1} \\ \text{+ No. of Level B noise x W-2} \\ \text{+ No. of Level C noise x W-3} \\ \text{+ No. of Level D noise xW-4}\end{array}}{\text{Total No. of braking stops}}$$

Different companies have used different weights and formula. The noise index is then related to the subjective rating scale. Refer Table 3.

		Not	Acceptable		Borderline			Acceptable		
Subjective Rating	1	2	3	4	5	6	7	8	9	10
Noise Index		>=4	3.5 - 4.0	3.5 - 4.0	3.0 - 3.5	2.5 - 3.0	2.0 - 2.5	1.5 - 2.0	1.0 - 1.5	<=1.0

Table 3 Example: Noise index vs subjective rating scale

4. Proposed Approach

The approaches described in section 3 does not address the following complexities:

- Squeal type and duration: The duration of the squeal, whether it is continuous, cyclic and chirp at start or end of the stop influences the customers' perception and subjective rating of the brake in a vehicle.
- Operating conditions: The conditions (temperature, pressure) when squeal occurs also needs to be considered. A stop at 300 degree C is less likely to be experienced by a customer than a stop at 100 degree C and thus needs to be "weighted" accordingly along with the repeatability of the noise.

Furthermore, the SPL measured at the brake source is higher than that experienced by the actual driver in the cabin due to the effect of distance, background noise and masking effects. While 70dB at the brake source is commonly used for passenger vehicles, a cut-off point as high as 80 dB may be acceptable for a light truck.

The following sections propose a different approach following the sequence of:

- Transferring Dynamometer test data to in-vehicle test data
- Noise dose determination
- Development of weighting functions on temperature and pressure
- Correlation of noise dose and subjective in-vehicle rating
- Noise index development

4.1 Transferring Dynamometer noise measurement to in-vehicle noise

If we assume there is no distortion in frequency content, the reduction in dB level from brake to cabin can be estimated theoretically. This approach however, may not be able to take into account the effect of the background noise but it is feasible to conduct a series of in-vehicle noise tests to compare the difference in SPL in the cabin and next to the wheel. These tests can be conducted at various vehicle speeds and on different types of vehicle. The information obtained can be stored in a database to be used to convert the Dynamometer SPL to the level as perceived by the driver.

4.2 Determination of noise dose

Once the above data conversion is completed, the results from a controlled test matrix can be used to confidently to represent the brake's "noise signature" as perceived by the driver. Noise generated at each brake application contains information such as frequency, duration and SPL. This information needs to be transferred into a single value before sensible decisions can be made. Traditionally, recorded noise was played back to human volunteers in order to gather sound perception data or dose, a time consuming and subjective process usually requiring a group of representative people. However, it would also be feasible if some of the published standardized noise metrics could be used instead. The approach proposed here will predict human subjective reactions to the noise including frequency content, amplitude, sharpness, duration etc.

Noise Metrics: A noise metric is an attempt to quantify the complex characteristic of the human ear and human psychology. It is used to predict the impact of a noise on an average person. The now commonly accepted curves of equal loudness contours are shown in Figure 2.

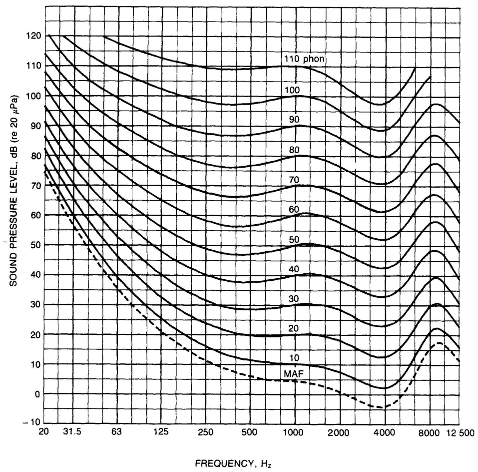


Figure 2 - Equal loudness contours (pure tones) [1]

The most basic metric is the A-weighting, which approximates the 40-phon line. However, it is not a good measure of loudness of complex sounds consisting of multiple tones or broad band noise. The equal loudness contours also do not reflect the subjective judgement of relative loudness. Hence, a second unit, the ‘sone’ was introduced. The 40 phon contour is labeled 1 sone and the 50 phon (2 sones) contour is judged twice as loud. Both the phone and sone can be referred as ‘noise dose’.

$$S = 2^{(P-40)/10} \qquad (1)$$

Stevens [2] introduced a method for calculating a loudness index. This is known as the Mark VI method which provides a quantitative measurement of the overall loudness, as well as the contribution of each octave band. This method is best suited for noises that are steady rather than intermittent. Zwicker [3,4] extended the above method with a hearing based method for noise measurement. This method calculates specific loudness and then total loudness. Whilst similar to the Mark VI method it accounts for the upward spread of masking and can be used with complex sounds with broad band and/or with strong line spectra. The following example shows results using a simple equal loudness calculation. Two candidate friction materials were assessed on the same brake system. The disc brake had a floating caliper design. The traditional SPL verses frequency distributions from the noise dynamometer for the two materials are shown in Figure 3 and Figure 4.

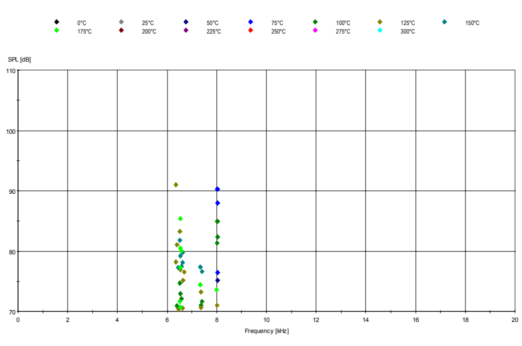


Figure 3 - Material A Noise Distribution

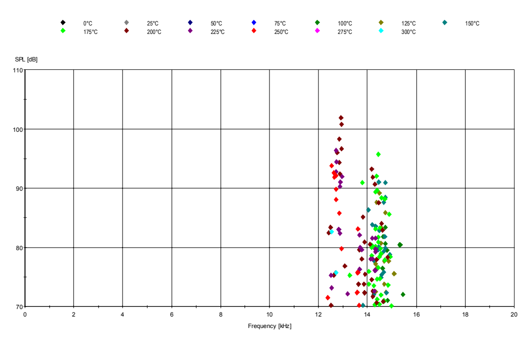
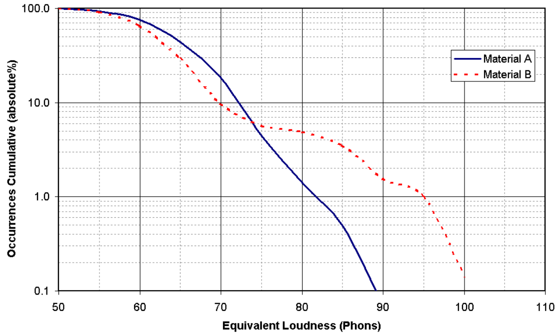


Figure 4 - Material B Noise Distribution

Material A had squeal between 6.5 and 8 kHz with a peak of 91dB at 6.4kHz. Material B had squeal from 12.5 to 15 kHz with a peak of 101 dB at 12.9 kHz. The equivalent loudness for these squeals can be read from Figure 2 with 98 Phones for material A and 97 phone for material B. Although material B has a noise at 12.9 kHz and Material A at 6.4 kHz with a 10 dB difference, they will both be perceived to be equally aloud. If the calculation is performed on all 1409 stops, a percentage % occurrence curve can be obtained for equivalent loudness as shown in Figure 5 (phones). Figure 6 shows the subjective loudness (sones).



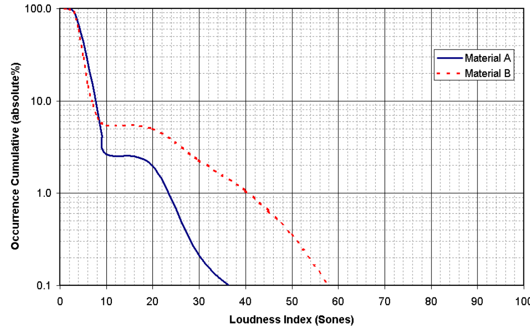
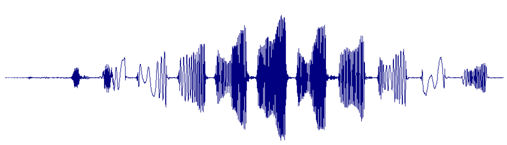


Figure 5 – Equivalent loudness occurrence.

Figure 6 – Subjective loudness occurrence.

The above curves show that material A has a better squeal performance than material B. This calculation assumes that the squeal was a pure tone at a constant level throughout the stop. However, a brake may squeal for only part of the stop either at the end or start and may induce multiple squeal frequencies. The Zwicker method, of calculating the specific loudness at each frequency band and then the total loudness can be used to deal with this situation. For example, Figure 7 shows a stop from a noise dynamometer test that had a cyclic noise as well as multiple frequencies, Figure 8. Both the Stevens and Zwicker method could be applied to the entire stop time to give a global noise dose. For example a value of 101.5 Phons is obtained using the Zwicker method and 108.4 using the Stevens Mark VI method. These calculations can be conducted on every stop and summarized accordingly.



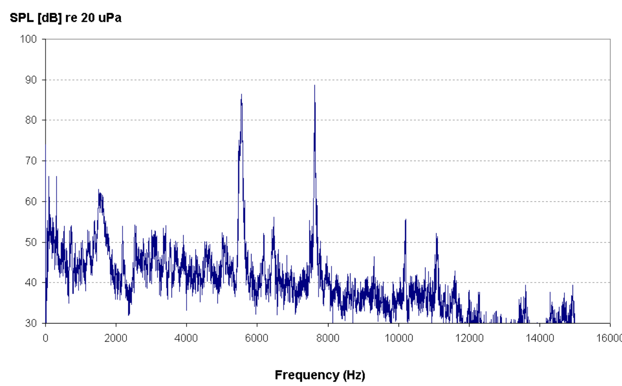


Figure 7 – Time history from squeal stop.

Figure 8 – Peak spectrum from a squeal stop.

4.3 Weighting function development for pressure, temperature, speed, repeatability etc

Most Dynamometer matrixes have been designed to screen noise events and do not fully represent the real customer usage such as vehicle speed, brake pressure and brake temperature. In order to take this into account, different weighting functions similar to those as shown in Figure 9 and Figure 10 can be applied to the noise dose determined at each brake application to give an equivalent noise dose/subjective noise dose.

4.4 Correlation between noise dose and in-vehicle subjective rating

In order to relate the N&V dose to the subjective rating scale used in Automotive industry, the noise dose defined by the sone can be used since it represents subjective loudness. One sone can be related to the subjective rating R10, ie not perceptible by the driver and 128 sones can be related to the subjective rating R1 – unbearable. The relationship between the sone and the subjective rating can be developed as shown in Figure 11. This relationship can be verified using trained evaluators and typical customers. The experimental methodology needs to cover an appropriate selection of assessors, assessment procedures, vehicle brands and right driving conditions.

4.5 Noise index development

Once the objective measurement from Dynamometer has been transferred into the in-vehicle subjective rating as described previously, the noise index can be calculated as the averaged subjective rating, which complies with the subjective design target.

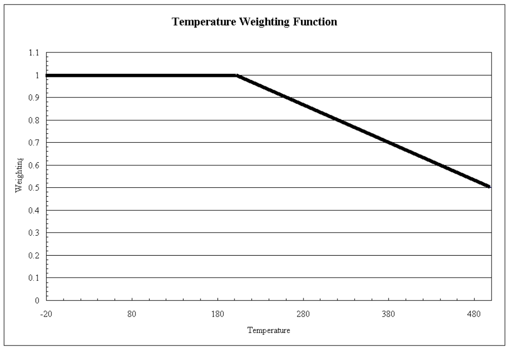


Figure 9 Temperature weighting function

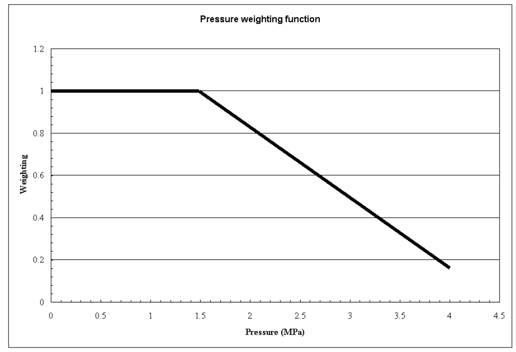


Figure 10 Pressure weighting function

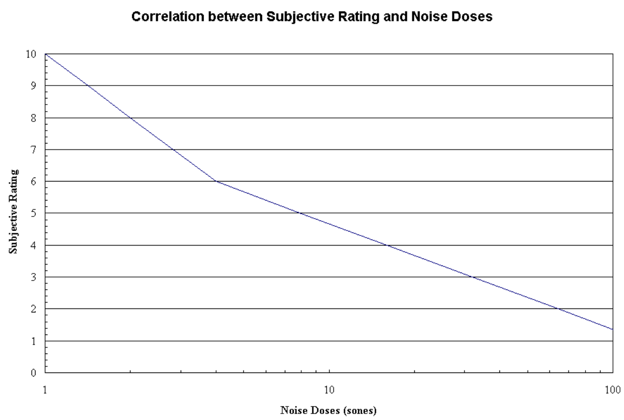


Figure 11 Proposed Relationship between Sones and Subjective Rating

5 Conclusions and Recommendations

- Many companies are starting to use models to convert the SPL from noise Dynamometer and Chassis Dynamometer tests to the subjective 1-10 rating, which normally is used in vehicle testing. Once this conversion has been made reliably many times, effort and money can be saved. It will be easier to choose which of two or more options will be perceived best by the final customers. If it can also be agreed within the brake community on a standard way of converting and interpreting noise Dynamometer and Chassis Dynamometer results into the subjective rating, much will be gained.
- It has been shown that a standardized loudness calculation can effectively rank the relative noisiness of one noise Dynamometer test to another. This could be expanded to take into account of age differences and the corresponding threshold shifts in hearing. There is the potential to further enhance the use of sound quality techniques to overcome the problem of correlating the objective Dynamometer output to the subjective vehicle rating. For a jury to listen to a squeal in a vehicle, people would have to drive the vehicle and report their ratings – an impractical, subjective, time consuming and expensive option. Therefore using a commercially available sound quality package, a database of vehicle squeals can be recorded and played back to an industry jury to develop a subjective squeal metric for a noise dynamometer.
- A similar approach can also be extended to cover brake-related vibrations such as shudder, based on the human response to vibration including frequency content, amplitude and duration.

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A DOUBLE-PULSED LASER HOLOGRAPHIC SYSTEM FOR INVESTIGATING BRAKE SQUEAL

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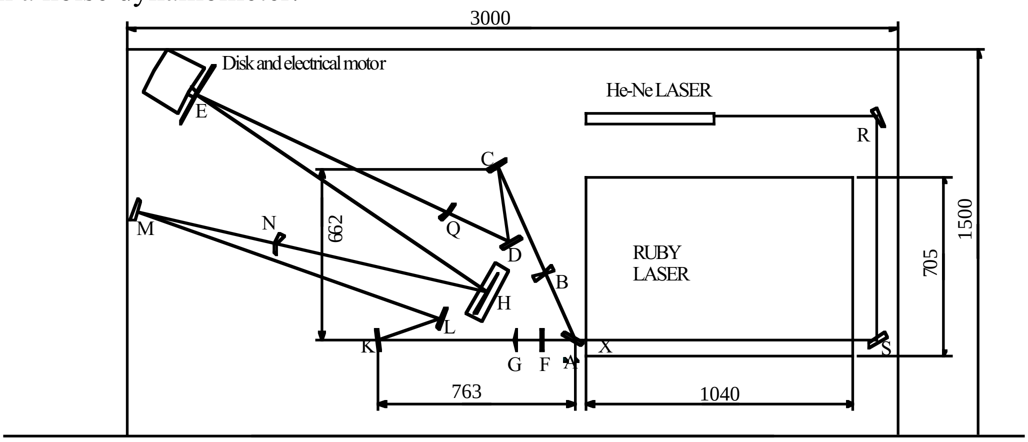
Abstract
In recent years, brake squeal noise has become an increasing source of customer dissatisfaction and of warranty cost. Despite numerous studies, the vibro-acoustic generation mechanism of brake squeal noise is not yet fully understood. A brake squeal normally involves complicated component vibration modes with pad/caliper exhibiting both bending and torsional modes simultaneously whereas the brake rotor will generally vibrate in a diametrical mode (with some exceptional cases vibrating in a longitudinal mode). The detection of these vibration characteristics is a very difficult task and even with care, some events may not be captured simultaneously. It would, therefore, be beneficial to be able to visualise the dynamic behaviour of a squealing brake under test in a noise dynamometer. The development of a double-pulsed laser holographic system is described and its application to capture the dynamic behaviour of a brake during squeal in an industrial environment is demonstrated.

Introduction

Brake squeal is generated by the vibration of an unstable vibration mode of the brake system. It has been one of the most serious problems in the automotive industry, which leads to customer dissatisfaction and increased warranty costs. Research into predicting and eliminating brake squeal has been conducted since the 1930s. As appropriately summarised in [1], "the history of NVH (noise, vibration and harshness) brake test technology is one that is strongly influenced by competitive thinking, eg, isolation of experts preventing them from stimulating exchange of ideas. As a consequence, when compared to industry wide resources involved, very little progress has been made in understanding the fundamentals of noise excitation, noise modelling, instrumental approaches to the study of noise and so on".

Recent reviews of brake squeal were given by Yang & Gibson [2] and Pappiniemi et al [3]. A better understanding of the vibro-acoustic generation mechanism of brake squeal would require analytical, numerical and experimental investigations. Since the squeal frequencies are highly dependent on the natural frequencies of the brake rotor, it is important to determine the vibration modes of the rotor and other associated components in a brake system in order to help predict unstable modes that may cause brake squeal. Some of the experimental investigations include traditional modal testing techniques using accelerometers which can only be applied to stationary brake components. Optical techniques, such as double pulsed laser holographic interferometry, have been used more recently to determine the mode shapes of a squealing brake rotor [3]. Included in the holographic image can be the rotor as well as the pads, anchor bracket and caliper. The technique can be applied to a brake system mounted on a brake dynamometer. Suspension components, such as the spindle, spring and damper, can also be included to simulate the on car performance of the brake system.

While the principles of double pulsed holographic interferometry are quite well known, the application of this technique to a noise dynamometer for in-situ testing of brake squeal noise is by no means a trivial exercise. The objective of this paper is to describe the development of a double-pulsed laser holographic system to visualise the dynamic behaviour of a squealing brake in a noise dynamometer.



OPTICAL COMPONENTS
A - high power beam splitter 50/50 split at 45 deg incidence, dia 1/4" AR coated
B, F - high power plane concave BK7 lenses 25.4 mm dia - 100 mm focal length, AR coated
C, D, L, K, M, R, S - low power mirrors
Q, N - low power concave lenses
G - low power convex lens
H - holographic plate in holder

Figure 1 Schematic of set-up for laser holography.

Experimental Set-Up

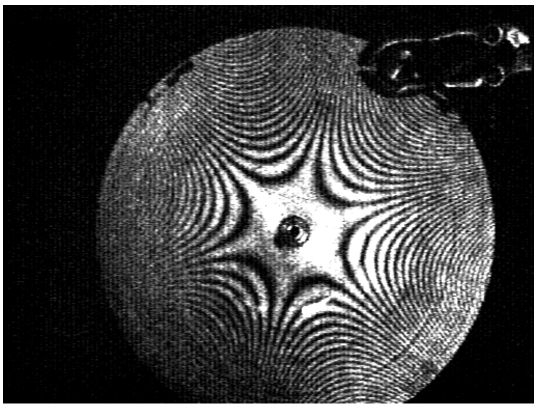
A holographic image is produced by triggering a laser at the maximum positive and negative displacement of a vibrating object. The difference in the optical path length, caused by the deformed shape of the vibrating object, creates an interference fringe pattern on a holographic plate. The mode shape can then be determined by interpreting the fringe pattern. The optical layout of a double-pulsed holographic interferometry system is shown schematically in Figure 1, similar to a Mach-Zehnder interferometer. In order to obtain two images, the light source is a JK-2000 1.2 J double-pulsed ruby laser with a coherence length of 1 m, a double pulse separation of 1-800 μs, a pulse duration of 40 nanoseconds and a pulse repetition rate of up to 6 pulses per minute. As shown in Figure 1, a high power laser beam splitter (A) is used to divide the laser beam into an object beam and a reference beam. In order to prevent damage of the optical components by the ruby laser concentrated beam, the laser beam is expanded by using a combination of concave (F) and convex (G) lenses. After that a combination of flat mirrors (K, L and M) is used first to direct the object laser beam to the brake disk and the reference beam (mirrors C and D) to the holographic plate (H) and, second, to maintain the same length of the object and reference beams. Two concave lenses (B and Q) are used in order to illuminate the brake disk by the object beam. The holographic plate (H) is placed so that the light of the object beam is reflected by the disk (E) onto the photo plate. Another concave lens (N) is used to illuminate the holographic plate (H) by the reference beam. Shown in Figure 1 are also a He-Ne laser and two flat mirrors (R and S) used for aligning the ruby laser optical set-up.

Results

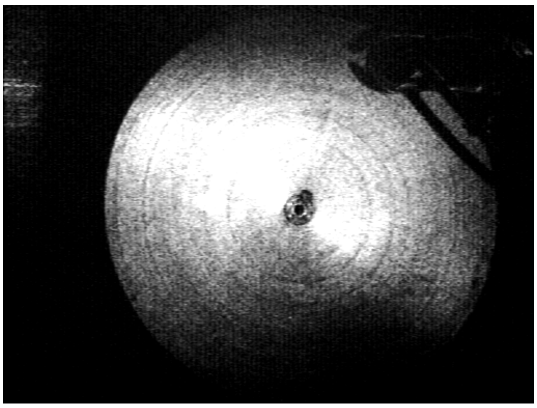
Vibrating Disk

The holographic system as depicted in Figure 1 was first set up in a laboratory environment. The test object is a disk which has a resonant frequency at 1026 Hz. The disk was excited by an electromagnet at 1026 Hz, thus giving a time separation τ of approx 487 μs between maximum positive and negative displacements. The signal driving the electromagnet to excite the disk was used to trigger the laser to pulse near the maximum positive and negative displacements of disk vibration with $\tau = 460$ μs. The fringe pattern, reconstructed from the hologram as shown in Figure 2(a), displays a mode shape that is consistent with that expected at the resonant frequency of 1026 Hz.

As brake squeal can occur at very high frequencies up to 12 kHz, it is important to test whether the holographic system works well with a small separation time between pulses. Considering a squeal frequency of around 10 kHz, the pulse separation time τ between maximum positive and negative displacements is 50 μs. There are no fringes in the reconstructed image (Figure 2(b)) under this condition, thus failing to reveal the mode shape corresponding to 1026 Hz. This is because the vibration displacement of the disk resonating at 1026 Hz is too small for it to be recorded with the laser being triggered at the maximum displacement and a short pulse separation time of 50 μs. Thus, in order to capture the mode shape at 1026 Hz with a short pulse separation time of 50 μs, the laser was triggered near the instant of maximum vibration velocity. This would result in an increase in vibration displacements compared with the condition in Figure 2(b). The reconstructed image shown in Figure 2(c) clearly reveals some fringes and by increasing the pulse separation time to 100 μs, these fringes are much more distinct as shown in Figure 2(d). Thus in order to use a disk resonating at 1026 Hz and a short pulse separation time of 100 μs to test out the system, the laser should be triggered near the instant of maximum vibration velocity.

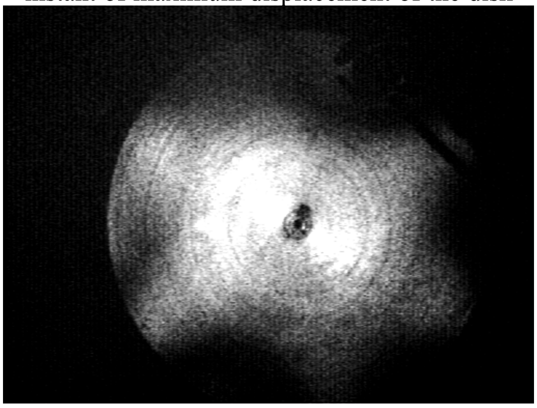


(a) non-rotating disk: $\tau = 460$ μs; pulses near the

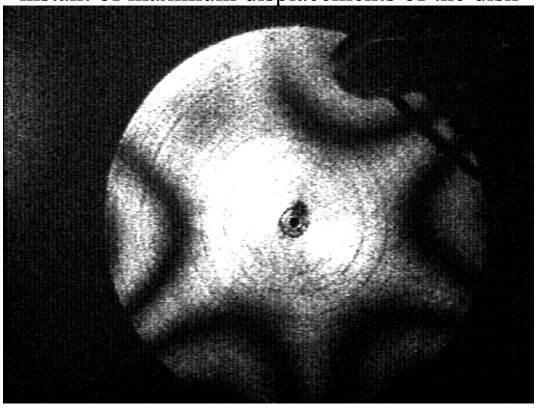


(b) non-rotating disk: $\tau = 50$ μs; pulses near the instant of maximum displacement of the disk

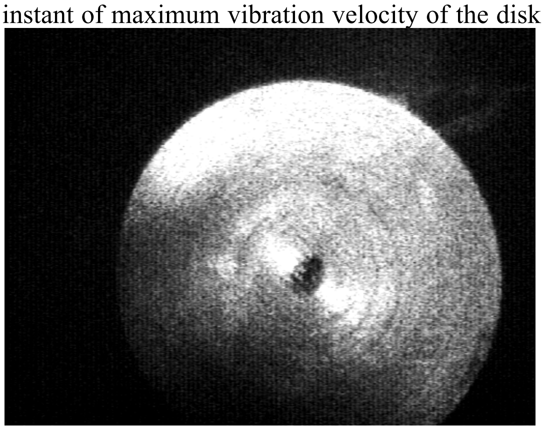
instant of maximum displacements of the disk



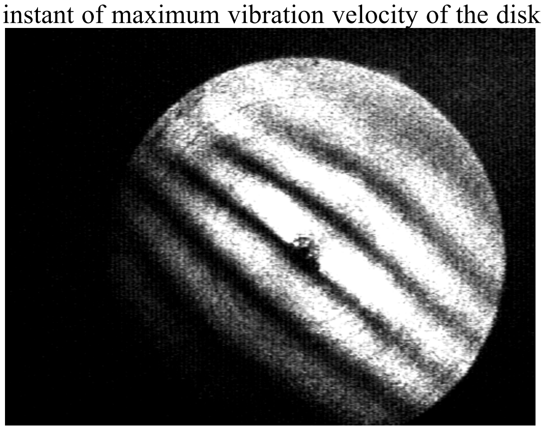
(c) non-rotating disk: τ = 50 μs; pulses near the instant of maximum vibration velocity of the disk



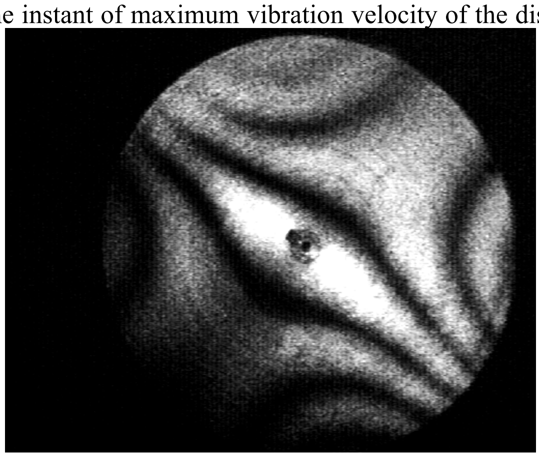
(d) non-rotating disk: τ = 100 μs; pulses near the instant of maximum vibration velocity of the disk



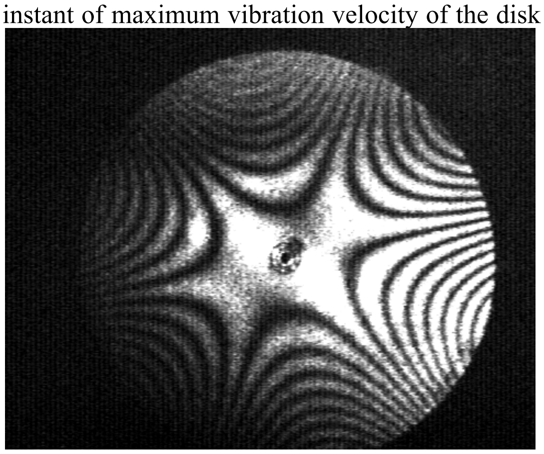
(e) disk rotating at 600 rpm: τ = 100 μs; pulses near the instant of maximum vibration velocity of the disk



(f) disk rotating at 60 rpm: τ = 100 μs; pulses near the instant of maximum vibration velocity of the disk



(g) disk rotating at 42 rpm: τ = 100 μs; pulses near the instant of maximum vibration velocity of the disk



(h) disk rotating at 30 rpm: τ = 100 μs; pulses near the instant of maximum vibration velocity of the disk

Figure 2 Fringe pattern for image reconstructed from a double-pulse hologram of a disk vibrating at 1026 Hz.

As the brake disk is rotating in the noise dynamometer, the effects of rotation on the quality of the hologram has to be assessed. In addition to exciting the disk at 1026 Hz with an electromagnet, an electric motor was used to rotate the disk at a given rotational speed as shown in Figure 1. The reconstructed image for the disk rotating at 600 rpm shown in Figure 2(e) does not reveal any vibration pattern. It was found that the maximum amount of tilt in the disk during half a revolution was 0.15 mm. In order to eliminate fringes due to disk tilting, the amount of tilt between the two laser pulses has to be less than 1/3 of the wavelength of the laser light. Since the wavelength of the ruby laser is 694 nm, the rotational speed of the disk has to be less than 462 rpm. The fringes shown in Figure 2(f) for the disk rotating at 60 rpm are, therefore, not due to the tilting of the disk but to the rotation of the disk. As the rotational speed is slowed down to 42 rpm, the fringes in Figure 2(g) start to reveal the mode shape of the vibrating disk. Further reduction of the rotational speed to 30 rpm reveals a fringe pattern (Figure 2h) that is very similar to that of the non-rotating disk (Figure 2a). It should be pointed out that the experiments for the non-rotating disk and rotating disk were conducted at different times with different spacings between the electromagnet and the disk (and hence different excitation forces). That is why the density of fringes shown in Figure 2(d) and Figure 2(h) is different.

Squealing Brake in a Noise Dynamometer

Once the holographic system was tested out in the laboratory environment, it was shipped down to PBR in Melbourne to conduct a test on a squealing brake in the noise dynamometer. The holographic interferometry optical set up is shown in Figure 3. Figures 3 a, b and c show the ruby laser layout next to the dynamometer cabin. A special wooden frame was made so that black plastic could be used to darken the area around the laser optical head during the ruby laser alignments. A rear brake with a solid rotor was mounted on the noise dynamometer as shown in Figure 3(d). The operating conditions were: walking pace to 30 km/h, temperatue from 80° to 150°C and below 1 MPa brake line pressure.

(a) (b) (c) (d)

Figure 3 Holographic interferometry optical set up at PBR International (Melbourne). (a), (b) and (c) showing ruby laser set-up outside the dynamometer cabin, (d) showing arrangement of the optics of holographic interferometry system, dynamometer and brake.

Preliminary measurements of the squealing disk with an accelerometer mounted on the caliper and a pressure microphone both indicate that the rotor is vibrating at 8 kHz. Thus, the two moments of maximum disk displacement are separated by 62.5 μs. The time separation of two ruby laser pulses was set to approximately 60 μs and the laser was triggered to fire at the instant of maximum vibration displacement using the accelerometer signal. The sound pressure level spectrum recorded at 0.5 m from the brake during the squeal is shown in Figure 4. The fringe patterns shown in Figure 5 for an image reconstructed from a hologram captured during the brake squeal test are in good agreement with the mode shape at 8 kHz predicted by the finite element analysis.

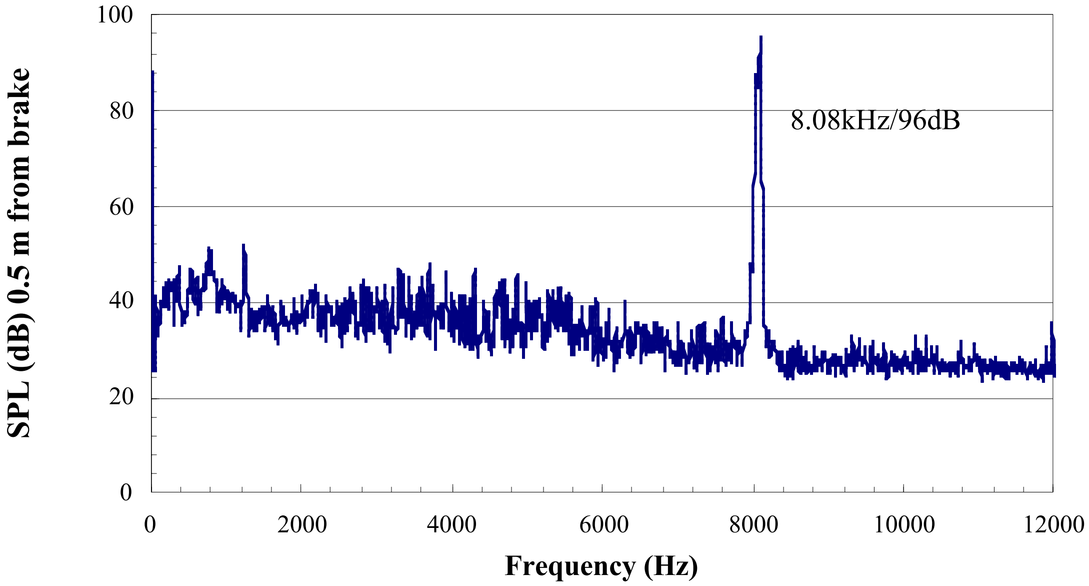


Figure 4 Example of sound pressure level signature of brake squeal.

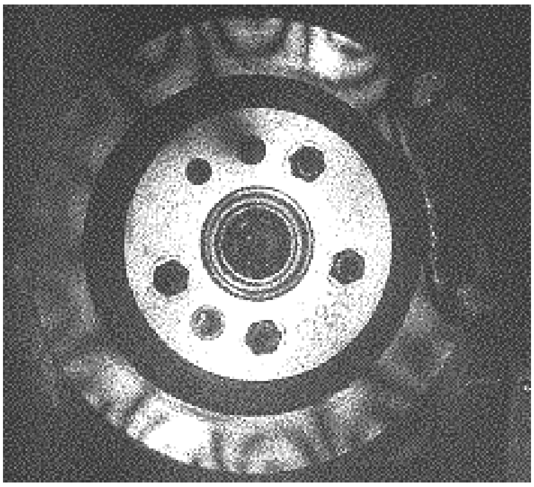


Figure 5 Fringe patterns for an image reconstructed from a hologram of the brake disk rotating at 30 rpm and producing a squeal noise of 8 kHz.

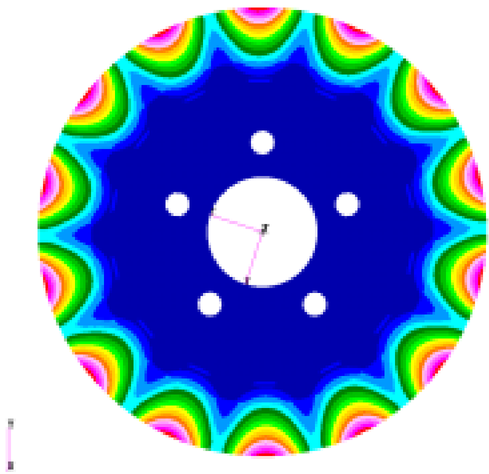


Figure 6 Finite element results of the mode shape of the disk rotor at 8 kHz.

Conclusions

The development of a double-pulsed laser holographic interferometry system in a laboratory environment has been described. The system has been applied to visualise the dynamic behaviour of a squealing brake in an industrial noise dynamometer. The fringe patterns reconstructed from holograms captured during brake squeal can be attributed to a bending mode of the solid rotor 8 kHz as predicted by the finite element analysis. This demonstration indicates that double-pulsed holographic interferometry can be successfully used in the study of the brake squeal noise in an industrial environment such as the PBR dynamometer.

Acknowledgment

This study forms part of a project funded by the Australian Research Council under the SPIRT scheme and the industry partner is PBR Automotive Pty Ltd.

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THE ROLE OF LOCAL GOVERNMENT PLANNING IN THE MANAGEMENT OF COMMUNITY NOISE

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Abstract
The role of local government planning is an often under utilised tool in the management of community noise.

This is despite community noise becoming an increasingly significant issue in the urban environment, as residential densities increase and the pressures of urban development results in the incompatible placement of conflicting land uses adjacent to each other. Combined with this is an increasing community expectation and demand for a higher standard of acoustic environment in their living and recreational places.

In many of the instances where noise is considered in planning policies, there has been a tendency to adopt noise criteria developed for regulating complaints from existing circumstances. Such criteria are not always appropriate for the assessment and design of new development.

While the regulation of noise sources is principally the responsibility of State Government Departments, Local Government has the principal responsibility for land use planning and development assessment.

My aim in presenting this paper is to highlight the important role land use planning plays as a component of community noise management and to highlight the opportunities that exist for noise policy makers to achieve acoustic objectives via the planning process.

The following paper is based on my experiences in Local Government in Queensland and will therefore present a Queensland perspective of the role of Local Government planning in the management of community noise.

Introduction

Addressing noise issues at the planning stage of development is the most cost-effective means of managing the noise environment, however, despite this fact noise is generally not well considered in the planning process and an end of pipe focus to noise management predominates. It has been my experience that many of the unresolvable complaints faced by noise regulators are the result of poor planning decisions.

Noise is a by-product of modern urban living. We require roads, railways, airports and industry and we also require places to live, schools and health care facilities in close proximity. It is the role of Local Government to integrate these conflicting land uses to achieve sustainable development via the planning process. The current performance based approach to development assessment means that Councils in Queensland can no longer prescribe prohibited development, but must assess development against its ability to achieve prescribed performance criteria.

The success of this performance-based approach to development assessment in protecting the community's acoustic environment is dependent upon the incorporation of appropriate performance criteria in the assessment process. In my view this has not happened effectively to date as planning decision makers and noise management decision makers (often the noise regulators) operate independently of each other without effective coordination, communication or integration.

To complicate this, I believe Local Government in Queensland is primarily development focussed and does not give adequate consideration in the planning process to protecting the community's acoustic environment. Noise and its impact is also largely trivialised at the Local Government and development industry level, which restricts the ability of noise management professionals and policy makers to have their issues considered in land use planning and development assessment. The cost of providing satisfactory acoustic environments (via house design and construction and noise source and transmission path controls) to protect the health and quality of life of existing and future communities, is often considered by developers to be unreasonable and restrictive to development. In my opinion this is a view often shared by many local government elected representatives. Political support is essential if sustainable noise environments are to be achieved via the development process. To do this noise management professionals and policy makers need to raise awareness and the profile of the need to manage noise pre-development rather than post development.

While I acknowledge that an appropriate balance between benefit and cost is necessary, the current urban planning process in Queensland appears to be tilted largely in favour of the unit cost of development, rather than future and wider costs when it comes to managing community noise.

A holistic approach to noise management would involve an examination of controls that can be applied at the source, transmission path and receiver. Such an approach would involve cooperation between State and Local Government, transport authorities, industry, the community and developers.

The Planning Process

In order to utilise local government planning mechanisms to achieve better on the ground outcomes for the acoustic environment, it is important for noise policy makers to understand the planning process.

Queensland's Integrated Planning Act adopts a performance-based system of development control that requires development proposals to demonstrate achievement with specified performance criteria and desired environmental outcomes.

This means that whereas in the past Councils could prescriptively prohibit development and prescribe buffer zones between incompatible uses, within their Planning Schemes, Council's can now only prescribe preferred uses and outcomes to be achieved. Essentially a developer can build anything anywhere provided the developer can demonstrate the achievement of the required performance criteria and desired environmental outcomes.

A key principal of Local Government Planning Schemes developed in accordance with the Integrated Planning Act, is the specification by the Local Government of its desired environmental outcomes (DEO's). The DEO's are broad statements of the principal goals or outcomes the Local Government wants to achieve or protect with respect to the various facets of the environment. The DEO's must reflect the community's vision and therefore must be developed with community consultation. Planning Scheme DEO's are delivered through Planning Codes, Local Area Plans and other planning instruments.

It is the Planning Codes that are used to assess development applications. Planning Codes are generally headed by statements of intent which reflect the Planning Scheme's DEO's.

As the statements of intent contained in Planning Codes are generally broad statements, they are supported by performance criteria that state more specifically the criteria that must be met in order to achieve the intent (and therefore the Planning Scheme's DEO's).

The performance criteria contained in a Planning Code may also be supported by a list of examples of ways in which the performance criteria can be met that are acceptable to the Council. These are often termed acceptable solutions. They are provided as a guide and are not mandatory. They only illustrate one way of meeting the associated performance criteria and are not intended to restrict the use of other methods. Developers may choose to adopt alternative methods of achieving the performance criteria provided sufficient justification, validation and evidence of the appropriateness of the alternative is provided. The aim of this approach is to provide some level of guidance without restricting innovation or alternative design or approaches.

An example of a Planning Code used to assess the noise impacts of a development application is illustrated in figure 1 below. (The example is not an actual Code but is presented to illustrate the core components of a Planning Code, namely, a Statement of Intent, Performance Criteria and Acceptable Solutions).

Figure 1: Example of a Planning Code

Intent: To achieve acceptable noise levels for internal and external living spaces that will protect the ability of occupants to have sleep, relaxation and communication without unreasonable interference from intrusive noise.

Performance Criteria	Acceptable Solutions
P1. The new development is to achieve the following design level noise criteria: • Inside bedrooms - Lmax not greater than 50dB(A) LAeq not greater than 35dB(A) • Inside living rooms – LAeq not greater than 40dB(A)	**A1.1.** The new development is designed, orientated and constructed to reduce the transmission of noise. For example by: ♦ using construction, insulation and glazing materials with a high noise transmission loss ♦ the reduction of the area covered by openings (eg windows and doors) in walls facing the noise sensitive place; **A1.2.** The new development uses noise attenuation measures such as earth mounds and fences between the noise source and the noise sensitive place. **A1.3.** The new development has appropriate buffer distances between the noise source and the noise sensitive place.

Assessment Criteria for Planning Purposes

If we consider the role of development assessment is to assess the appropriateness of a proposed use for a subject site with respect to protecting noise sensitive uses from unreasonable impacts from intrusive noise. One of the first questions policy makers must consider is what elements of the community's acoustic environment do we want to protect? For example do we want to protect sleep, relaxation or communication etc? This is important as the acoustic value to be protected will influence the noise assessment or performance criteria selected.

Once the values of the community's acoustic environment to be protected have been determined, the next question is what are the appropriate planing assessment criteria to protect those values? It is important that the planning assessment criteria selected are related to the human response to noise associated with each of the acoustic values, as the human response to noise is different for each of the above acoustic values and will also differ depending on the noise source.

There is currently a lack of specific planning assessment criteria for noise for Local Government to apply to development assessment. This is despite the wealth of research information produced by the scientific and academic community concerning human response to noise exposure. I believe the science being produced by the research community is not being effectively communicated to the body who can practically apply noise science in the field (ie. Local Government).

In the absence of specific planning assessment criteria, it is common practice for consultants and Councils to use State Government noise laws or codes of practice as the planning criteria to assess the acceptability of new development. This regulatory criteria is not appropriate in many instances for planning (development assessment) purposes, as the State Government laws and codes generally have an end of pipe focus and are designed principally for resolving complaints, setting license conditions and protecting State Transport infrastructure.

When a Local Government receives a development application it must consider the impacts of the proposal upon noise sensitive uses to ensure there is no unreasonable impact upon their acoustic values.

It is my experience that where a new noisy activity is proposed adjacent to existing residents, the existing residents have a high expectation that their existing acoustic values will not be impacted upon by the introduction of the new noise source. This expectation is generally much higher than that expected by people moving into or already living in existing noisy areas (for example if the noisy activity was there first).

I acknowledge that regulatory criteria needs to be set at levels that can be practicably achieved in existing circumstances to resolve complaints. Particularly in the case of resolving noise complaints, where for historical reasons, residents are located adjacent to existing noise sources.

However, while the noise criteria specified in the regulatory legislation may be appropriate for addressing complaints in existing circumstances, I do not believe they are appropriate to be used as design level noise criteria for planning purposes.

Design Level Noise Criteria

Redland Shire Council has started using a Design Level Noise Criteria approach for the assessment of development applications. That is the Council specifies the noise criteria which the new development is to be designed to achieve in order to meet the DEO or intent for the acoustic environment stated in a Planning Code. Such criteria is not used for regulatory purposes but is only used to assess development and to ensure the physical aspects of the development are designed and constructed to prevent future noise impacts.

To date the Council has based the development of its Design Level Noise Criteria upon various guidelines such as the World Health Organisation Community Noise Guidelines and Australian Standards and published research papers.

The Design Level Noise Criteria are generally developed to be specific for different noise sources, as people generally react differently to different noises e.g. traffic noise, industrial noise and animal noise.
Figure 2 below provides an example of Design Level Noise Criteria. The criteria are taken from Redland Shire Council's *"Transitional Planning Scheme Policy -Impact of Transportation Systems on Urban Amenity"*. They represent the design levels for road noise that proposed new noise sensitive places subject of application under the Integrated Planning Act are to be designed to, in order to protect sleep, passive recreation and communication.

Figure 2: Example of Design Level Noise Criteria

Measurement Location	Design Level Road Traffic Noise Criteria
1m in front of the most exposed part of a proposed new noise sensitive place	• For a State controlled road: Road traffic noise levels are to comply with the external noise criteria specified in Section B6 of the *Road Traffic Noise Management Code of Practice*, published by the Queensland Department of Main Roads. That is: *63 dB(A) L10(18 hour) or less, where the L90 (8 hour) between 10pm and 6am is greater than 40dB(A), or* *60 dB(A) L10(18 hour) or less, where the L90 (8 hour) between 10pm and 6am is less than or equal to 40dB(A).* • For another public road: In accordance with Schedule 1 of the Environmental Protection (Noise) Policy 1997.
Inside bedrooms of a proposed dwelling house, multiple dwelling or accommodation unit.	(a) Average Lmax (10pm-6am) not greater than 50dB(A), and (b) LAeq(1hr)(10pm-6am) – not greater than 35dB(A)
Inside living rooms of a proposed dwelling house, multiple dwelling or accommodation unit.	LAeq(1hr)(6am - 10pm) – not greater than 45dB(A)
Inside other proposed noise sensitive places	In accordance with the maximum recommended design sound levels specified in Table 1 of *Australian Standard 2107: Acoustics-Recommended design sound levels and reverberation times for building interiors.*
External formal living space of a proposed dwelling house, multiple dwelling or accommodation unit.	LAeq(1hr)(6am to 10pm) not greater than 55dB(A)

Conclusion

Local Government land use planning has an important role to play in the management of community noise.

While it is predominantly Federal and State laws and policies that set the framework for noise management in Queensland, their application in land use planning is interpreted through Local Government planning schemes, policies and codes.

In my view noise management in Queensland has a largely end of pipe focus to the management of community noise, in which noise laws and codes of practice are designed to resolve problems once they have occurred, rather than focusing on preventing the problems pre-development.

This situation is complicated by the lack of coordination, communication and integration between planning decision makers and noise management decision makers, the pro-development focus of Local Government and the trivialisation of noise as a significant issue.

There is a need for noise management professionals and policy makers to raise awareness and the profile of the significance of noise impacts with planning decision makers, politicians and the development industry.

There is also a need to develop specific noise assessment and performance criteria for planning purposes.

I would like to encourage noise policy makers to focus on the utilisation of planning mechanisms to manage community noise, as I believe this is the most cost effective means to achieve acoustic policy outcomes.

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TRAFFIC NOISE ASPECTS OF MASTER PLANNING

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Abstract
The planning of residential communities frequently uses the Master Planning approach. Noise is one of the environmental impacts investigated during the Master Planning phase, predominantly due to transport corridors.

In Queensland, the Environmental Protection (Noise) Policy (EPP(Noise)) indicates that the "acoustic quality objective" is the objective of achieving an ambient level of Leq (24 hour)55 dB(A) or less for most of Queensland's population living in residential areas. Some local authorities pursued an approach that, as a duty of care consideration, this objective is to be attained even in cases such as transportation noise where usually less restrictive noise level standards apply. It is evident that residential developments long major roads would require a detailed noise investigation.

This paper investigates the implications of Master Planning in terms of road traffic noise due to collector roads and associated amelioration measures. Typical amelioration measures include setback distances, acoustic barriers and optimal road cross-sections, to meet the acoustic quality objective. It also outlines the implications for developers and their approach in dealing with road traffic noise.

Introduction

The planning of residential communities frequently uses the Master Planning approach. The aim of this approach is to achieve a fully planned and integrated community, including acceptable environmental impacts in residential areas. Noise is one of the environmental impacts investigated, predominantly due to transport corridors, but they may include sources such as adjoining industry, sports centres etc.

This paper investigates the implications of this approach in terms of road traffic noise. Major and sub-arterial roads are an obvious source of noise, and already the subject of detailed studies and not part of this scope of this paper. However, this investigation has revealed that, although often ignored, some collector roads should also be considered, and the amelioration measures that may be implemented.

Noise Nuisance

Noise is the most widely reported form of pollution affecting the community, with road traffic noise being one of the main sources of annoyance and complaint. The Organisation for Economic Co-Operation and Development (OECD) claims that transport is the major source of environmental noise, with road traffic being the chief offender (EPP(Noise) – Regulatory Impact Statement page 6.). Road traffic noise impact on residential communities is also widely documented. Excessive levels of road traffic noise interferes with and affects the well being of an affected community, which includes its social and economic amenity (EPP(Noise), Section 10). More specifically, road traffic noise, when at unreasonable levels, affects the well being of "individuals", and their opportunity to sleep, relax and converse (EPP(Noise), Section 10).

The relevant Queensland State Government legislation pertaining to noise pollution is the Environmental Protection Act 1994 (the "Act") and its subordinate, the Environmental Protection (Noise) Policy 1997 (the "EPP(Noise)"). The object of the EPP(Noise) is to achieve the object of the Act, which is to protect Queensland's environment while allowing for development that improves the total quality of life, both now and in the future, in a way that maintains the ecological processes on which life depends, i.e. Ecologically Sustainable Development (ESD) (Section 3 of the Act).

The intent of the Queensland Environmental Protection legislation is to protect the acoustic environment such that the wellbeing of communities and individuals, including their opportunity to have sleep, relaxation and conversation without unreasonable interference from intrusive noise, is maintained. This is also referred to as protecting the "Environmental Values" of a community/individual.

Master Planning Aspects

In Queensland, Local Government is essentially the public sector entity, which deals with land use applications, i.e. development proposals. Such applications are assessed by local government under the auspices of the Integrated Development Assessment System "IDAS", and its governing legislation, the Integrated Planning Act 1997 (the IP Act). Sometimes developers of large residential community development proposals use a "Master Planning" approach, in conjunction with Town Planning Schemes. In some Local Government areas, the Master Planning approach precedes the IDAS system. This can afford Local Government officers and development entities more scope and opportunity to ratify and resolve many of the town planning, environmental health, engineering, environmental conservation and other issues. This also allows the opportunity to address the likely the future road traffic noise impact on proposed residential areas.

Local Government officers, in conducting their noise assessments of "Master Plans" need to identify the relevant potential noise sources, and investigate how these potential noise sources can be controlled, such that once the residential community is established, they are not exposed to unreasonable levels of environmental noise. The interface between proposed new major transport corridors, collector roads and dwelling lots is the most common situation in which these potential noise issues arise. Collector roads are roads located in a built-up area which collect local traffic leaving a locality and connecting it to a sub-arterial road.

Local Government

When assessing the potential impact of road traffic noise at the residential interface, Local Government officers need to apply relevant planning noise levels, or criteria, on which to stipulate terms of reference to development entities. Based upon the design capacity of the relevant road, such planning levels or criteria are then used to determine what noise amelioration measures are required to control the predicted noise impact to the stated acceptable levels.

Section 15 of the EPP(Noise) refers to "Planning Levels" (Schedule 1 of the EPP(Noise)), and these are frequently relied upon by the development industry as the relevant criteria to use, when determining the degree of required noise amelioration. Section 15 also states that "in deciding reasonable noise level for the activity, the administering authority must have regard to the acoustic quality objective and all the relevant circumstances for the particular case." In addition, the EPP(Noise) describes roads as "beneficial assets", recognising that, although the operation or use of beneficial assets may have significantly adverse effects on the "environmental values" (as discussed above), they are necessary for the community's environmental, social and economic wellbeing (Section 5 EPP(Noise)).

The EPP(Noise) "Planning Levels" for public roads are as follows:

> *…….assessed 1 m in front of the most exposed part of an affected noise sensitive place—*
> *(a) the following levels assessed as the L10 (18 hour) level—*
> *(i) for a State-controlled road—68 dB(A);*
> *(ii) for another public road—63 dB(A);*
> *(b) 60 dB(A), assessed as the highest 1 hour equivalent continuous A-weighted sound pressure level between 10.00 p.m. and 6.00 a.m.;*
> *(c) 80 dB(A), assessed as a single event maximum sound pressure level.*

The EPP(Noise) (Section 5(2)) states that the operation of a beneficial asset, (includes public roads) "may have significantly adverse effects on the environmental values." The Users Guide for the EPP(Noise) explains that the Planning Levels are not design goals and do not presume to protect the environmental values of the human environment. Essentially the Planning Levels are applicable for the state and local authority "road builders".

Local Government has a duty of care in terms of environmental impacts. Given that the objective of the Act, the EPP(Noise) and the IP Act is to achieve "ecological sustainability", it is evident that by relying solely on the "Planning Levels" being implemented, does not fulfil a Local Government's duty of care obligations, where it knows that:

- the "Planning Levels" do not presume to protect the environmental values of the human environment; and
- people living within an environment exposed to noise from the beneficial asset may be adversely affected by that noise.

In this regard, the application by Local Government of the “planning levels” alone as an appropriate noise level criteria for noise sensitive/residential development, is not a “sustainable” rationale when considering the object of the Act, the EPP(Noise) and the IP Act (“ecological sustainable development”). For example, some local councils consider this is a fundamental principle pertaining to the potential impacts of road traffic noise at the land use planning stages of development.

Local government could approach proposals and applications for residential development, where transportation noise is identified as being a significant issue, by diligently applying the principles of ecologically sustainable development and ensuring that an appropriate noise level criteria is applied to protect the environmental values of future occupants of noise sensitive uses. The use of the Master Planning tool can facilitate this process.

In the case of Local Government in Queensland, duty of care would be complied with by meeting the “acoustic quality objective” referred to in Section 11 of the EPP(Noise). The objective is to achieve an ambient noise level of Leq (24 hour) 55 dB(A) or less, measured as an L_{eq}(24 hour), for most of Queensland’s population living in residential areas. The term “most” is assumed to cover the existing residences already exposed to high noise levels, and does not allow the opportunity for new residences to exceed the acoustic quality objective.

Implications of Achieving Acoustic Quality Objective

From a Master Planning perspective, what are the implications of applying duty of care expressed as the acoustic quality objective in proposed residential estates, particularly with respect to road traffic noise?

The ambient noise level in a residential area is measured at least 3.5 m from a façade to avoid the influence of reflections. The EPP(Noise) does not stipulate where the Leq (24 hour) 55 dB(A) noise limit is to be met. It is assumed that the Leq (24 hour) 55 dB(A) is to be met in outdoor recreation areas.

ASK Consulting Engineers has developed some basic templates relating to minimum setback distances of residences from collector roads meeting the Leq (24 hour) 55 dB(A) limit. The CRTN88 noise model was used for this purpose. The templates are shown in Figures 1 and 2 and show respectively the minimum setback distances from the nearest edge of the road, assuming a 7 m wide dense graded asphalt pavement for ground level and first floor receptors. The figures include a number of scenarios with varying traffic volumes and percentage commercial vehicles. The figures show that as the traffic volume increases setback distances also have to increase.

Limiting the speed limit to 50 km/hr rather than 60 km/hr has a significant impact on setback distances; the effect of percentage commercial vehicles on setback distances is less significant.

Figure 1. Minimum Setback Ground Floor Receptor From Edge Of Road Without Amelioration Measures To Meet 55 dB(A) Leq(24hour)

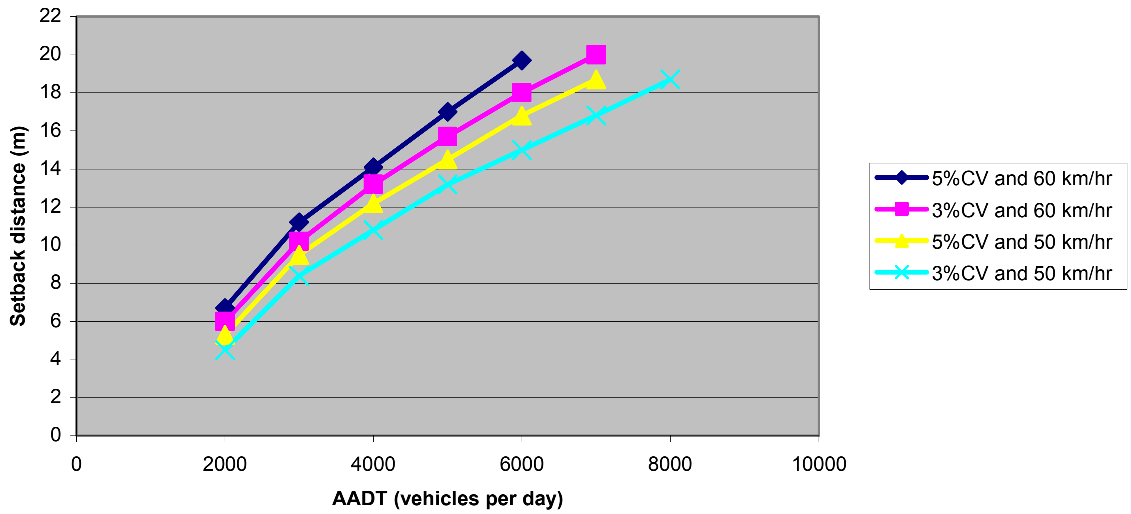
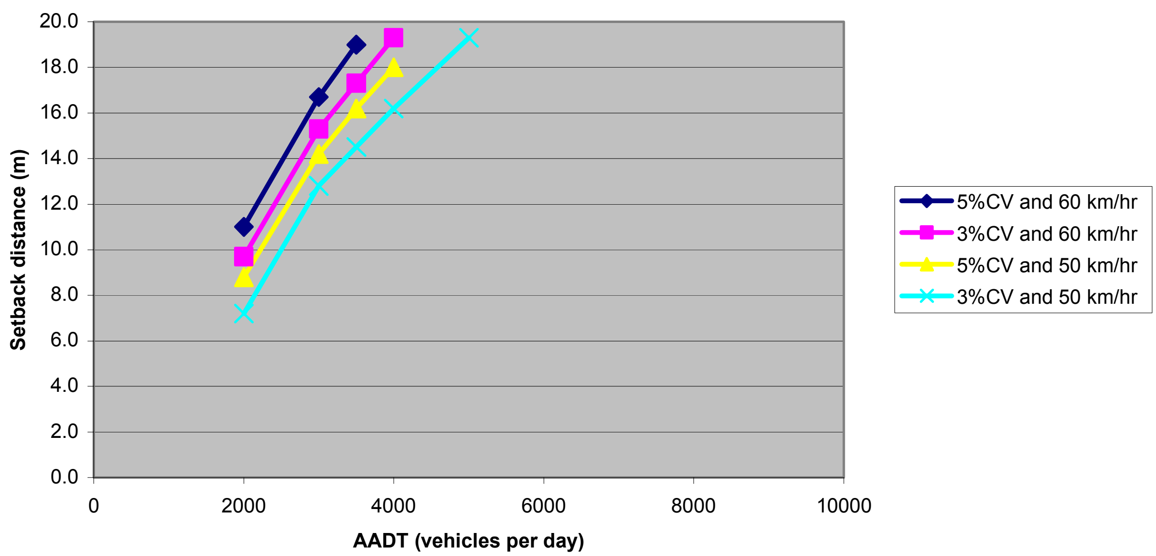


Figure 2. Minimum Setback First Floor Receptor From Edge Of Road Without Amelioration Measures To Meet 55 dB(A) Leq(24hour)



From the attached figures it is apparent that acoustic impact assessment would need to carried out for traffic flows as little as 2,000 AADT (average annual daily traffic flow). For outdoor recreation areas having separation distances less than the distances shown for the various scenarios indicated in Figures 1 and 2 noise ameliorative measures would be required. Measures acceptable to Local Government include: appropriate setback distance from the road; lowering of road traffic speed; acoustic barriers, which may not be desirable or practical along some collector roads, e.g. where the road is not access controlled, optimal road cross-sections to increase separation distance.

Conclusion

Some Local Governments in Queensland apply the acoustic quality objective of Leq (24 hour) 55 dB(A) to developments to comply with their duty of care requirements. For this scenario, the results of this paper indicate that Master Planned community developments should address traffic noise impacts associated with collector roads.

Noise modeling results indicate that collector roads adjoining residential areas, with traffic volumes as few as 2,000 AADT, would require acoustic impacts to be considered and may require acoustic treatments, such as noise barriers, increased separation distances and lower traffic speeds.

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Note: Comments made in this paper by Richard Leeson do not necessarily represent the express written policy or long term strategic planning policy objectives of Caloundra City Council.

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FROST FAN NOISE POLICY - THE ISSUES

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Abstract

Frost fans incorporated in wind machines are used by farmers to protect their crops (fruit and vegetables) from frost damage in susceptible areas. The wind machines are typically 10 to 12 meters tall with 5.5 metre long impellers. They produce a noise which is repetitively variable in level as the fan hub rotates. This gives a helicopter type of character noise. The machines only come into use during low temperatures (typically –2°C) and during temperature inversions. These conditions normally occurs in the early hours of winter mornings when there are clear skies. The noise can be 20 dB to 30 dB higher than the night time background levels at residences in rural areas. Noise Policy will need to take into account all the issues involved. These include the noise level above background and the psychoacoustics - particularly the unpredictability and the temporal structure of the noise and the special circumstances of the machine's use. Also to be considered are the number of nights per year the machines are likely to be used and the social worth of the farming activities.

Introduction

Many agricultural areas of Australia are susceptible to winter frosts which can be the cause of damage to crops. Wind machine systems are used to protect fruit and vegetables crops against frost damage. They are typically 10 metres to 12 metres high with 5.5 metre long fan impellers (see Figure 1). The impeller is driven by a diesel or gas fuelled engine through a series of gears that cause impeller blades to rotate and the head to oscillate. Engine speeds are typically 2300 revolutions per minute (rpm) and rotation speed of the impeller is typically 590 rpm. The wind machines can be controlled by a thermostat to enable automatic start-up when temperatures drop to pre-determined levels e.g. 0º to -2º C (Celsius).

Wind machines utilise temperature inversions in the upper atmosphere and cause a heat transfer by forced convection. On a clear winter's night in an agriculture area, inversions could result in the temperature of the air at 15 metres from the ground being 6º C or more higher than the ground temperature. The warmer air from the atmosphere is moved downward by the wind machine and mixed with the colder air surrounding the trees and soil as shown in Figure 2.

Figure 1. The Frost Fan Impeller.
(Courtesy of the Amarillo Wind Machine Company, USA [1]).

The wind machines are an effective means of protection from frost damage but they do generate noise. The noise nearly always starts at a time late in the evening or night and often continues until the early hours of the morning. Hence there is a potential for sleep disturbance and justifiable noise complaints from local residents.

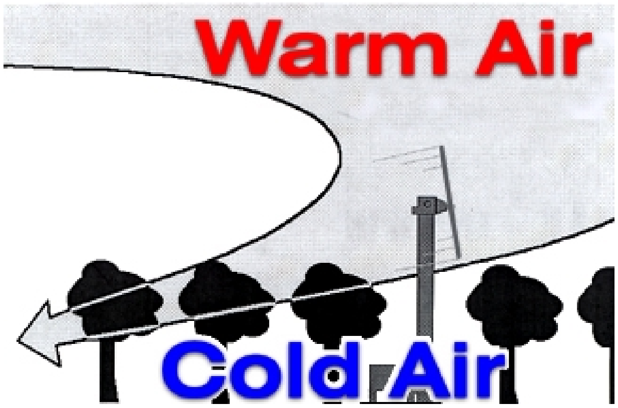

Figure 2. The Wind Machine Principle. (Courtesy of the Amarillo Wind Machine Company, USA) [1].

The Need For Wind Machines

Farmers need to protect their crops from damage, which can occur from insects, droughts and sunburn as well as frost. While all of these factors can take their toll, and market conditions can quickly trim farmer's profits, a frost can cause the total loss of a crop in less than 12 hours.

The installation of a wind machine is one option that the farmer has to prevent frost damage. However, farmers do have other options for example:-

- Change to a product which is not prone to frost damage;
- Use alternative frost prevention methods such as ground heating and irrigation;
- Use no frost prevention methods and accept the risk of crop losses due to frost damage.

Some of these options may not be practicable or viable in certain agricultural areas. It one case [2] a farmer made a claim that the prevention of frost damage was critical to producing fruit of an export quality. The point was made that the frost damage is not necessarily discernible by external examination of the fruit and only discovered when sold in the overseas markets (e.g. Japan or the USA). The industry generally suffered losses from frost in 1998 when the loss of revenue from the USA market alone was, reportedly, over 1 million US Dollars.

The Noise

As air passes over the impeller, the aerofoil shape of the blade forces the air in a direction perpendicular to the direction of the movement of the blade. At the trailing edge of the blade the air tends to curl around to form vortices. As these vortices get to a critical size, they break away from the impeller and another vortex is formed. It is the action of vortex shredding that creates the noise. The noise fluctuates in level by approximately 7 dB to 11 dB as the frost fan hub rotates by 360 degrees (see example in Figure 3). This gives the noise a character that is similar to that of a helicopter. The frequency could be described as broadband but there is significant energy in the octave band centered on 63 Hz shown in Figure 4.

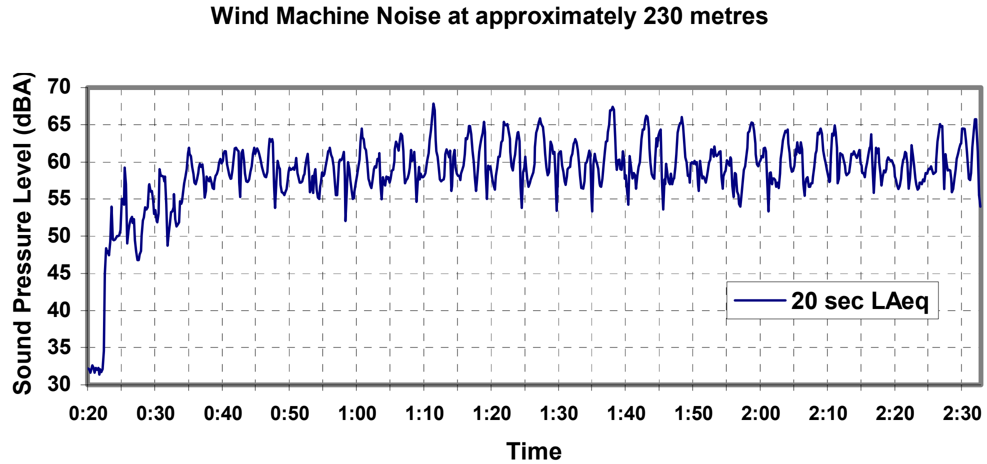

Figure 3. The Wind Machines Noise Level. This Graph shows the Fluctuations in Noise Level over an Approximate 5 Minute Cycle.

The sound pressure level at a distance of approximately 250 metres is typically between 50 dBA and 60 dBA depending upon topography and meteorological conditions. This can be compared to background noise levels (L_{A90}) which could easily be 30 dBA or below in rural or rural / residential areas.

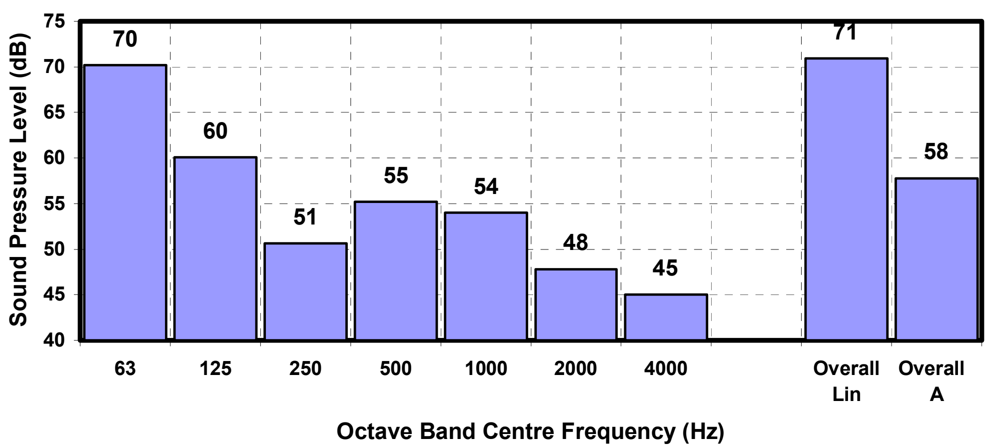

Figure 4. The Wind Machines Noise Spectrum. This Graph shows an example of the Octave Band Frequency Response of the Machines.

The Criteria

Even though the noise contains unpleasant characteristics and could be 20 dB to 30 dB above the background it is not obvious that it is an unacceptable noise. Other factors must be taken into account when deciding upon criteria. The wind machine only operates in cold conditions and usually at night when it is assumed receivers are indoors with windows closed. In Australia wind machines are not required to be in use every day. It may only be necessary to operate them from 5 to 30 nights per year depending upon the number of nights when a frost occurs. This could change significantly from area to area and from year to year.

To the author's knowledge there are no specific criteria given for wind machines or frost fans apart from the South Australian Environment Protection Authority [3]. This is still in draft form only. This states that :- *" Frost fans should not be used if the measured noise level of the fans, when measured as L_{Aeq} exceeds the background noise level by more than 5 dB(A)* ***AND*** *when measured as L_{Aeq} exceeds the prescribed outdoor criterion level in the following table. If the outdoor criterion level cannot be met then the indoor criterion level may be used."*

Table 1 EPA (SA) Criteria

Location of Affected Premise	Outdoor Criteria (L_{Aeq})	Indoor Criteria (L_{Aeq})
Noise Sensitive	45 dBA	25 dBA
Any Other Zone	55 dBA	35 dBA

A noise sensitive zone is defined in the draft criteria as a zone primarily intended for noise sensitive uses such as residential or rural living and the like. That is a zone where land use ancillary to the residential use of the land should not adversely interfere with the residential character of the zone. Areas not classified as 'noise sensitive' could therefore still include those areas where people sleep.

The L_{Aeq} must be measured over at least one complete rotation of the fan hub, although at least three rotations have been suggested. It is reasonable to expect that a lower number of complaints will occur if the machine is only used a few times per year. However, no allowance is made for the number of nights the wind machine is to be used. This is due to the complications involved in the regulation and enforcement of a '*number – noise'* trade off.

It is normal practice, when considering night time sleep disturbance problems to assume that windows may be partly open. This noise source may be considered as a special case because it only operates during frost conditions. Not all people would want their windows closed, even during the coldest of nights, but is it reasonable to expect people to close their windows on the nights when the fan noise occurs?

The South Australian criteria was upheld in NSW case law [2] when the Honorable Justice R. N. Talbot concluded *"Pursuant to s 39 of the Land and Environment Court Act 1979, the court determines that in accordance with s 264 of the POE Act, any noise control notices given in writing to the applicant prohibit the company from causing the frost control fan……… to be operated in such a manner as to cause emission from the premises between the hours of 22.00 hours and 07:00 hours on any day, of noise that when measured at a point* *one metre from any residential bedroom window outside the subject property is in excess of 55 dBA L_{Aeq}."*

It was later agreed that the L_{Aeq} must be taken over a 15-minute interval and that there is a need to exclude any extraneous noise from the measurement. The formal orders of the Court [2] provided for a notice requiring that *"the logarithmic average of the equivalent noise levels ($L_{Aeq,\ 15\ minutes}$) measured over three consecutive 15 minutes periods shall not exceed 55 dBA on any separate three days within a 60 day period, provided that where the logarithmic average of the measured levels over three 15 minute periods does not exceed 55 dBA by more than 2 dB, it shall not be taken into account."*

The Psychoacoustics

At least two fundamental errors can arise from the psychoacoustics of noise annoyance from sources such as frost fans. The first is to assume that the "A" frequency weighting adjusts the noise level to the subjective response of the human ear, and the second is to assume that noise annoyance is one-dimensional, dependant only on noise level. Confusion over the 'A' frequency weighting comes from the two sets of equal loudness contours – one from Fletcher and Munson [4] and another from Robinson and Dadson [5]. As pointed out by Scannell [6] the 'A' weighting frequency filter can be regarded as a high-pass filter with a cut-off frequency (10 dB down point) at about 250 Hz. It was specified for sound level meters as long ago as 1936 [7] and derived from work by Harvey Fletcher [4] using only eleven observers who listened to pure tones through headphones. The 'A' weighting approximately follows the Fletcher and Munson 40 phon curve (± 3 dB). However the equal loudness contours were re-determined under more stringent conditions in 1955. Here ninety subjects were used and the loudness level for the 40-phon curve shows that the 'A' weighting under estimates the loudness of low frequencies by 6 dB to 8 dB. Even if the 'A' weighting was a good universal predictor of loudness it is not a good predictor of annoyance for complex sounds. Annoyance is multi-dimensional, in fact, at low sound pressure levels the character of the noise (e.g. temporal structure and frequency content) can become by far, the dominant factor in the annoyance perception. This was clearly shown in research carried out by Scannell [8] where subjects compared a low frequency repetitive impulse noise to pink noise for both loudness and annoyance. He found that for annoyance, any penalty added to the objective measurement for a source with unpleasant character must be level dependant with a higher penalty for lower sound pressure levels.

The fact that character is more important than the level can be realized by considering the simple case of a 'dripping tap' noise when trying to sleep. Wind machines when perceived indoors with windows closed become a low frequency noise and a noise that is constantly varying in level over approximate five-minute cycles. A certain level may be required to invoke sleep disturbance but once woken almost any audible level from wind machine noise is likely to cause a high degree of annoyance. Assuredly, the measured indoor 'A' weighted sound pressure level is almost irrelevant.

Anxiety and negative reactions to noise (and other similar stressors) can be reduced if they are predictable [9], [10] and [11]. Unfortunately the noise from wind machines is largely unpredictable, as the start-up is dependent mainly on metrological conditions. Accurate weather forecasting in the long-term or even medium-term is notoriously difficult.

It is hypothesized that people living close to a wind machine, if awoken, are lively to have an adverse reaction to the noise at levels only slightly above their audibility. This is mainly because of the unpleasant character created by the temporal structure of the frost fan noise. It gives the impression that when the noise level decreases it is going to stop – only to shatter the receiver's hopes when the noise level rises again. This repeats approximately every five minutes and could continue throughout the night. Any objective measurements, particularly indoors, must take the psychoacoustics of the noise into account rather than simply relying upon the frequency weighted sound pressure level.

Conclusion

Wind machines can be of significant benefit to fruit and vegetable farmers. They can provide them with an insurance against the risk of crop destruction from frost. The machines are likely to be in use less than thirty nights per year and possibly only five to ten nights per year. However, the noise from the frost fan and wind machines is likely to be the cause of adverse reactions by neighboring residents. The assumption that the problem is one-dimensional and can be controlled by criteria based on sound pressure level alone, particularly the indoor 'A' weighted sound pressure level, is likely to underestimate the problem. Factors such as the number of events per year, the unpredictable start-up, temporal structure and frequency content of the noise must be carefully accounted for in any assessment.

Are wind machines a necessary part of the future in agriculture areas or are they, to coin a phrase [12], a new form of 'acoustic violence'? Further research is urgently needed to set a reasoned Noise Policy for frost fans. The Policy will need to take into account all the issues considered in this paper. This includes the noise level above background, the psychoacoustics, the number of nights per year the machines are likely to be used and the social worth of the farming activities.

A reasoned and well thought out Noise Policy for frost fans and wind machines is required before this relatively new form of noise generator is allowed to reshape the night time agricultural soundscape.

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PERCENTILE POLICY PERILS

PROBLEMS WITH THE USE OF PERCENTILES FOR NOISE CONTROL POLICY

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Abstract

A statistical study has highlighted problems with using the L10, and percentile values in general, as a sound pressure level index for describing the component level of a noise source under investigation. For a condition where the noise source is partially submerged into the ambient noise, typically the aim of noise control policy, the source component percentile level derived can be in significant error. The error is related to the distribution in level of both the noise source under investigation and that of the ambient noise. The study showed that the equivalent continuous noise level, Leq, is not prone to these errors and is, technically, a much more reliable and accurate noise level index for use in noise control policy.

Introduction

The development of noise control policy has been influenced to some degree by the constraints of noise monitoring equipment. Prior to the introduction of sound level meters with digital processing, the level of a particular sound source was determined by observing the levels indicated by analog metering on the sound level meter and making a subjective judgement on the typical or average maximum noise level. In this context an ‘average maximum’ sound pressure level definition for use in noise policy was sensible. However, since the demise of analog metering and the introduction of sophisticated statistical sampling sound level meters, determining an ‘eyeball’ average maximum noise level has been displaced by the use of the L90 and the L10 percentile values to represent average minimum and average maximum values of a sampled soundfield. Additionally, noise criteria commonly specify a particular sound pressure level to be met by the source under investigation at a receiver location, the source component level.

This paper presents the results of an investigation into the validity of component percentile values for noise control policy.

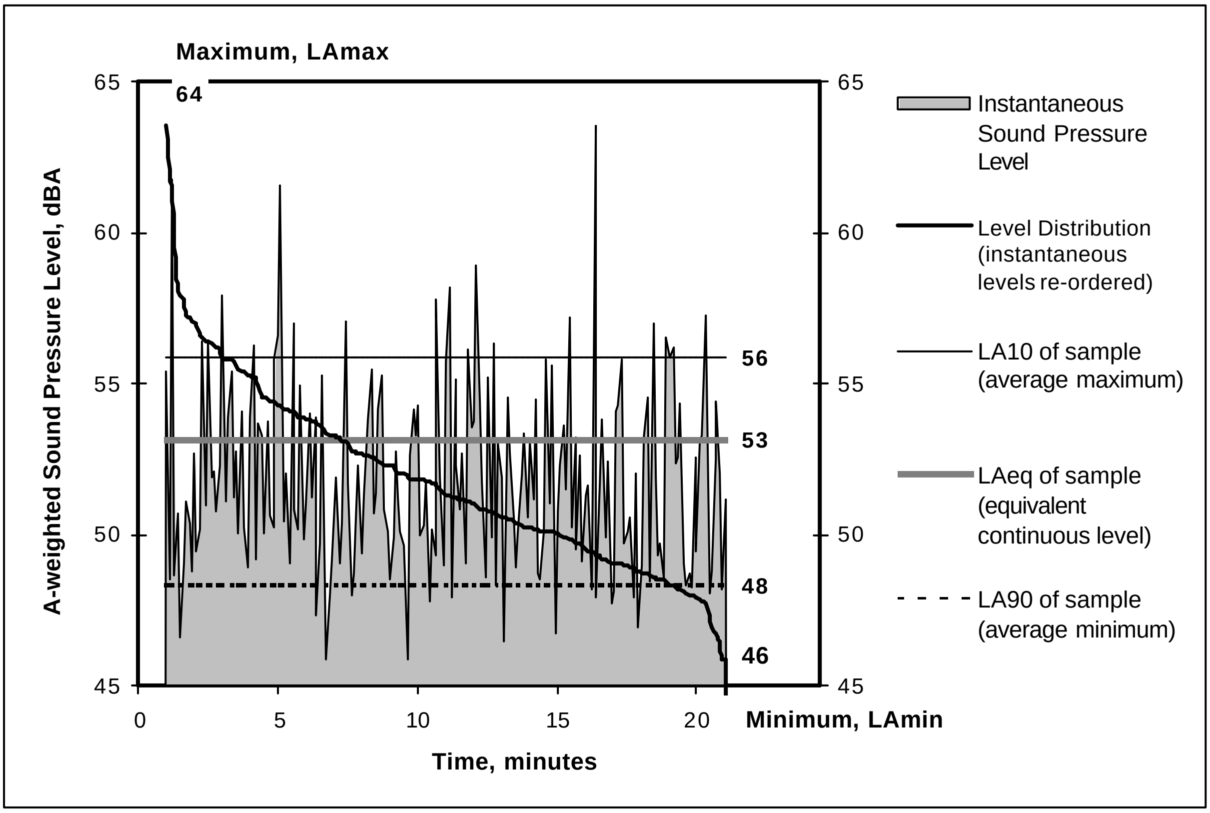
The Assessment Problem

To obtain statistical values of a soundfield, current day sound level meters take samples multiple times per second, typically every 100 ms (10 times a second). At the end of a 15 minute period at this constant sampling rate, the meter has 9000 values of the instantaneous level of the soundfield stored in memory.

To derive the percentile values of the measurement sample, the stored instantaneous sound pressure level values are processed by reordering them according to level rather than time and the percentile levels can then be determined from the relative position of an instantaneous value in the order. The equivalent continuous sound pressure level is determined from the logarithmic average of all of the instantaneous sound pressure levels sampled over the interval and is a measure of the mean sound energy of the noise level over the interval.

Figure 1 depicts an example of a 20 minute sample of a time varying sound field and the Lmax, L10, L90, Lmin and Leq values derived from the instantaneous values measured over the interval.

Figure 1 Noise Level Indices



Since noise criteria are generally defined with reference to the background noise level[1], it can be assumed that ambient noise is present in any measurement. Therefore, because of the contribution from ambient noise, the noise level of a noise source under investigation cannot be measured directly. What can be measured are the ambient noise itself (source not present) and the noise source under investigation including the contributions due to the ambient noise.

We wish to demonstrate that we can derive the component level of the noise source under investigation from a finite number of samples measured of the ambient noise and of the noise source under investigation plus the ambient noise contribution.

[1] the average minimum level of ambient noise, typically for a particular time of day

Model

In order to show the effects of noise level sampling, a simulation experiment was set up where the sound pressure level distributions of the 'ambient noise' and the 'noise source under investigation' were precisely know.

The model generated values[2] for the instantaneous 'ambient' and noise 'source' sound pressure levels and from these the instantaneous 'source plus ambient' levels were created by logarithmic addition. The 'ambient', the 'source' and the 'source plus ambient' instantaneous values were then ordered by level and the percentile levels determined.

The 'inferred source' component percentile levels were derived by the logarithmic subtraction of the 'ambient' percentile (ordered) values from the 'source plus ambient' percentile values[3]. These 'inferred source' percentile values were compared to the 'source' percentile values, the known correct values. For each simulation run, the 'inferred source' Leq value was also calculated from the logarithmic subtraction of the 'ambient' Leq from the 'source plus ambient' Leq.

The distribution used for the ambient noise was based on the results of three weeks of ambient noise level logging in a rural location. The instantaneous values of the ambient noise were generated by a multipart polynomial representing the cumulative probability of the ambient noise level distribution[4].

The instantaneous source values were generated from a range of basic distribution types (constant, uniform variation, normally distributed) to investigate the resulting behaviour of the derived source component levels.

Some Examples

The following figures depict the distribution in sound pressure level of the source noise including ambient noise, the ambient noise, the actual source noise and the inferred source noise. The portions of the inferred source percentile levels that are above the source percentile levels in the figures represent an overestimate of the source component percentile level. Conversely, the portions of the inferred source percentile levels below the source percentile levels represent an underestimate of the source component percentile level.

The error in the inferred source component L10 and Leq are given in each of the figures. The values of the source L10 and the ambient L90 are indicated. The ambient L90 level used in the simulation was 34 dBA and the noise source L10 values were chosen to show the effect of approaching this value.

The first two examples are for the simple case of a constant noise level source, one that is a constant 45 dBA and the second a constant 34 dBA. For these examples, the inferred source percentiles, including the L10, and the inferred Leq level are correct. The next set of examples is for the situation of a noise source with levels distributed uniformly over a given range. The final set of examples is for a noise source with levels that are normally distributed.

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[2] 2000 values were used for each 'measurement sample'. This represents the number of values that would be obtained from a measurement of around 3.3 minutes at 10 samples per second.

[3] This is a more controlled experiment than would exist in the field, as the ambient noise component is stationary in the simulation. In the field, two measurements of ambient noise which are not taken at the same time and at location would be expected to differ.

[4] The polynomial function provided a mapping from random percentiles, uniformly generated between 0 and 100, to percentile levels.

Constant Level Noise Source

Figure 2(a) Noise Source a Constant 45 dBA at Measurement Location

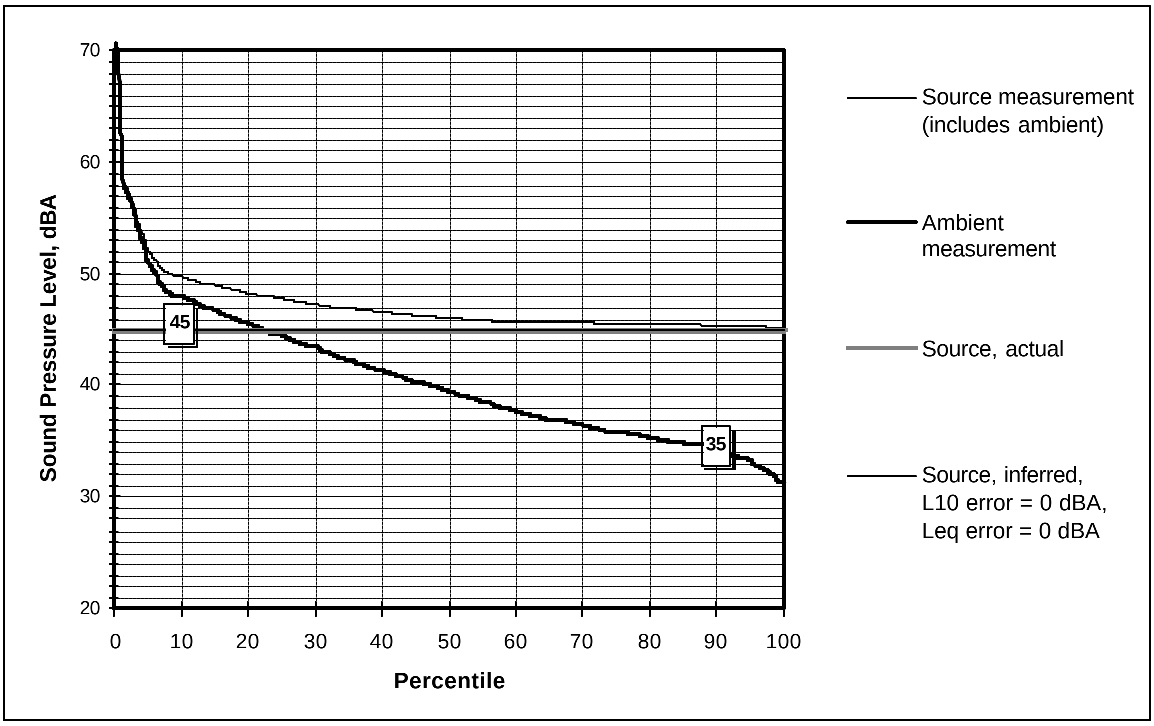
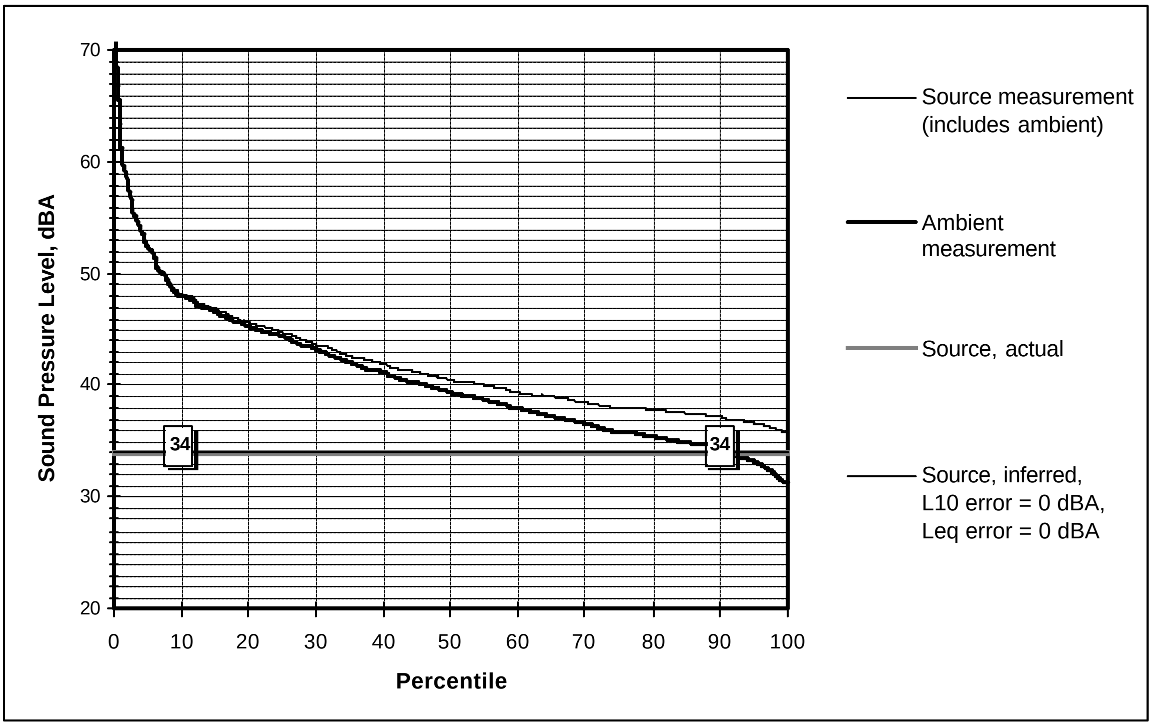


Figure 2(a) Noise Source a Constant 34 dBA at Measurement Location



Uniformly Distributed Noise Source Levels

Figure 3(a) Uniform Noise Source Level Distribution, 30 dBA to 45 dBA

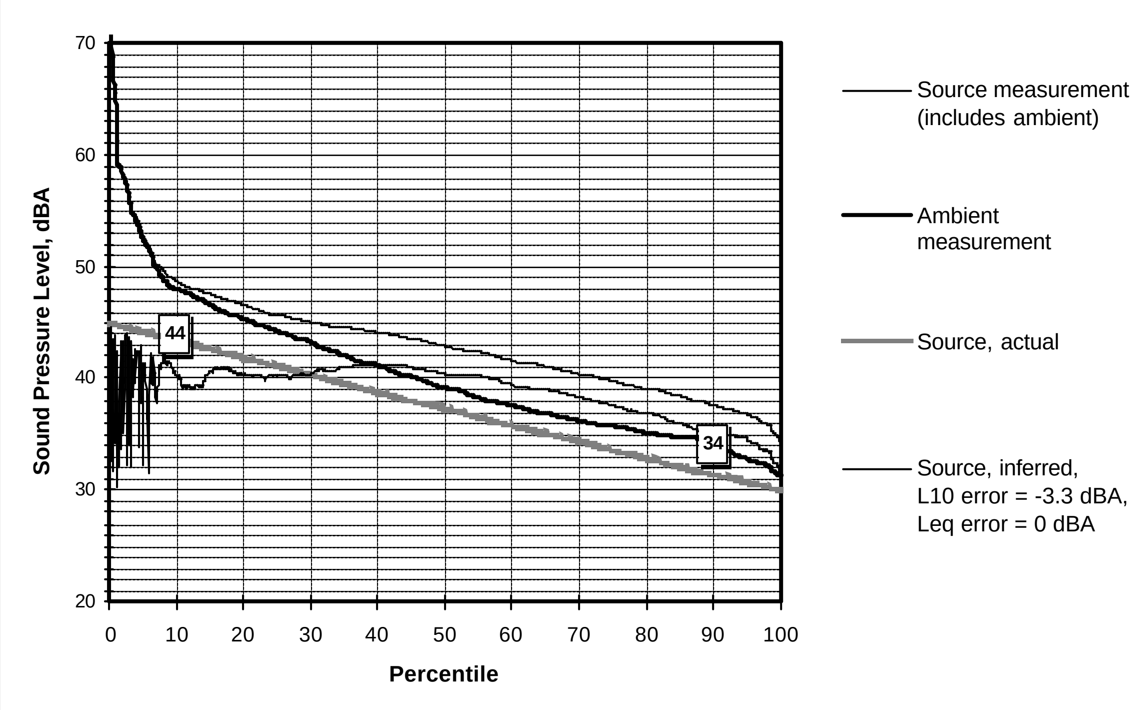
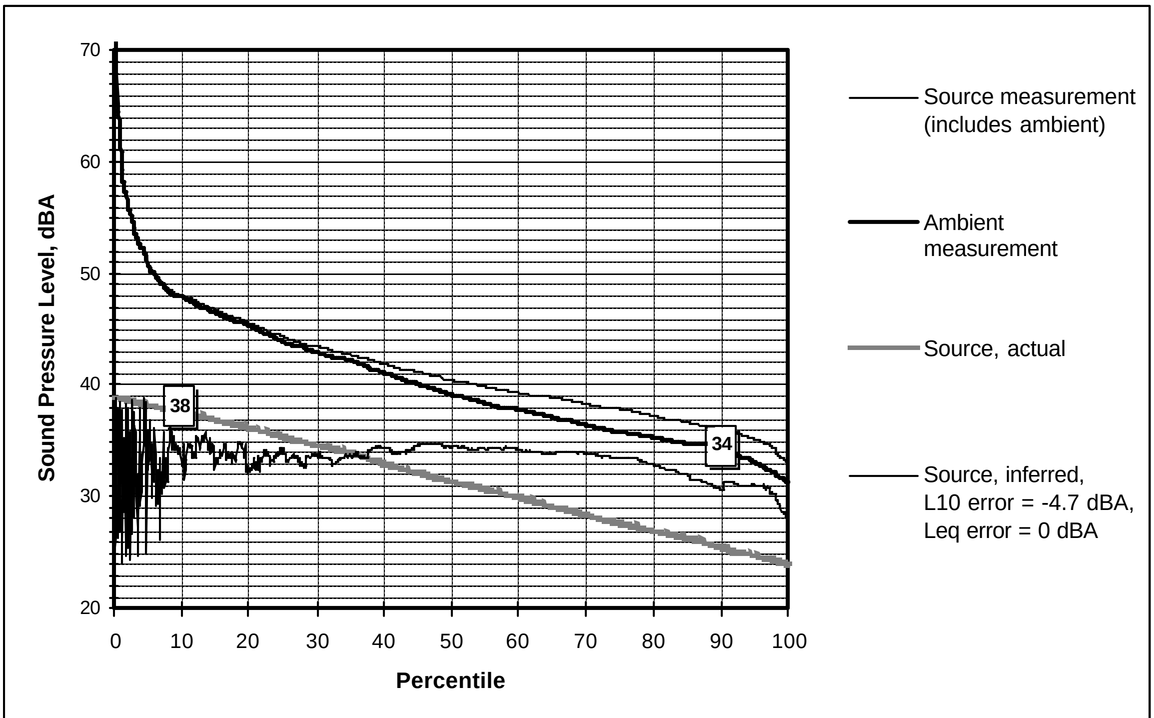


Figure 3(b) Uniform Noise Source Level Distribution, 24 dBA to 39 dBA



Uniformly Distributed Noise Source Levels cont'd.

Figure 3(c) Uniform Noise Source Level Distribution, 20 dBA to 35 dBA

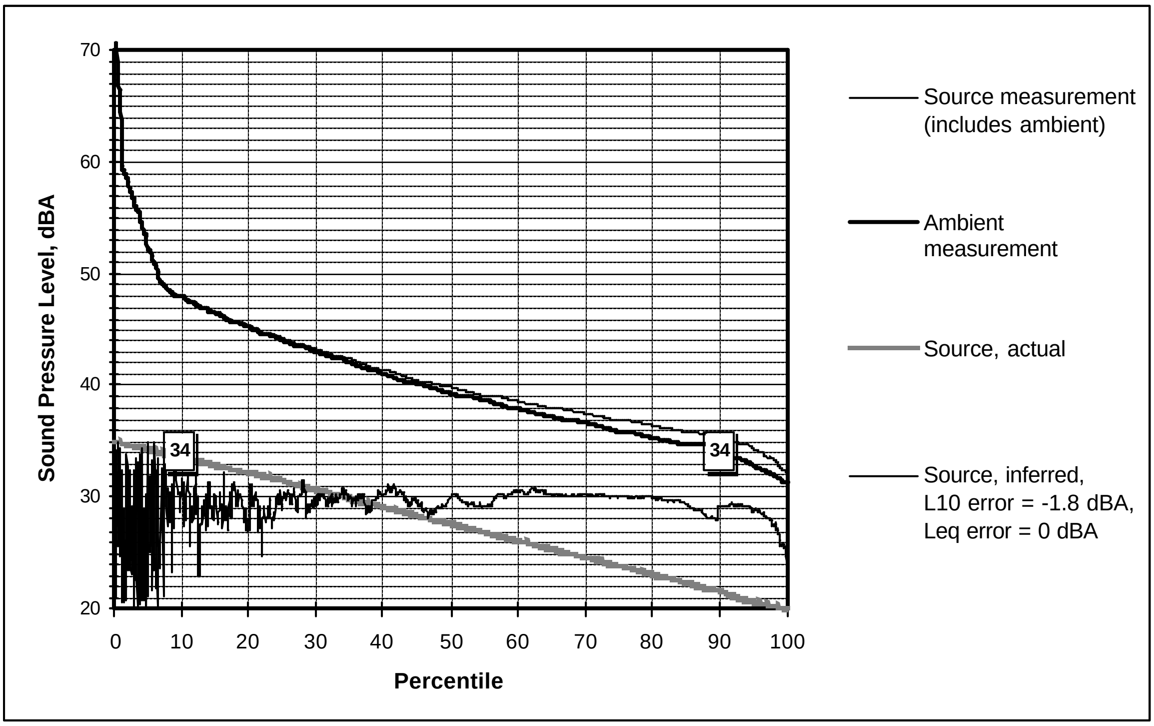
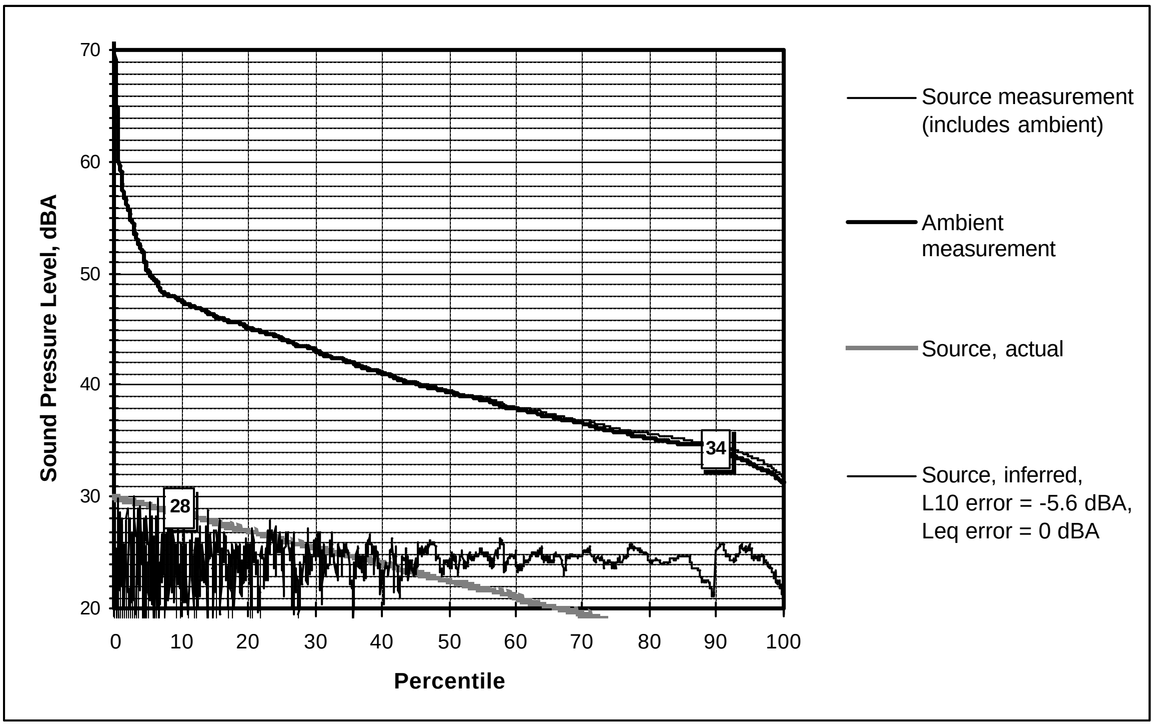


Figure 3(d) Uniform Noise Source Level Distribution, 20 dBA to 35 dBA



Normally Distributed Noise Source Levels

Figure 4(a) Normal Noise Source Level Distribution, Mean 45 dBA, Stdev 10 dBA

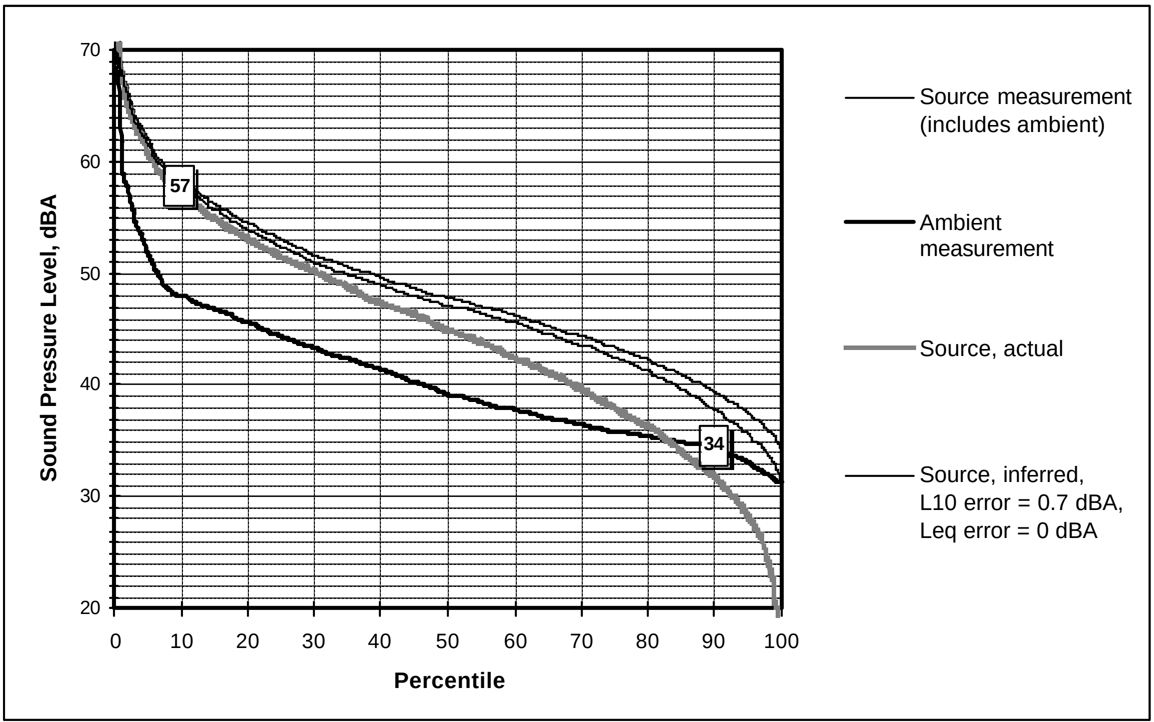
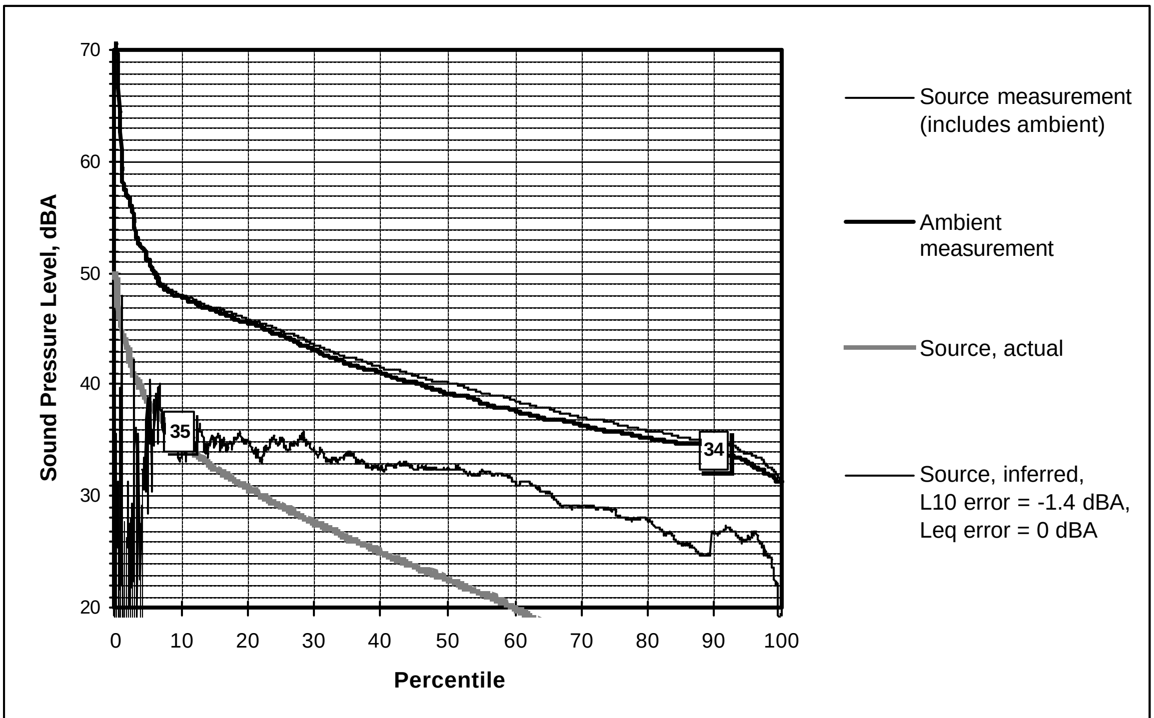


Figure 4(b) Normal Noise Source Level Distribution, Mean 22 dBA, Stdev 10 dBA



Normally Distributed Noise Source Levels cont'd.

Figure 4(c) Normal Noise Source Level Distribution, Mean 22 dBA, Stdev 15 dBA

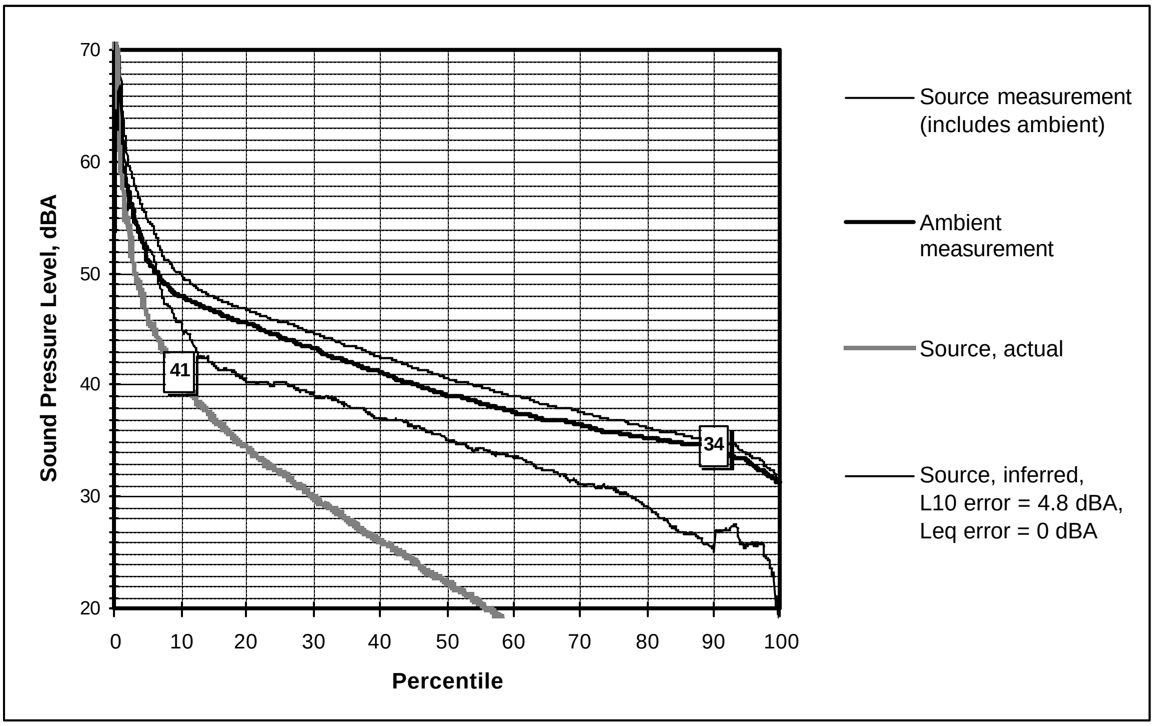
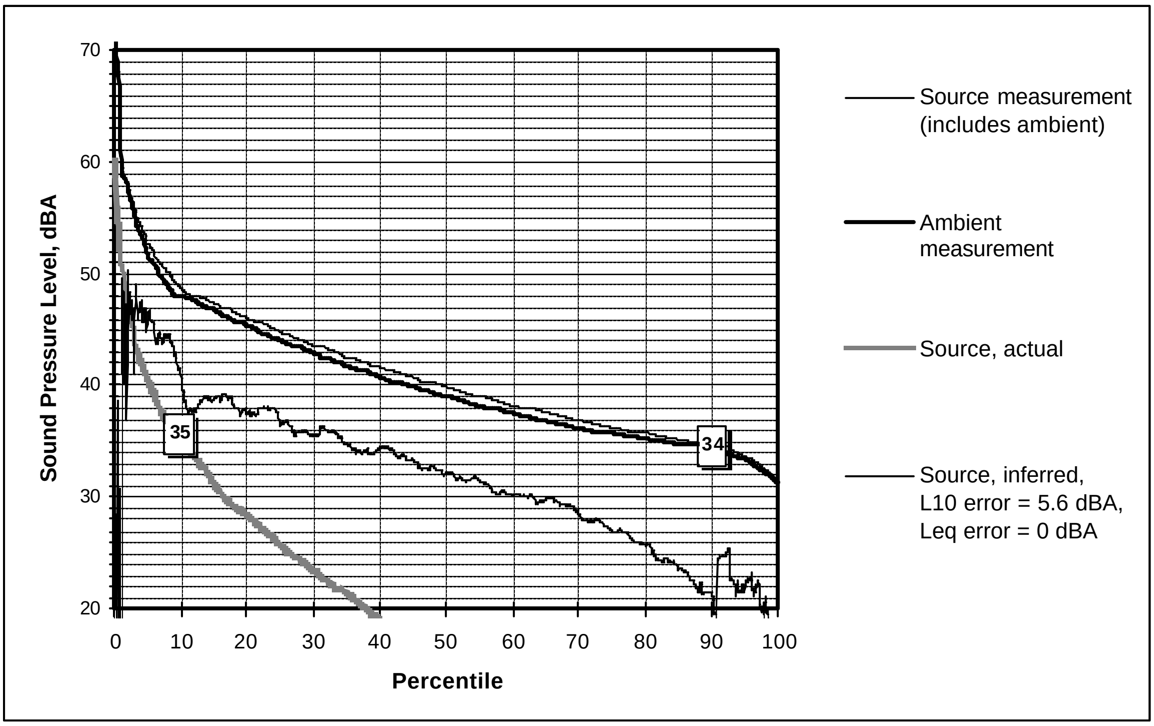


Figure 4(d) Normal Noise Source Level Distribution, Mean 15 dBA, Stdev 15 dBA



Normally Distributed Noise Source Levels cont'd.

Figure 4(e) Normal Noise Source Level Distribution, Mean 22 dBA, Stdev 10 dBA

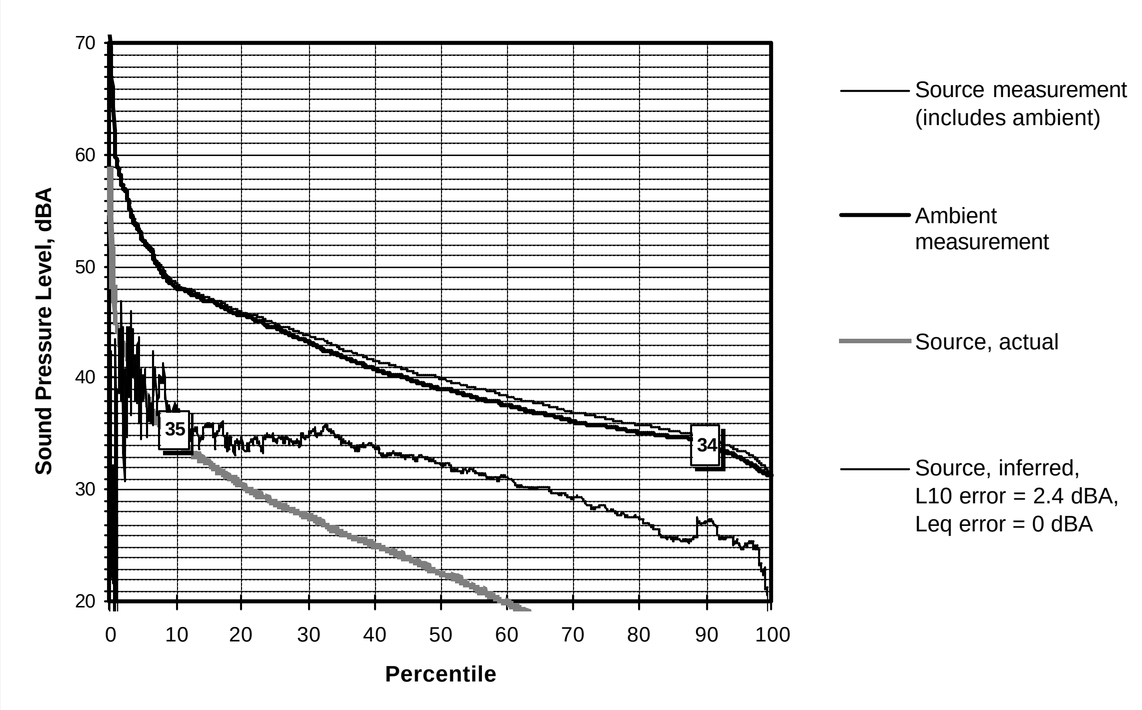
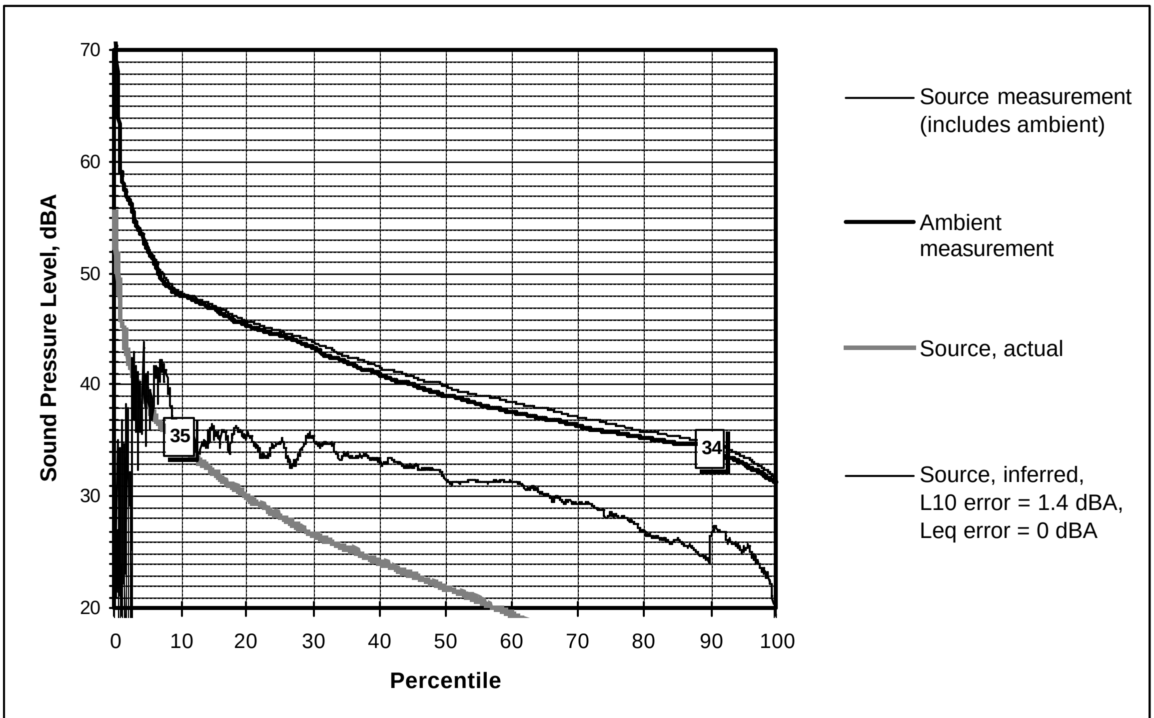


Figure 4(f) Normal Noise Source Level Distribution, Mean 22 dBA, Stdev 10 dBA



Discussion of Results

For a constant noise source level, the source levels inferred were correct. It is noted that this situation is only likely for a constant level noise source at a short distance from a receiver. Introducing some variation in the noise source level generated errors in the percentile values of the noise source inferred from measurements of the ambient and the noise source plus ambient[5].

In the case of a uniform distribution of noise source levels and a typical ambient noise distribution, the noise source percentiles were in significant error and the lower percentiles (Lmax to L30) underestimated. In addition to this, the values of these lower percentiles were unstable.

In the case of normally distributed noise source levels and the ambient noise distribution modelled, the noise source percentiles were again in significant error, however in this case the L10 was generally overestimated. Of most interest are the repeated samplings depicted in Figures 4(b), 4(e) and 4(f). For these three simulations, with identical noise source and ambient characteristics, the inferred source L10 value derived was different in each case and was both over and underestimated.

The Leq inferred for the source component was not in error for any of the simulations.

Conclusions

The results of the study indicated that, except for the condition where the sound pressure level of a source was well above the ambient level or was constant in level at the reception point, the source component percentile level derived from measurements may be significantly in error, both underestimating and overestimating the actual source component value. Additionally, the lower percentiles derived, including the Lmax, L01, L05, and L10, were unstable, i.e. repeated measurements did not necessarily result in the derivation of the same source component level, even though the ambient and noise source level distributions were unchanged.

No cases of error were noted in any cases examined for the inferred source component equivalent continuous level. On the basis of the results of the study, it is suggested that noise criteria based on the L10 percentile value of the source are seriously flawed and should be superseded by criteria based on the equivalent continuous level.

References

Hassall, J.B., Zaveri, K., Acoustic Noise Measurements, June 1988 5th Edition, Bruel & Kjaer

5 These are the only two quantities that can actually be measured.

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A SYSTEM FOR AUTOMATICALLY DETECTING THE DIRECTION AND LEVEL OF NOISE SOURCES

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Abstract
This paper describes an unattended monitoring system which allows environmental noise to be assigned to various directions of arrival at the measurement point. The system uses three microphones placed in a triangle about 0.5 metres apart. For each microphone pair, the cross-correlation between the signals is used to find values of time delay, and hence angles of approach of a noise signal, at which the received noise is at a maximum. Where all three cross-correlations give maxima at the same angle, a source is assumed to exist. L_{eq} *noise levels from sources within each 5-degree angle range are accumulated, and saved for post-processing.*

The system should have application where noise from a single source (such as a mine or industrial plant) needs to be monitored in isolation, or where some noise sources (such as traffic) need to be excluded from a measurement.

Introduction

A common problem in monitoring environmental noise is the difficulty in assigning the measured noise level to a specific source. This problem becomes acute where the monitoring is performed to check compliance with legislative requirements or conditions of consent, and often results in ambiguity which hinders the enforcement of these conditions.

In addition, some policy guidelines require assessment of noise from specific sources only. For example, in determining certain noise criteria the NSW Government's Industrial Noise Policy requires measurement of noise from "industrial" sources only, excluding noise from traffic and other sources.

Current methods of assigning measured noise to a specific source include the use of time-history or spectral information, the use of short sections of recorded audio signal and, ultimately, full-time attended monitoring to identify the dominant noise sources at all times. All these methods have a limited range of applicability, and none is suited to routine monitoring of noise from general sources.

This paper describes a system for automatically detecting sources of environmental noise by direction, and recording the L_{Aeq} noise level arriving at the monitor from each detected source. The system thereby apportions the total L_{Aeq} noise level at the monitor location into directional components, allowing:

- accurate monitoring of noise level compliance for a source in a known direction;
- exclusion of noise arriving from certain directions; and/or
- determination of which of a number of sources is the dominant contributor to noise at the monitor location.

Methodology

Operating Principles

The monitoring system is based on a principle described by Harris and Ledwidge[1] in which the direction of a sound source may be determined from the time delays between signals arriving at multiple microphones. These delays may in turn be found from the cross-correlation functions between signals from pairs of microphones.

When the same signal arrives at two microphones at different times, the cross-correlation function will have a local maximum at a delay equal to the time difference. The value of the maximum is related to the level of the signal arriving with that delay, by:

$$L_{sig} = L_{tot} + 10 \log(C)$$

where L_{sig} is the noise level of the signal, L_{tot} is the total noise level recorded in the sampling period and C is the value of the cross-correlation function at the relevant delay. The angle of arrival and the distance to the source are then related to the delay time, although for a single microphone pair these are not determined unambiguously. If noise arrives simultaneously from two directions, there would be two peaks in the cross-correlation function, and the estimated levels of both signals would be given by the above formula.

Peaks in the cross-correlation function also occur for other reasons. If the noise signal has peaks in its auto-correlation function (generally associated with a tonal or narrow-band signal), these will also appear in the cross-correlation. Maxima also occur simply due to the random nature of the signals involved. In addition, two closely-spaced peaks may appear as a single maximum, particularly for low-frequency signals or where one signal is significantly weaker than the other.

The detection system described here uses three microphones arranged in an equilateral triangle. Cross-correlation functions are formed between each of the three microphone pairs, and all local maxima in these functions are found. An algorithm then searches for sets of three maxima which could all represent a source in approximately the same direction, and at the same distance. The computed noise levels from all sources within a specified range of angles are accumulated, giving an estimate of the total L_{Aeq} noise level arriving at the monitor from that direction.

In some cases, the search algorithm will detect "spurious" noise sources based on a set of random maxima which happen to occur at time delays corresponding to a real noise source in some direction. However, such artifacts tend to occur in isolated noise samples, which are typically of 1-second duration, and experience indicates that their contribution to the L_{Aeq} noise level over an extended period is negligible.

Of more concern is the non-detection of real sources due to one or more cross-correlation peaks being "buried" by peaks from higher-level sources with a similar delay. This may result in some sources not being detected at all, or in the L_{Aeq} level due to low-level sources being underestimated, because the sources are detected in some 1-second samples but not others. This issue is discussed further below.

Implementation

In practical implementation of the system, the three microphones are located in an equilateral triangle with side L = 0.5m. Signal from each microphone is A-weighted and sent to an analogue-to-digital converter sampling at 44.1 KHz. One second of audio data is accumulated, and then processed while the next sample is accumulated. Using a 1.5GHz processor and optimised calculation routines, processing can be accomplished within 1 second, allowing real-time operation with no loss of data.

Data processing consists of the following operations.

1. For each of the three microphone pairs, a cross-correlation is formed between the two signals, with delays ranging from $-L/c$ to L/c where c is the speed of sound. Note that because the value of c may change significantly with temperature, a temperature sensor is incorporated into the system and queried on a regular basis to update the value used in calculations.

2. The processing algorithm finds all local maxima in each of the three cross-correlation functions, and searches for "matching" sets of three maxima which could represent the same noise source. The tolerance used in matching source angles is typically set at 10°. Each maximum is assigned to at most one source – where two assignments are possible, the assignment giving the highest source level is taken.

3. The process described above is applied in each one-second sample period. The noise level of all sources detected in each 5° angle range is accumulated on an energy basis, giving an estimate of the L_{Aeq} noise level arriving at the monitor from each of 72 directions. These accumulated levels are typically recorded every 5 minutes throughout a monitoring period. The results can be displayed in real time, and can be post-processed to give noise levels over any relevant time period.

Note that the algorithm used assumes all noise sources are at an angle of less that 15° above the horizontal, and at a distance of at least 3L from the centre of the microphone array. Noise from other sources would form part of the "unassigned" component of the total measured noise.

Testing

Tests of the system were conducted in an open park, using loudspeaker sources located approximately 25 m from the microphone array. Existing ambient noise was generally due to distant traffic, birds and similar sources. Its level was quite constant throughout the testing period at 54 – 55 dBA L_{Aeq}, and the direction of origin was diffuse, although there was a tendency for concentration in one 30° range of angles, corresponding to a distant major road.

In the first series of tests, the noise level from a single loudspeaker was initially set to be much higher than the ambient level at the monitoring location, so that the noise level from the source (broad-band pink noise or recorded traffic noise) could be taken to be the total measured level. The source output (as monitored by a sound level meter close to the speaker) was then reduced until its level at the monitoring location was at or below the ambient level. The noise level originating from the source direction, as measured by the directional monitoring system, was then compared with the actual known noise level from the source. This situation is considered to be representative of typical noise monitoring tasks, where the noise level from a source of interest is at or below the ambient L_{Aeq} level.

Typical results of this testing are shown in Figure 1. (More detailed results are available from the author.) As the source noise level is reduced, the total measured noise level at the monitor first reduces and then stays stable at the ambient level of 54 – 55 dBA. However, the level detected from the source direction continues to give an accurate indication of the true source level (to within 1 dBA) for source levels at least 5dB below the ambient. As the source level decreases further, the "measured" level drops below the true level because in some 1-second samples the source was not detected. This behaviour was repeated for other types of source noise including octave-band filtered pink noise (at all frequencies) and recorded impulsive noise.

The second series of tests was more stringent, using two loudspeaker sources separated by an angle of approximately 25° at the monitor, set to produce different noise levels, both of which were significantly above the ambient. The noise level due to each source was measured individually, and then the two were measured simultaneously using the directional monitor, over a period of 30 seconds.

Results of this test are shown in Figure 2, for different combinations of noise types from the two speakers and different relative noise levels. In all cases the monitor detected two sources in the correct directions, to within 10°. Figure 2(a) shows the measured noise level for the louder of the two sources in each test, compared with its true level. In all but one case, the level of the louder source was accurately measured to within 1dBA, in the presence of noise from the second source.

On the other hand, the true L_{Aeq} noise level from the lower-level source was consistently underestimated, due to the source not being detected in some samples, as described above. In situations such as this, the "measured" level for lower-level sources should be regarded as a lower limiting value. An upper limiting value can be set by assuming all "unassigned" noise is actually associated with the source in question.

Figure 2(b) shows the range of estimated noise levels obtained in this way. The range covers the true source noise level in all cases, although sometimes the range is admittedly very large. Best results were found when both sources were recorded traffic noise, which varies with time, rather than one or both being a constant level of pink noise. This is considered more likely to be representative of typical measurement situations. For the traffic/traffic case, a secondary source which is over 10dBA below a dominant source and separated from it by 25° in angle could be identified, and its noise level estimated to within a range of about 6dBA.

Operation

At the time of writing this paper, a permanent directional noise monitor has been installed for approximately two weeks close to a coal mine in the Hunter Valley. Figure 3 shows a typical example of the results obtained. In this 5-minute monitoring period, from the total measured L_{Aeq} noise level of 39.5dBA, 38.4dBA could be attributed to sources detected by the system, of which 35.3dBA resulted from sources in the range of angles which is highlighted in the Figure (corresponding to a known source). It is hoped that further results from operating monitors can be presented at the Conference.

Conclusion

The system described in this paper provides a means of automatically assigning measured L_{Aeq} noise levels to sources located in specific directions. If one source is dominant during a 1-second sample, the level and direction of that source will be accurately recorded to within about 1dBA and 10° respectively. Sources which are not dominant will also be detected, but more care needs to be exercised in estimating their level, and in some cases it may be necessary to quote a range of possible noise levels.

It is hoped that a monitoring system such as that described here will allow more accurate identification of noise sources in the field, as well as reliable checking of compliance with regulations which limit noise emissions from specific sites.

Reference

1. Harris, R.W. and Ledwidge, T.J. Introduction to Noise Analysis, pp 62-63. Pion, 1974.

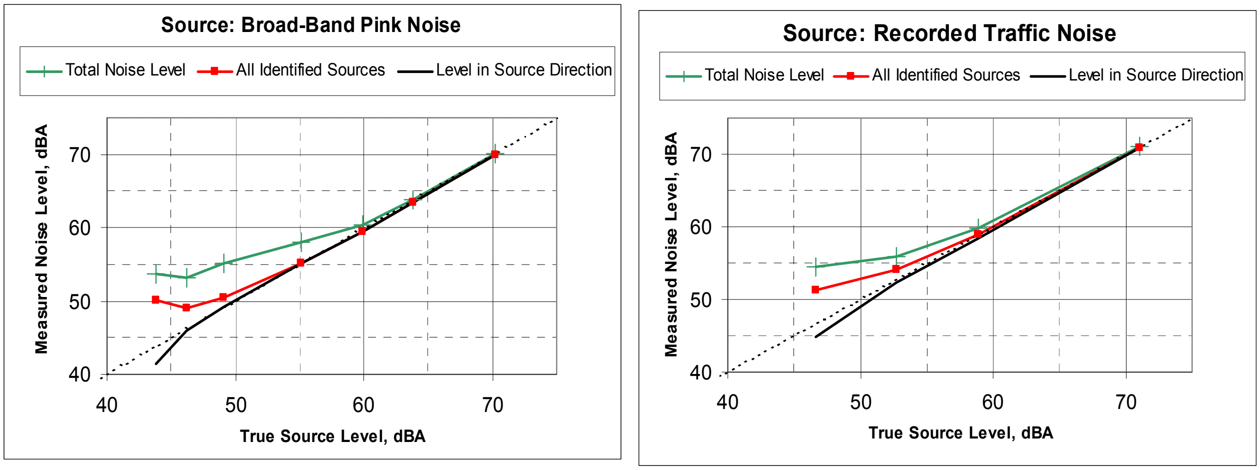

Figure 1 Detection of a Source in the Presence of Background Noise
(a) Broad-Band Pink Noise Source
(b) Recorded Traffic Noise Source

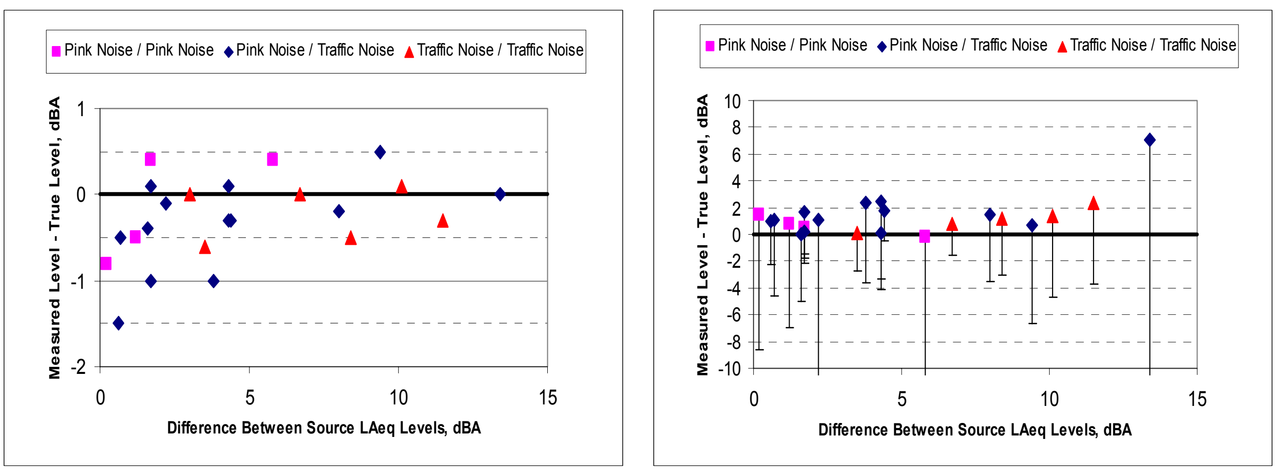

Figure 2 Detection of a Source in the Presence of Another Source
(a) Detection of the Higher-Level Source
(b) Detection of the Lower-Level Source

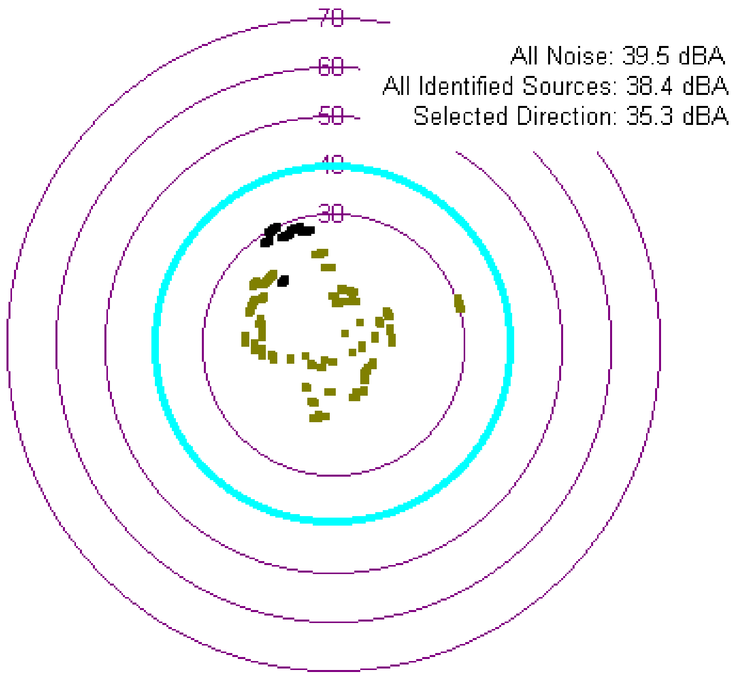

Figure 3 Typical Output from 5-Minute Sample of Environmental Noise

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ASSESSMENT OF ENVIRONMENTAL NOISE FROM RAILWAY TRANSPORTATION AND SLEEP DISTURBANCE

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Abstract

There are a number of different systems used for assessment of environmental noise from railway operations in Australia at present. The NSW EPA is known to be currently considering policy on this matter. This paper presents data developed during recent railway noise studies and control activities and provides some discussion and review of what may and may not be acceptable in terms of sleep disturbance, and what other parameters may be suitable for assessment, beyond the currently used L_{AMax} *and* $L_{AEQ.24hours}$*. The use of SEL of < 90 dB(A) for individual rail event assessment is suggested for typical passby events of 1 minute, along with* $L_{A01.15min.}$ *of <76 dB(A) for use with unattended logged data, for rail activities to not cause annoyance in 95% of the exposed population.*

Introduction – Background and Objectives

This work commenced as part of a project to assess and then consider controls for a private freight rail line in 2001. The monitoring program gathered a range of statistical data easily available on standard instruments, able to be downloaded for manipulation later. Both attended and unattended measurements were made of rail operations.

The intention was to try to obtain data which could correlate the time of train events with logged data of environmental noise parameters. Standard parameters known to be used in assessment of transportation noise were L_{AMax} and L_{AEQ}. These were available on unattended logging instruments, along with statistical data. SEL and noise character was recorded during attended monitoring. Unattended logging of SEL is more difficult to arrange. It was relatively easy to compare the attended data with criteria, but what was also being sought was a way to consider the unattended, logged data with train passby events and criteria. The problem with field measurements of L_{AMax} is that you can never be completely sure about what caused it - any momentary event, such as a bird, dog barking, or motor cycle can cause it to be stored.

Graphs of 15-minute samples of L_{AMax}, L_{AEQ} and L_{A01} were plotted against time along with train events, shown in Figures 1, 2 and 3. Squares show train up times, triangles down. For the L_{AMax} data there is obviously a lot of "noise" in the data – that is, there are maximum events occurring which are related to train passby events as expected, but there are just as many of a similar or greater level when there is no train event. This can be expected for any measurement location where there is exposure to road traffic noise much more frequently than train noise, because the L_{AMax} can be an event lasting $1/8^{th}$ of a second or whatever the sample interval of the instrument. The L_{AEQ} graph had less noise and more visual correlation to train passby events, but doesn't indicate the maximum sound level occurring during a passby.

Figure 1. Rail Study LMax Results 24 to 27 April 2001

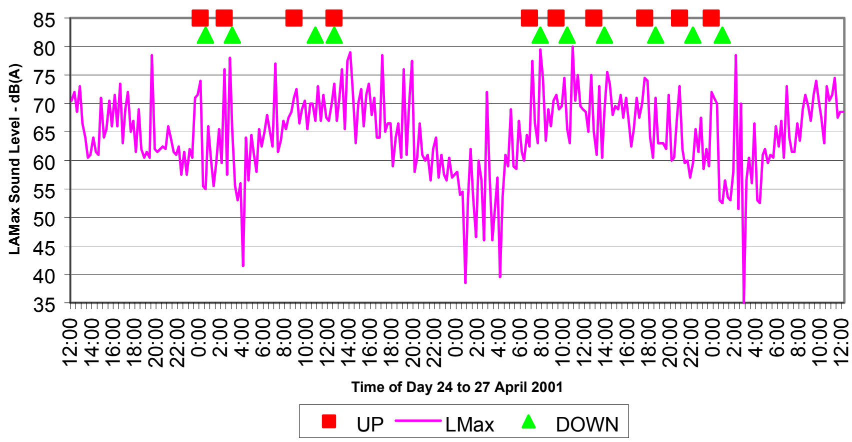


Figure 2 Rail Study LEQ Results 24 to 27 April 2001

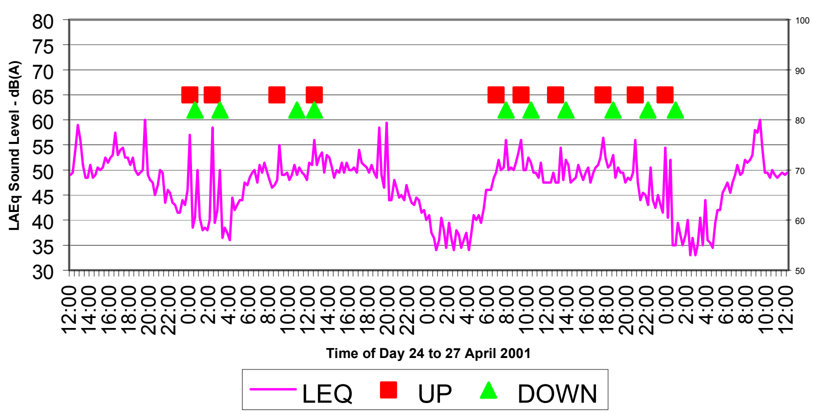
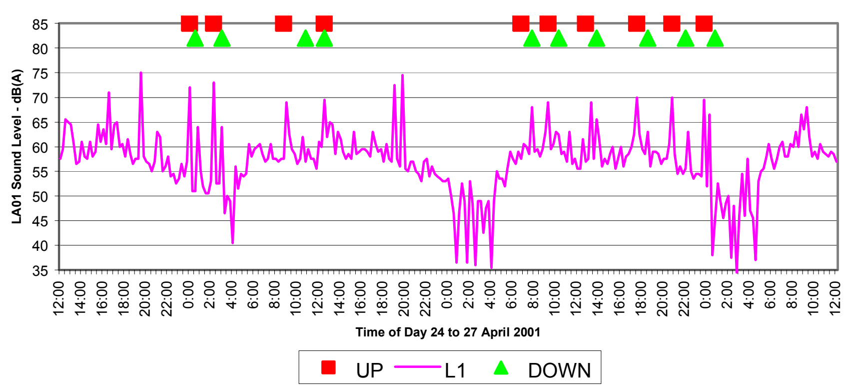


Figure 3. Rail Study L01 Results 24 to 27 April 2001



L_{A01} is the 1% exceedance A-weighted sound level – that is the sound level exceeded for 1% of the measurement time interval. With the L_{A01} data in Figure 3, there also appeared to be less visual noise and a higher correlation to train passby events than L_{AMax} (although there were still some events of similar level when there were no train passby events). This seemed logical, as a train passby typically lasts for 40 to 60 seconds for the measurement location, and the maximum may occur over a period of 5 to 10 seconds or more.

This is long enough to become the $L_{A01.15min.}$ (a period of 9 seconds in a 15 minute interval), whereas a car passby maximum may only be 2 to 4 seconds, if that. The attended data had (unweighted) L_{Max} - L_{01} difference results of 1.7 dB average, compared to the difference for the adjacent ambient period of 2.4 dB average (for approximately 50 measurements each). This caused consideration of whether $L_{A01.15min.}$ would be a better metric.

This then led to a review of papers on rail and transportation noise affecting sleep disturbance and annoyance, and what the L_{AMax} values used or promoted as criteria were based on. Was it the L_{AMax} sound levels that caused people to awaken, or have some other effect, and how were they measured or assessed in the first place? The objective was to see if $L_{A01.15min.}$ logged data, correlated to rail passby event times, could make a reasonably easy parameter to measure. So the work was from the aspect of measurement of sound levels, not the assessment of annoyance or sleep disturbance and its dose-response, which is a different field of activity. Along the way, this paper briefly reviews other work on sleep disturbance and the effects of rail and transport noise. It is not intended to be a comprehensive or exhaustive review of the current status, as there is not enough time or space. But it may be of assistance to policy-makers in developing improved criteria for environmental noise from railways.

Sleep Disturbance and Annoyance Criteria

Australia

The effects of night-time noise were a major issue in the field work on which this paper was based, as a number of trains operated at night. In New South Wales (NSW) where the work was undertaken, the regulator is the Environment Protection Authority (EPA). Currently their only recent policy on transportation noise is in the 1999 Environmental Criteria for Road Traffic Noise (ECRTN) (1). This provides a fairly comprehensive review of sleep disturbance from transportation noise, especially road traffic and aircraft. An earlier policy document, the Environmental Noise Control Manual (2), had given criteria for sleep disturbance based on the emergence of the event noise above the background. This was for $L_{A01} \leq L_{A90} + 15$ dB. No measurement interval was given but it was assumed to be 15 minutes or longer. The ECRTN concluded that sleep disturbance from transportation was related to the emergence of the noise event above the background, the maximum sound level of the events and the number of events in a night. However the EPA noted that more research was needed into sleep disturbance and traffic noise and chose not to set any criteria. The ECRTN indicates that the EPA acceptable criteria still allow for 10% of the exposed population to be annoyed. Sleep disturbance is not considered in their current Industrial Noise Policy 2000 (3).

The Roads and Traffic Authority of NSW (RTA), the “operator” of most of the State’s roads, developed an interim policy on Sleep disturbance from the EPA 1999 document (4). This notes that maximum internal sound levels below 50 to 55 dB(A) are unlikely to cause awakening reactions, one or two noise events per night with maximum internal noise levels of 65 to 70 dB(A) are not likely to significantly affect health and wellbeing, and L_{AEQ} is ok as a parameter where road traffic is continuous rather than intermittent, but where $L_{AMax} > L_{AEQ} + 15$ dB, the $L_{AEQ.9hr}$ is not sufficient alone (to assess sleep disturbance).

The EPA of NSW is currently preparing a policy document for rail noise and hopefully this will contain more information on sleep disturbance from rail noise. The policy position of other states in Australia has been difficult to obtain and many appear to be waiting on NSW. Western Australia has criteria based on $L_{AEQ.24\ hour}$ alone. The current general criteria in NSW for rail noise are $L_{AEQ.24\ hour}$ 55 dB(A) for new developments and 60 dB(A) for existing operations, and L_{AMax} of 80 dB(A) for new developments and 85 dB(A) for existing operations. This does not appear to consider night-time noise events, the number of events above a specific level or the characteristics of the noise – wheel squeal, low frequency diesel or the faster noise of passenger rail cars, which are relevant in assessing the potential for annoyance and sleep disturbance. The EPA also applies licence conditions to locomotives used on NSW public railway systems. These are maximum operating levels under all service conditions 0 to 50 kmh, as L_{Max} at 15 metres of 87 dB(A) and 95 dB Linear.

International

Most of the recent work on assessment of rail noise appears to have been in the area of high-speed rail. In a 1991 UK study (5) there was a comparison of objectives for rail noise in Europe, Scandinavia and Japan. The UK, Denmark and Sweden had objectives had both L_{AEQ} and L_{AMax}, for the period - the UK criteria had both day and night levels while Denmark and Sweden had 24 hour levels. Other European countries had L_{AEQ} levels for different times of the day and night, while Japan had a 24-hour L_{AMax} criterion. The range of L_{AEQ} external façade levels had a minimum of 40 dB(A) (Switzerland) and the lowest L_{AMax} reported was 73 dB(A) for external (UK) and 50 dB(A) internal (Sweden).

The US EPA has standards for locomotive operation on interstate carrier operations for locomotives and rail cars, but they are based on emitted noise received at 30m rather than residential receiver noise (6). The maximum sound level from a moving locomotive is 90 dB(A). For rail car operations, the sound level depends on the speed of operation, being 88 dB(A) at less than and up to 75 kmh, and 93 dB(A) at speeds greater than 72 kmh.

Road Traffic Criteria and Effects compared to Rail

A large number of studies, papers and reports were reviewed to identify the extent of research into rail noise and sleep disturbance and annoyance. Many of these were similar to those reviewed in the ECRTN. Studies on sleep disturbance had included field and laboratory trials and measured physiological changes as well as subjective responses. Some had used recorded events of aircraft, road or rail traffic and aircraft studies had done field trials at locations close to airports or major roads. It is assumed that the maximum sound levels used or occurring were relatively well controlled and caused by the sources under investigation. That is, there were likely to be no extraneous noise sources causing maximum sound levels sufficient to have a response on annoyance or sleep disturbance. This is different to what may occur in logged measurements in the field, as noted in the introduction, where any event, such as a briefly passing car, truck , dog barking or bird squawk could cause the maximum.

Typical of many studies were a 1997 paper by Öhrström (7) into the difference in effects of rail noise with and without accompanying vibration from the train passby and the effects of low level road noise during the night. The rail study used *calculated* maximum sound levels to compare with annoyance responses. A similar road noise study by Öhrström in 1995 (8) had 12 subjects in a laboratory who were played recorded road traffic noise at different sound levels. Both studies found increased annoyance or sleep disturbance with increasing noise level and number of events.

A common item found in several papers was the consideration that rail noise is less annoying than equivalent levels of road traffic noise. The UK rail report (5) also described a 1982 study where sleep disturbance is considered significant when 25% of the population is likely to suffer some disturbance from all causes. Facade *(external)* equivalent noise levels at which these occur are L_{AEQ} 55 dB(A) steady noise and road traffic and 60 dB(A) for aircraft and trains. The corresponding maximum noise levels L_{AMax} are 80 dB(A) for steady noise, 75 dB(A) for road traffic and 85 dB(A) for aircraft and trains. The report also noted that aircraft and train noise become significant at $L_{AEQ} > 60$ dB(A), but if there are more than 20 events per night it could occur at a lower value of L_{AEQ} for which the L_{AMax} of individual events exceeds 85 dB(A).

Öhrström (7) also noted a study by Moehler in 1991 (9), that a majority of rail noise studies reported in the literature show that railway noise causes less general annoyance (4 to 15 dB) than road traffic noise. The paper recommends that for less than 5% of the exposed population annoyed or rather annoyed, rail noise objectives should be L_{AMax} 80 dB(A) and $L_{AEQ.24\ hrs}$ 55 dB(A). If strong simultaneous vibration is present, action against vibration or a longer distance between houses and the railway line is needed, corresponding to a 10 dB(A) lower noise level than in areas without vibration. As noted earlier, the EPA of NSW considers that with their criteria, significant annoyance may still occur in up to 10% of the exposed population.

Few of the studies reviewed considered wheel squeal in their discussions. One 1996 paper (10) did discus the problem of wheel squeal in railway yards. For the work from which this current paper developed, wheel squeal on narrow radius bends was a major source of high sound levels at high frequency (~3kHz), which resulted in significant (anecdotal) annoyance in the exposed population.

Alternatives to L_{AMax} and L_{AEQ} as Objectives

None of the papers reviewed gave guidance or consideration into the use of L_{A01} in place of L_{AMax}. The use of SEL for assessment of event noise was discussed in some papers for aircraft noise (References 11 to 14). One paper suggested that below outdoor noise event levels of 90 dB(A) SEL and 80 dB(A) L_{AMax}, aircraft noise events were considered most unlikely to cause any measurable increase in overall rates of sleep disturbance (13). These levels could be applied to railway noise as suitable criteria, provided there is no associated wheel squeal or other annoying characteristics of the passby event. They are considered suitable as criteria based on the field measurements done of rail noise. TNO have also developed a relationship of SEL to the probability of awakening for different time history characteristics. However it is a relationship rather than a recommended criterion (12).

The Difference between LMax and L01 for Rail Passby Events

Field data of L_{AMax} and L_{A01} from the work were reviewed to assess the relative values of the $L_{AMax.15min}$-$L_{A01.15min}$ difference between rail events and non-rail events. As noted earlier, the attended (unweighted) data had L_{Max}-L_{01} difference values averaging 1.7 dB for the train passby events, compared to the ambient period immediately after the train passby of 2.4 dB for just over 50 measurements. Typical event periods were around 1 minute. A similar analysis was made for the 21 days of logged data. The analysis showed higher differences than occurred with the unweighted attended data - the differences for the rail events were an average of around 4 dB, compared to 7 dB for the non-train periods. The number of samples for train events however was relatively low (67 total and 15 for nights). Further measurements of periods with train passby events are warranted to obtain a better statistical basis. The objective of such measurements would be to further develop a suitable $L_{A01.15min.}$ criterion for a train passby event. This would be based on the current acceptable range of L_{AMax}, with the difference coming from these results. At present, based on the above analysis, a difference of 4 dB is considered a reasonable starting point for train passby events.

Conclusions

A review of papers and reports of community annoyance and sleep disturbance from transportation noise and rail noise in particular has confirmed a number of well-known aspects. The dose-response relationship for rail depends more on maximum sound level than 24 hour or night period L_{AEQ} because of the intermittent nature of rail noise events. The number of events is an important aspect, with more than about 20 events above maximum internal sound levels of 65 to 70 dB(A) being considered significant. Rail noise may be less annoying than road traffic noise for equivalent sound levels but this needs further work in the area of sleep disturbance.

No studies have indicated statistical values for considering L_{A01} versus L_{AMax} values, but some have commenced using SEL for passby noise event assessment. Outdoor noise event levels of less than 90 dB(A) have been suggested as unlikely to cause sleep disturbance effects for aircraft noise. This value also could be relevant for a rail noise event descriptor.

Analysis of measured data for a small freight rail operation has indicated that the L_{Max}-L_{01} difference of 4 dB could be used to provide an $L_{A01.15min}$ criterion for periods containing rail events, when using unattended logged statistical sound level monitoring methods. Further measurements are required to confirm that 4 dB is a reasonable value for train passby periods. A suitable objective for $L_{A01.15min}$ is 76 dB(A), based on aircraft noise studies.

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EXTERNAL AND INTERNAL ACOUSTIC TESTS ON A MODERN PASSENGER TRAIN WHILE IN-MOTION

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Abstract

Acoustic tests were conducted both outside and inside a modern passenger train while stationary and while in-motion. These tests were conducted for the purpose of obtaining an appreciation of outside to inside noise levels on this train.

A four-car train set was instrumented with 15 acoustic transducers; 10 sound (6 external and 4 internal) and 5 vibration. All 15 channels were recorded concurrently on digital tape. During the in-motion tests the train traveled at speeds in excess of 100km/h in open-country and at much lower speeds inside tunnels. The recordings were then analysed in the laboratory and corrections were applied to external channels to discount the effect of wind induced noise on microphones. External and internal noise levels at a range of speeds in open-country and in tunnels were then compared.

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NOISE CONTROL MEASURES FOR THE PROPOSED MELBOURNE AIRPORT RAIL LINK

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Abstract
The proposed Melbourne Airport Rail Link has been the subject of an on-going planning study since 1998. In 2000, noise limits were developed for the proposed Rail Link. These noise limits were based on the (then) current NSW EPA Guidelines for Railway Noise, and were found to be easily achievable due to the presence of wide buffer zones, and design features such as speed-limited curves and deep cuttings. While these features may not be present in future rail projects, it is anticipated that future implementations of the policy will incorporate a flexible interpretation which will lead to a maximisation of community benefit, rather that slavish adherence to achieving particular noise limits.

Introduction

Marshall Day Acoustics was commissioned by the Victorian Department of Infrastructure to provide a noise and vibration impact assessment for the proposed Melbourne Airport Rail Link. Three potential corridors where considered. These were:

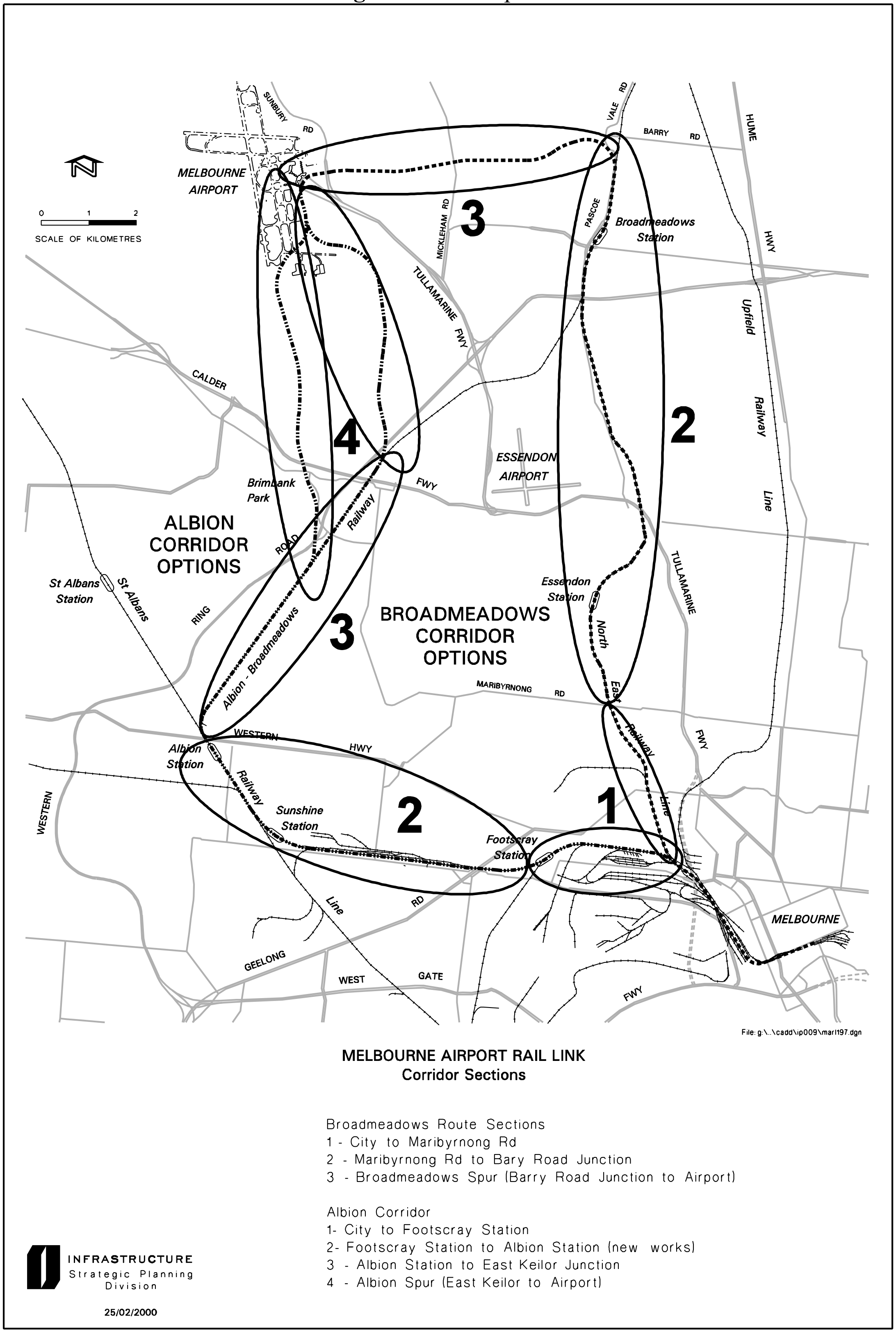
- The Albion West corridor. An existing railway line would be utilized heading west from the city. From there, a new line would be built heading north to the airport.
- The Albion East corridor. Similar to Albion West, but with a different approach to the airport.
- The Broadmeadows corridor. An existing railway line, heading north from the city through mainly residential areas to a point east of the airport where a new line would be constructed connecting to the airport.

For the Albion options, there was one rail service scenario only, namely a special purpose Express service extending north to the airport and stopping only at one or two locations en route.

For the Broadmeadows corridor, there were three service scenarios, namely the Express service; the Limited Express service which would use conventional trains stopping at selected stations; and the Suburban Extension service which would simply extend the existing suburban service along new track to the airport.

Both 18 hour and 24 hour services were evaluated. Figure 1 shows the route options.

Figure 1 Route options



NOISE IMPACT

Briefly, noise impact was assessed in terms of community effects such as annoyance, sleep disturbance and interference with speech communication. The impact assessment was weighted according to the number of residences affected and, predictably, showed that impacts were greatest along the Broadmeadows corridor where the number of residences was greatest. This is shown in Table 1.

Table 1 Number of affected residences

Corridor	Section	No. of affected residences
Albion West	Existing	190
	New	2
	Total	192
Albion East	Existing	320
	New	50
	Total	370
Broadmeadows	Existing	1,010
	New	200
	Total	1,210

NOISE LIMITS

Like road traffic noise, railway noise is controlled by:

- Setting environmental noise objectives at affected residences and other noise sensitive locations
- Specifying noise limits on noise emission from noise railway vehicles
- Specifying in-service noise emission limits.

Of these, the State of Victoria only has limits on noise emission from new railway vehicles, as specified in the Railways of Australia Manual.

Environmental noise objectives were developed for this project by the Director of Public Transport, acting under advice from consultants Watson Moss Growcott, with Marshall Day Acoustics acting in a review capacity. The recommended noise limits were:

- For new sections of railway line built on new rail reserves
  - L_{eq}24 hr 55dB(A)
  - L_{max} 80dB(A)

- For existing sections of railway line affect by this project
  - L_{eq}24 hr 60dB(A)

These noise limits were based on the (then) existing NSW EPA Guidelines for Railway Noise. The L_{max} criterion was dropped from the existing sections of railway line as this would cause noise control measures to be dictated by the L_{max} noise levels from existing freight movements, a component of the existing railway noise environment that was completely unrelated to the Airport Rail Line Project.

It was strongly recommended that adequate guidelines for the interpretation and implementation of the policy be developed prior to construction of the Airport Rail Link. Matters to be addressed by the guidelines should include:

- which types of land uses are to be protected by noise (e.g. residences, schools, pre-school centres, noise-sensitive community centres, etc.)
- what allowance will be made for future rail traffic growth
- how to determine whether a given residence is covered by the policy (e.g. which noise limit applies to residences affected by noise from both new and existing sections of railway)
- how to undertake noise measurements for the purposes of determining compliance with the policy (e.g. measurement location, whether to consider upper storeys, or just ground floor, etc)
- methods for determination of compliance in areas affected by other noise sources
- specific guidance on noise control for large open space areas.

NOISE CONTROL ON NEW SECTIONS

For both the Albion and Broadmeadows corridors, a number of factors conspire to make noise control unnecessary for the Express service options. All three alignment options were located below flight paths for Melbourne airport, placing them in areas where residential development had been prohibited. This generally led to wide buffer zones between the railway line and residences.

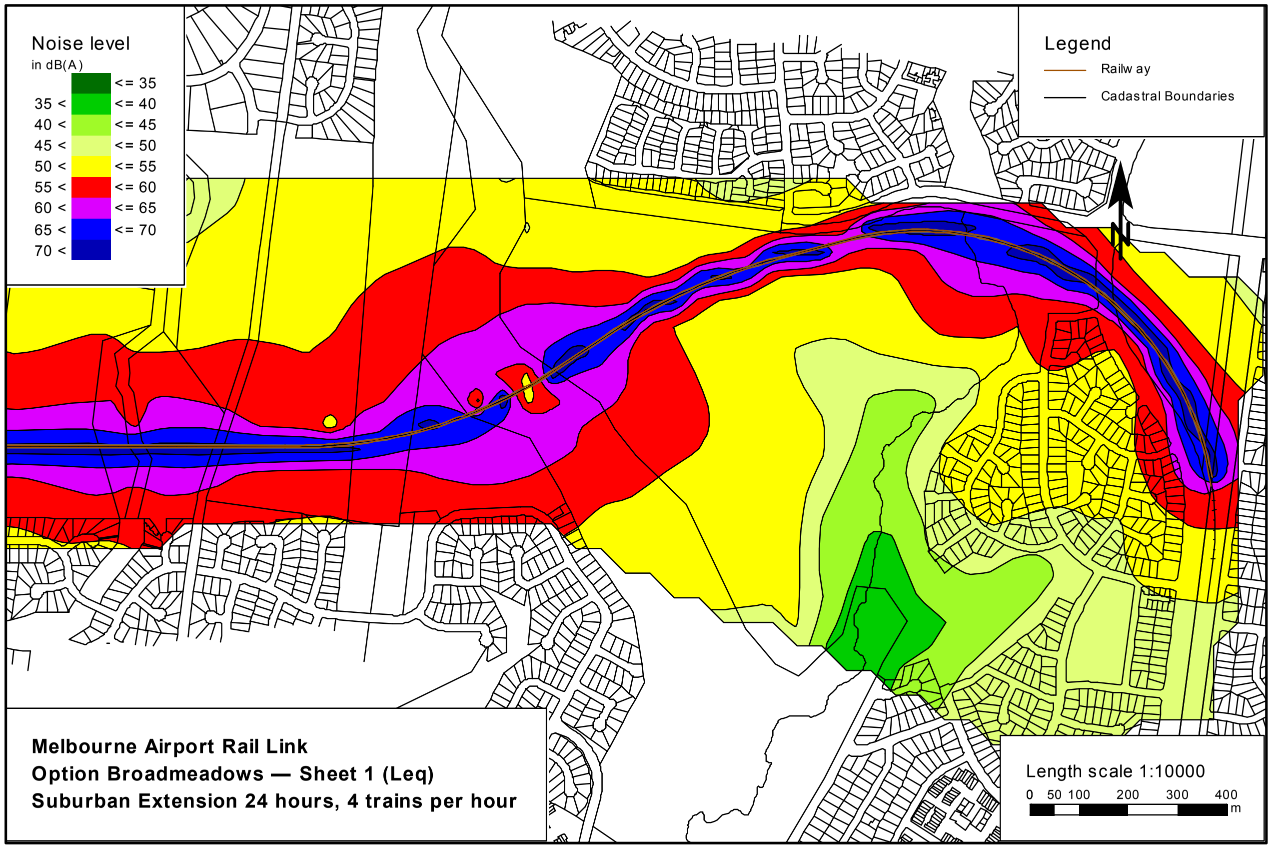
For the Broadmeadows corridor, there was one section of new railway line that passed close to residences, but this was in the middle of a speed-limited curve. This required express trains to slow down from their normal speed of 130km/hr to 80km/hr, reducing noise emission by about 7dB(A). Deep cuttings were also necessary in the Broadmeadows corridor to allow the train line to pass below Pascoe Vale Road and Mickleham Road.

According to the noise modelling, the wide buffer zones and other design features resulted in noise levels lower than the noise limit, and no purpose-built noise control was required for the Express options.

The Limited Express and Suburban Extension scenarios on the Broadmeadows corridor used conventional suburban trains which, at 80km/hr, were 1-2dB(A) noisier than the express trains at 130km/hr. These trains could travel through the speed-limited curves at their full running speed and without purpose built noise control, were expected to exceed the noise limits for new sections of railway line. Special purpose noise barriers (as opposed to cuttings) up to 2m in height were likely to be necessary for a total length of about 2km.

Figure 2 provides an example of a noise contour plot for the 24-hour Suburban Extension scenario running on the Broadmeadows alignment, without noise control. It can be seen that some of the residential blocks have predicted noise levels greater than the 55dB(A) noise limit.

Figure 2 Sample noise contour plot



Note that for new sections, it was the L_{eq} criterion that determined the noise control measures. Because of the buffer zones present, the L_{max} criterion was not critical.

NOISE CONTROL ON EXISTING SECTIONS

On existing sections, noise modelling was not required, as this was a planning study without a concrete proposal to evaluate. However, the proportion of residences that would need to be protected and the overall quantity of noise barriers was estimated, as shown in Table 2.

Table 2 Approximate extent of noise control for existing sections

Corridor	Proportion of residences that may exceed noise limit	Length of railway line that may require noise control
Albion West	50-80%	2km
Albion East	50-80%	3-4km
Broadmeadows	30-50%	5-8km

Note: For the Suburban Extension scenario, there will be no change to the noise environment near the existing railway line and noise control will not be implemented.

In most cases noise levels will only exceed the limit by a few decibels, and it was felt that noise barriers would not need to exceed 2m in height.

CONCLUSIONS

The State of Victoria has entered into the world of railway noise control by developing a noise policy for a specific project, namely the Melbourne Airport Rail Link. For this project, noise limits based on the (then) current NSW EPA Guidelines were achievable, but this may only be due to factors unrelated to noise control, namely the presence of a wide buffer zone and design features such as deep cuttings and speed-limited curves.

The noise limits for this project have set a precedent for future rail infrastructure extension projects in Victoria. It is not necessarily going to be the case that the noise limits can be so easily achieved in the future. It is recommended that the guidelines for interpretation and implementation of the policy allow for flexibility, and focus on maximum community benefit, rather than strict adherence to achieving particular noise limits.

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A PROPOSED LOW FREQUENCY NOISE ANNOYANCE GUIDELINE

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Abstract

Items such as boilers, pumps, transformers, cooling fans, compressors, oil and gas burners, foundries, washing machines, electrical installations, diesel engines, asynchronic motors and ventilation and air conditioning equipment are sources of high level low frequency noise having frequency content less than 100 Hz. These sources exhibit a spectrum which characteristically shows a general increase in sound pressure level with decrease in frequency.

Annoyance due to low frequency noise can be high even though the dBA level measured is relatively low. Typically, annoyance is experienced in the otherwise quiet environs of residences, offices and factories adjacent to or near low frequency noise sources. Generally, low level/low frequency noises become annoying when the masking effect of higher frequencies is absent. This loss of high frequencies may occur as a result of transmission through building fabric and in propagation over long distances.

It has been demonstrated that the dBA measure is not a valid basis for determining the justification of a complaint for those cases where the intruding noise contains most energy in the lower frequencies. With the proper combination of waveform, frequency and pulse repetition rate of low frequency sound falling inside the "sensorially sensitive" Beta frequency range of 13 Hz to 40 Hz (recorded as an electroencephalograph, EEG) many people may experience euphoria, heightened awareness and vivid dreams and the associated "fight/flight" mode at the high end of the Beta frequency range

The frequency of a "beat note" (modulated tone) superimposed upon the primary acoustical signal, caused by some noise sources e.g. a battery of cooling fans can coincide with the frequency of the human brain's Delta waves (1 to 3 Hz) that are strongest in the deepest part of the sleep cycle (3^{rd} and 4^{th} stages).

As a result of the incidence of low frequency noise complaints experienced by residents in Queensland, a low frequency noise annoyance guideline has been developed by the Environmental Protection Agency.

The technical paper will describe the main elements of this guideline including the:

- *low frequency noise criterion adopted for initial screening inside home environments in terms of Linear, A-weighted and one-third octave band sound pressure levels in the range 0 to 100 Hz*
- *measurement procedure*
- *special requirements for measurement equipment. In particular the analyser noise floor to be at least 10 dB below the corrected hearing threshold level (L_{HS}) in the low frequency region.*

The evaluation is based on comparing the one-third octave band low frequency sound with the values for L_{HS} of the ISO median hearing threshold level for otologically normal hearing young adults.

The increased annoyance impact of low frequency "rumbly" noise where it is possible that the loudness may change from imperceptible to loud at the modulation rate of the noise at a particular one-third octave band frequency is accounted for by comparing measured levels with the median hearing threshold levels (L_{HS}), corrected by 5 dB.

Introduction

Items such as boilers, pumps, transformers, cooling fans, compressors, oil and gas burners, foundries, washing machines, electrical installations, diesel engines, asynchronic motors and ventilation and air conditioning equipment are sources of high level low frequency noise having frequency content less than 100 Hz.
These sources exhibit a spectrum which characteristically shows a general increase in sound pressure level with decrease in frequency.

Annoyance due to low frequency noise can be high even though the dBA level measured is relatively low. Typically, annoyance is experienced in the otherwise quiet environs of residences, offices and factories adjacent to or near low frequency noise sources. Generally, low level/low frequency noises become annoying when the masking effect of higher frequencies is absent. This loss of high frequencies may occur as a result of transmission through building fabric and in propagation over long distance.

It has been demonstrated that the dBA measure is not a valid basis for determining the justification of a complaint for those cases where the intruding noise is unbalanced in that it contains most energy in the lower frequencies.

With the proper combination of waveform, frequency and pulse repetition rate of low frequency sound falling inside the "sensorially sensitive" Beta frequency range of 13 Hz to 40 Hz (recorded as an electroencephalograph, EEG) many people may experience euphoria, heightened awareness and vivid dreams and the associated "fight/flight" mode at the high end of the Beta frequency range.
The frequency of a "beat note" (modulated tone) superimposed upon the primary acoustical signal, caused by some noise sources e.g. a battery of cooling fans can coincide with the frequency of the human brain's Delta waves (1 to 3 Hz) that are

strongest in the deepest part of the sleep cycle (3^{rd} and 4^{th} stages) and result in further distress.

Low Frequency Noise Criterion

Initial Screening

Based on experimental evidence and on field annoyance data, where an unbalanced noise immission occurs, the overall sound pressure level, dB (Linear) inside residences should not exceed 50 dB to avoid complaints of low frequency noise annoyance.

If the dB (Linear) measurement exceeds the dB(A) measurement by more than 20 dB, a third octave band measurement must be carried out.

Measurement Procedure

Measuring quantities

The primary measuring quantities are the Linear and A-weighted sound pressure levels for initial screening while $1/3^{rd}$ octave band levels are measured in the relevant frequency range (0 to 100 Hz).

Time of measurement

Measurements are made at a time when and at a place where the complainant explicitly states that the sound was audible (mostly at night).

Measurement Location/Protocol

The measurements are carried out in the most exposed room at the most exposed location regularly occupied by people. The windows and doors have to be closed. Measurement is usually taken in a corner of the bedroom at 1.0 to 1.5m above floor level and about 0.4 to 0.5m from both walls.

A microphone and digital audio tape (DAT) recorder are placed in the room where the complainant finds the sound most audible or where the disturbance is greatest; in the majority of cases the bedroom is the location selected as complaints mainly occur at night. The equipment can be left with instructions for recording until the complainant has experienced (and recorded) a period when the sound is clearly audible. The equipment is left long enough (days, sometimes up to weeks) to ensure relevant recordings can be made.

The microphone is suspended in rubber bands on a tripod to provide vibration isolation.

Measurement Equipment

The entire measurement chain must measure down to a few Hertz and have a flat frequency response (+/- 0.5 dB at frequencies of 10 Hz up to several kHz). The instrument noise level must be at least 10 dB below the corrected hearing threshold level in the low frequency (LF) region as adjusted from Table 1.

Evaluation/Assessment

Check whether noise contains dominant low-frequency components.

- Identify disturbances by listening to the recordings and analyse time histories of the Linear and A-weighted levels of recorded sound
- Determine broad band L_{Aeq} and L_{LINeq} for a representative measuring time interval, typically 10 minutes
- Determine if $L_{LINeq} - L_{Aeq} > 20$ dB. If so
- Measure the 1/3rd octave band levels, as equivalent sound pressure levels using Linear frequency weighting for frequencies <= 100 Hz
- Compare the 1/3 octave band low frequency sound with the values L_{HS} of the ISO median hearing threshold level for otologically normal hearing young adults (18 - 25 years) (Table 1)

Table 1 Median hearing threshold levels

fc (Hz)	8	10	12.5	16	20	25	31.5	40	50	63	80	100
LHS (dB)	100	96	92	88	78	66	59	50	43	37	31	26

- The increased annoyance impact of low frequency “rumbly” noise where it is possible that the loudness may change from imperceptible to loud at the amplitude modulation rate of the noise at a particular one-third octave band frequency is accounted for by comparing measured levels with the levels from Table 1, corrected by 5 dB i.e. the corrected level for 50 Hz is 38 dB and not 43 dB.
  This could be the case for poorly designed HVAC systems that generate large turbulent fluctuation at low frequencies and which can include fan surging with concomitant noise level surging of 10 dB or more
- In the application of this proposed guideline to some individual cases consideration will need to be given to the fact that the median hearing threshold levels (HTLs) exceeded by 90% of young subjects is 7.5 dB lower than the HTLs given in Table 1 and the HTLs exceeded by 90% of the older population (55-60 years old) is 4.5 dB lower than values given in Table 1.

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