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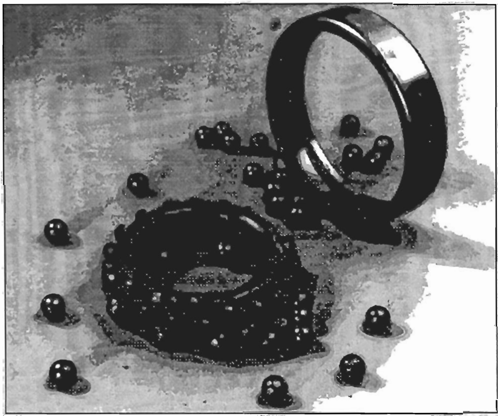

Condition Monitoring Special Issue:

- **Fault Detection**
- **Vibration Analysis**
- **Neural Networks**
- **Expert Systems**

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***COVER :** Damaged rolling element bearing, see paper by Baillie and Mathew.*

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Editorial

In this December issue we have, once again, papers focussed around a special topic. This time our emphasis is at the engineering end of the wide spectrum of acoustics, and concerns the use of vibrational analysis to monitor the condition of machines. This is a topic of great practical importance, for much of our life depends on the reliable operation of generators, pumps and engines, and the detection of incipient faults allows the machine to be shut down for preventative maintenance. Not only does this avert catastrophic failures, but it also extends the time for which the machine can be allowed to run between physical inspections. The techniques in this field have grown steadily in sophistication and power in recent years, and it seems likely that this growth will continue as computer analysis techniques improve in power. We are grateful to our four invited authors for this timely survey of an important field.

The Academy of Science has just launched the new primary-school science project "Primary Investigations" developed by the Australian Academy of Science. These brochures have been sent to all primary schools in Australia, and the initial response has exceeded all our expectations. This project has been supported by the Australian Foundation for Science, a foundation of which the Australian Acoustical Society, along with many other scientific societies, is a member. It is only by working together in this way that we can hope to accomplish major projects of this type. And it has been indeed a major project. The materials, which include books and equipment, were developed over a period of three years and subject to an extensive year-long trial involving 12000 children in 38 schools throughout Australia. The Foundation hopes that this initiative will revitalise science teaching in all Australian primary schools — is the school your children attend participating?

There is another way in which scientific societies are working together to promote the welfare of science and technology in Australia, and that is through FASTS, the Federation of Australian Scientific and Technological Societies, of which again the AAS is a member. The aims of FASTS are to act as a political and industrial lobby group in the interests of its member societies, to persuade government and the community of the importance of our craft, and to see that science and technology receive an appropriate share of the resources expended for the good of the community.

By collaborating in these ways, the scientific and technological community in Australia is making its presence felt, not for selfish reasons, but because we believe that the future prosperity of our country depends in large measure on the way in which we understand, develop and use the powerful and sophisticated tools that are now available to us.

Neville Fletcher

see page 104 for Society Enquiries

MACHINE FAULT DETECTION AND DIAGNOSTICS USING VIBRATION ANALYSIS

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Abstract: Vibration analysis is now a powerful tool in the detection, diagnosis, and prognosis of incipient faults in operating machines. This paper gives a brief overview of the way in which various faults manifest themselves in the vibration signal, and how the information can be extracted using a variety of analysis techniques.

1. INTRODUCTION

One of the most exciting areas of development in mechanical engineering in the last twenty years or so has been in the field of maintenance engineering, in the introduction of systematic maintenance management systems, and in particular "predictive maintenance" or "condition-based maintenance" where planned maintenance is carried out primarily on the basis of the actual condition of the machines rather than just at regular intervals. There are obvious economic benefits and improvements in safety to be gained if machines can be run as long as possible between shutdowns, while maintaining a low incidence of unexpected breakdowns. To do this requires the availability of condition monitoring techniques, which allow the determination of the internal condition of continuously operating machines, and the detection and diagnosis of incipient faults a reasonable time (several weeks to several months, depending on the nature of the equipment) before the machine has to be shut down for repair.

There are two main ways of getting information from the inside to the outside of operating machines and thus determine their internal condition:

The Lubrication System Wear particles are carried by the lubricant to filters, magnetic traps and sumps from which they can be extracted and examined by chemical and/or microscopic analysis to determine wear rates and identify the components concerned. Internal leakage of water and other fluids can also be determined by this method.

Vibration Analysis Most faults give rise to changes in the vibration signals, both locally and at remote points which are accessible from the outside when the machine is operating. This paper is concerned with the applications of vibration analysis, and in particular with techniques which can be used to give advance warning a long time in advance of the point where repairs have to be carried out. Since the initial symptoms are often at high frequency and since piezoelectric accelerometers (acceleration sensitive transducers) have a very wide frequency range (typically 1 Hz to 10 kHz) and dynamic range (typically 120 dB) this paper is concerned primarily with the analysis of the signals from accelerometers mounted on the bearing housing or other part of the machine casing. In fact, accelerometers (in conjunction with electronic integrators) also make the best velocity transducers, although electrodynamic velocity transducers can be used for some of the techniques described here. Velocity is often the best parameter to use for evaluating condition (particularly at the fault detection stage) as its spectrum is usually the "flattest" (requiring the least dynamic range over a wide frequency range) and velocity levels being most indicative of stress levels, (the two aspects being closely related).

Before discussing particular techniques, it is worthwhile examining how different types of faults in machines give rise to identifiable vibration signatures.

2. GENERATION OF FAULT SYMPTOMS

There are a number of simple faults which reveal themselves directly in the time signal or perhaps in a simple spectrum. Among these are unbalance (primarily at the speed of rotation of the shaft) and misalignment (at the low harmonics of shaft speed, depending on the type of coupling, but typically at the second and other even harmonics, since the stiffness often varies twice per revolution). Mechanical looseness often gives rise to impacts occurring each revolution, which in turn results in a series of harmonics of the shaft speed in the spectrum, the number being greater the shorter the impact. Because the looseness may be interpreted as a variable stiffness, it is also possible to excite exact subharmonics of the shaft speed if these are close to resonances.

Electrical Machines In electrical machines, the electromagnetic forces give rise to additional vibrations over and above those generated mechanically. As an example, a localised fault in the stator gives impulses for the passage of each rotating pole, in other words at twice mains frequency (100 Hz in Australia) independent of the number of poles. For two pole synchronous machines, this is identical to the second harmonic of shaft speed but it is possible to distinguish them by varying the load (since the electromagnetic forces vary strongly with the load). In any case it would normally be possible to distinguish between them by switching off the power, as after a very short time only the mechanical effects are left, and these vary with the decreasing speed of the machine. For induction (asynchronous) motors the harmonics of shaft speed are slightly less than the harmonics of mains frequency, although it will normally be necessary to use zoom FFT analysis to distinguish them (see below). A localised fault on the rotor gives an electrical unbalance which rotates at shaft speed, but can normally be distinguished from mechanical unbalance by being strongly modulated by a frequency corresponding to the passage of the poles of the rotating field with respect to a point on the rotor. This frequency is equal to the "slip" frequency (difference between the actual and synchronous speeds) multiplied by the number of poles.

Some components of rotating machines have vibration signatures which are somewhat more complicated, but which can be interpreted by using signal analysis techniques which are a little more advanced. Typical of the latter cases are gears and rolling element bearings.

Gears Even gears with a perfect profile generate vibrations under load because of tooth deflection, and in particular the variations in the latter as the load is supported by varying numbers of teeth through the meshing cycle. Other vibrations arise from profile errors, both those from the original machining, and from wear in service. The vibration signal can be considered as a carrier component at the meshing frequency (coming from the variations in stiffness at the mesh) amplitude modulated by two groups of geometric deviations of the teeth of each wheel:

(1) A variation at the mesh frequency which represents the sum of the mean deviations over all teeth on each wheel.

(2) Variations at the rotational frequency of each wheel which represent the deviations of the individual teeth around these mean values. These deviations may be divided once again into two groups according to the degree of localisation of the deviations, eg distributed, such as eccentricity and distortion due to heat treatment, or localised, such as cracks and spalls.

From the point of view of vibration monitoring, it is important to recognise that the vibration level is greatly affected by load, so that comparisons for determining condition must be made under virtually identical load conditions. This being the case, any changes detected are most likely due to geometric changes coming from wear and/or local faults. The resulting time signals, and even spectra, often appear quite complex, but basically only contain components at the harmonics of the rotational speed of the two gears in mesh, and analysis methods exist such as time synchronous averaging and cepstrum analysis (see below) which facilitate the extraction of relevant information.

Bearings Rolling element bearings also have vibration signatures which although complex, are typical and contain explicit information. When there is a local defect on one of the surfaces coming in contact this gives an impulse whose magnitude depends on the load supported by the surfaces. The resulting vibration pulse represents the sum of the impulse responses of all the resonances excited by the impact, often from several hundred Hz to several hundred kHz. The information of interest is contained in the repetition frequency of the impacts, and also in the frequencies of modulation of the latter. Figure 1 illustrates this for local faults in the various components such as the inner race, the outer race, the ball (or roller) and the cage.

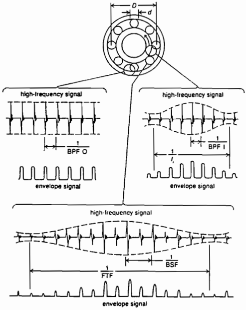

Figure 1. Typical vibration signals generated by localised faults in rolling element bearings

The repetition frequencies of the impacts from faults in the various components may be calculated from the following formulae, which neglect any slip between the components (which may be several percent).

Ballpass frequency, outer race:

$$BFPO = \frac{n f_r}{2}\left[1 - \left(\frac{d}{D}\right)\cos\phi\right] \quad (1)$$

Ballpass frequency, inner race:

$$BPFI = \frac{n f_r}{2}\left[1 + \left(\frac{d}{D}\right)\cos\phi\right] \quad (2)$$

Ballspin frequency (rate of impact on the same race):

$$BSF = \frac{D}{2d}\left[1 - \left(\frac{d}{D}\right)^2 \cos^2\phi\right] \quad (3)$$

Fundamental train frequency (cage speed):

$$FTF = \frac{f_r}{2}\left[1 - \left(\frac{d}{D}\right)\cos\phi\right] \quad (4)$$

where

n = number of balls or rollers
f_r = shaft rotational speed
d = ball or roller diameter
D = pitch circle diameter of balls or rollers
ϕ = load angle from radial

For unidirectional load, the signal for a fault in the outer race would not be modulated, but for inner race faults it tends to be modulated by the shaft speed (because of varying load and transmission path) and for rolling element faults by the cage speed (typically 40-45% of the shaft speed).

Even when the fault pulses are visible in the time signal, they are not always evident in the raw spectrum. To understand this, consider a simple hypothetical case where it is supposed that a single resonance frequency is excited by an outer race fault. If the speed were exactly constant, and if all pulses were identical, the spectrum would be a harmonic line spectrum whose shape (envelope) would have the same form as the energy spectrum of a single impulse. Note that this spectrum would be concentrated around the resonance frequency, and the component at the fundamental BPFO (Equ. 1) is relatively small, meaning that it would often be masked by other low frequency effects. Moreover, in practice small variations in shape and spacing of the impulses (for example because of speed fluctuations) mean that the higher harmonics tend to merge into a continuous noise like spectrum where information about the repetition frequency is lost. At the same time it can be appreciated that the "envelope" of the time signal would contain the desired information without being unduly affected by the small variations referred to.

Reciprocating Machines Techniques for reciprocating machines are much less developed than for rotating machines, but some progress has been made in recent years. The vibrations produced by reciprocating machines such as IC engines and reciprocating compressors are quite different in character from those produced by rotating machines, usually consisting of a series of impulses coming from different impulsive events in the machine cycle (eg combustion, piston slap, valves opening and closing etc). Combustion related problems are often visible in the cylinder pressure signal, so one approach is to reconstruct the latter from externally measured acceleration signals when it is too difficult or expensive to mount pressure transducers in each cylinder[1,2]. Other techniques borrow from the approach of experienced mechanics, who have learnt that the sound produced by many faults is difficult to characterise in terms of its time or frequency representations individually, but rather by changes in frequency or tonal patterns within each cycle, and thus representations are sought which show changes in frequency content with time[3]. Another approach which shows promise is torsional vibration analysis, as changes in both cylinder pressure and mechanical events would change instantaneous crankshaft torque and thus the pattern of speed fluctuations[4].

3. ANALYSIS TECHNIQUES

Spectral methods The most common analysis technique is frequency analysis, usually by FFT (fast Fourier transform) techniques, as the development of the FFT algorithm in 1965[5] revolutionised the speed with which this could be done and there are now a large number of FFT analysers on the market, many of them portable and battery operated for field use. Their diagnostic capability is considerably enhanced if they have the possibility of zoom analysis (high resolution analysis over a specified frequency band rather than from zero to a maximum as given by the basic FFT algorithm). Figure 2 shows an example where what appears to be a high second harmonic of shaft speed in a baseband analysis proves on zoom analysis to be a number of components, of which the second harmonic of shaft speed is considerably lower in level than the second harmonic of mains frequency, and thus that the dominant vibration has an electrical rather than a mechanical source.

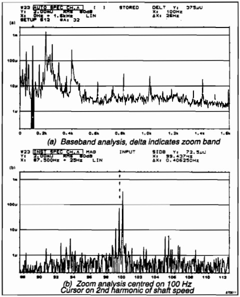

Figure 2. Use of zoom in induction motor diagnostics (a) baseband spectrum implying a high level at the second harmonic of shaft speed (b) zoom spectrum showing that the high level is actually at twice mains frequency

FFT analysis suffers from the limitation that the frequency resolution is limited by the reciprocal of the data record length, and in recent years there has been a tendency to try other so-called parametric spectral analysis techniques such as the maximum entropy method[6] which gives better resolution for short records (basically by assuming that the signal behaviour outside the sample analysed continues in a fashion most similar to its behaviour within the record). Ref. 7 gives an example of the application of parametric techniques to bearing diagnostics.

Cepstrum analysis The cepstrum is defined as the inverse Fourier transform of the logarithmic spectrum, and can thus be considered as a sort of spectrum of a spectrum. One of its properties is thus to enhance periodic features of a spectrum (eg families of uniformly spaced harmonics and sidebands) in the same way that a normal spectrum analysis extracts information about the periodic content of time signals. Figure 3 shows an application to the diagnostics of a bearing fault[8] where a number of the harmonics (though not the fundamental) of the BPFO are apparent in the (logarithmic) spectrum and give a strong component in the cepstrum at a "quefrency" (reciprocal of frequency spacing, actually time) corresponding to BPFO, and clearly showing that the latter is 4.1 times the shaft speed (thus corresponding to a particular bearing). Note that the logarithmic conversion of the spectrum is important, as the autocorrelation function (inverse Fourier transform of the linear power spectrum) does not show the harmonic family at all, because most of the BPFO harmonics are more than 20 dB lower than the dominant spectral components. Since gear faults tend to produce sidebands as a result of modulation by the rotational speeds of the two gears in mesh, cepstrum analysis is also very useful in gear diagnostics[9] and it has also been used to detect damaged blades in a turbine which give a similar effect[10].

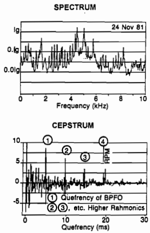

Figure 3. Spectrum and cepstrum for a gearbox with a bearing fault

Another property of the cepstrum is that forcing function and transmission path effects are additive (as they are in the logarithmic spectrum from which it is derived) but often also separated into different regions (at least where the forcing function is impulsive and periodic as in gearboxes and IC engines). It has been shown that it is possible to extract the transfer function by curve fitting analytical expressions to the appropriate part of the response cepstrum[11], and this should provide a means of separating the force and transmission path effects in acceleration response signals, even where the force cannot be measured. As an example of the application of such a technique, an increase of the second harmonic of the toothmesh frequency in a gearbox would normally be taken as an indication of wear, but could possibly occur if a resonance frequency dropped (eg as a result of a developing crack) so as to coincide with the toothmesh harmonic and give an increase for an unchanged forcing function at the mesh. The latter case would be much more serious, and therefore more important to detect.

Demodulation techniques It has already been shown that in vibrations produced by faults in rolling element bearings, it is often the envelope which contains the desired information, which may be disguised in the raw spectrum. The envelope can be determined by amplitude demodulation techniques, and in particular using a combination of Hilbert transform and FFT techniques[12]. Likewise, torsional vibration represents a phase (or frequency) modulation of an otherwise uniform shaft speed, and can be determined by phase demodulation techniques using the same principles[13].

Usually, the signal must be bandpass filtered before generating the envelope, in order to remove masking vibrations at other frequencies, and enhance that part of the signal where the bearing fault dominates over other effects. Both can be done using an FFT zoom processor, as it can be shown that the (complex) output from such a processor has the same amplitude (ie envelope) function as the signal produced by bandpass filtration of the zoom band. The envelope signal can then be frequency analysed to determine the basic pulse repetition frequencies and whether they are modulated by shaft or cage speed. Figure 4 illustrates this for the same case as Fig.3, and at the same time shows the advantages to be gained from producing the envelope in this way. Figure 4(a) shows the envelope signal obtained by zooming in the frequency band 2.2-3.8 kHz, which is dominated by harmonics of BPFO 206 Hz (see Fig. 3). These components are however considerably less than an octave removed from a 20 dB higher gearmesh tone in the vicinity of 4.5 kHz, and could not have been separated except by using filters of antialiasing quality (120 dB/octave) as used in the zoom process. Figure 4(b) shows the corresponding envelope analysis, confirming the BPFO of 206 Hz. The above example was for a high speed machine, where the bearing fault harmonics are separated and visible in the spectrum. Ref. 12 gives another example for a slow speed machine (a paper machine) for which the bearing fault primarily excites resonances in the vicinity of 5 kHz, even though the shaft speed is less than 2 Hz. The envelope spectra generated by zooming around 5.4 kHz show the harmonics of BPFO (15.4 Hz) quite clearly for the faulty bearing, even in the presence of contaminating pulses from pneumatic lubricators (approx. 5.5 Hz) in both bearing signals. A zoom spectrum in the same range as used for the envelope analysis had the appearance of white noise, and gave no information on the repetition frequencies.

Similarly, in determining torsional vibration signals by phase demodulation of shaft encoder signals, it is also generally necessary to bandpass filter around one of the harmonics of the pulse repetition frequency, and the zoom process is also useful for doing this, as it can be shown[13] that the zoom process removes the (linear) phase variation corresponding to the carrier component, leaving only the phase modulation signal. Phase demodulation gives the torsional vibration in terms of angular displacement, while its derivative, frequency modulation, gives it in terms of angular velocity. Torsional vibration can also be expressed in terms of angular acceleration (the derivative again of angular velocity) but there is no term for the corresponding modulation. Figure 5 shows a result from Ref. 14 where the acceleration signal from a gearbox was both amplitude and phase demodulated around the toothmesh frequency, the phase variations revealing an incipient crack before it showed up in the amplitude signal.

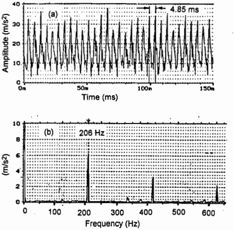

Figure 4. Envelope analysis for fault of Fig. 3. (a) envelope signal obtained by zooming in range 2.2-3.8 kHz (b) spectrum of envelope signal

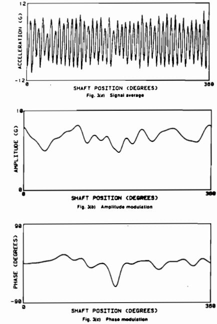

Figure 5. Advantage of phase demodulation of toothmesh signal for early detection of a fatigue crack[14] (a) Signal average (b) Amplitude modulation (c) Phase modulation

Time-Frequency Analysis These techniques basically use windowing techniques to evaluate the change of spectral information with time (since the Fourier transform theoretically integrates over an infinitely long time signal for each spectrum value). In the STFT (short term Fourier transform) technique, the frequency resolution is the reciprocal of the time resolution, and a compromise must be reached between the two. The Wigner-Ville distribution[15] appears to give a better simultaneous resolution in the two domains, but suffers from spurious interference components. A variety of modifications of the Wigner-Ville distribution reduce the interference terms while still retaining some advantage in resolution over the STFT. Ref.[3] recommends a procedure using unmodified Wigner-Ville analysis to determine the time-frequency pattern with optimum resolution, while at the same time using variation in analysis parameters to vary (and thus identify and eliminate) interference patterns while leaving major events in the same location (though with reduced resolution). Figure 6 shows the results for the pressure signal in a diesel engine. Another approach which gives resolution varying with frequency is wavelet analysis[16]. This actually gives a result very similar to constant percentage bandwidth (eg 1/3 octave) analysis, but does not suffer from the disadvantage of varying impulse response time (ie delay) with frequency.

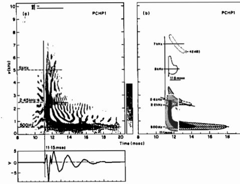

Figure 6. Time-frequency analysis applied to a diesel engine signal[3] (a) cylinder pressure signal and its Wigner-Ville distribution (b) inferred distribution on removal of interference

4. CONCLUSION

From the brief overview given in this paper (and the others in this issue) it can be seen that the application of vibration analysis in machine condition monitoring is soundly based and can be used with confidence in a wide range of situations. Even so there are a number of areas where advances continue to be made and where even more reliable results can be expected in the future. Although not fully discussed in this paper, automated fault detection is already available, and automated fault diagnosis is coming closer with the developments in expert systems and neural networks. The same applies to prognosis or life prediction. This continues to be an area of mechanical engineering where exciting things are happening.

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DIAGNOSING ROLLING ELEMENT BEARING FAULTS WITH ARTIFICIAL NEURAL NETWORKS

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Abstract: Vibration condition monitoring has been used extensively to detect and diagnose faults in rolling element bearings, as often faults can be identified by their characteristic patterns of vibration. Artificial neural networks have been demonstrated to provide an effective new method for fault diagnosis in rotating machinery in terms of cost and reliability. This paper introduces the popular new pattern classification tool of neural networks, and examines how they have been implemented to diagnose faults in bearings.

1. INTRODUCTION

The importance of machine condition monitoring has expanded considerably in the past decade due to the increased complexity of plant equipment and high costs associated with shutdown. Condition-based maintenance can improve the safety and reliability of machinery operation, and can play a significant role in extending the life of aging equipment. The cost savings compared to a periodically-based maintenance program have also attracted the keen interest from industries wishing to reduce production costs.

A machine condition monitoring program should be driven by economic, operational, and safety considerations rather than for the sake of adopting new technologies. It is important that the condition monitoring program produces concise information to enable operators to make informed decisions when planning maintenance. It is all too easy for companies to fall into the technology trap, often carrying out condition monitoring for its own sake, producing piles of information for which no one has the time nor expertise to analyse.

The amount of data that can be collected from modern instruments can easily outweigh the rate at which human diagnosticians can analyse and interpret the data. Instead, an automated system providing concise and reliable assessment of the current machine condition for the maintenance personnel is required. This precludes the necessity for experts in vibration analysis to sift through the entire plant's data, and reduces any delays in the analysis of the data. It is important that any potential catastrophes be diagnosed quickly, so that there is sufficient lead time prior to a breakdown.

Artificial neural networks have recently emerged as a popular tool for signal processing and pattern classification tasks, and are now finding a wide variety of applications in industry. The use of neural network technology is ideally suited to the automated processing and classification of the large volume of vibration signals that are encountered in a condition monitoring program. The aim of this paper is to examine typical applications of neural networks for vibration condition monitoring of rolling element bearings. A demonstration is also given of how to build and train a neural network to diagnose faults in a rolling element bearing.

2. FAULT DIAGNOSIS OF BEARINGS

Rolling element bearings are a common cause of failure in modern rotating equipment (Figure 1). In fact, about 90% of rolling element bearings fail prematurely. Premature failure is usually a result of inappropriate operating conditions, rather than poor quality bearings supplied by the manufacturer. The primary causes of early failure in bearings[1] has been identified as:

- Contamination by dirt and water. Bearings are precision items of equipment, and need to be treated as such. General neglect and harsh operating environments can cause problems.
- Overstress caused by overloading of the bearing. This may be due to incorrect installation of the bearing, or excessive loading due to misalignment or imbalances in machine shafts. Occasionally, even machine design faults may cause excessive loads on bearings.
- Lack of sufficient lubrication. Incorrect or insufficient quantities of lubricating oils and greases are very common causes of bearing damage. It is commonly characterised by excessive overheating of the bearing.
- Defects created after manufacturing. Rough handling of bearings during mounting can damage bearing components. Excessive static loads on machinery can also cause deformations in the bearing raceways.

A suitable condition monitoring technique needs to be established to detect impending failures of bearings in time for maintenance to be scheduled, avoiding costly breakdowns and potential damage to machinery and personnel. Vibration based monitoring has become very popular for the detection and diagnosis of faults in rolling element bearings. The reasons for the importance of vibration-based analysis in a fault diagnostic system can be summarised as follows:

- The diagnostic system must accurately provide the operator with the *cause* and *location* of the fault. Vibration monitoring provides one of the best indicators of machine health and is an excellent indicator of developing defects in rotating machinery. Vibration is generated by internal forces within the machine, and as a consequence, reflects the very nature of the generating mechanism.
- The system should provide indication of the *severity* of the fault. This is useful for the scheduling of maintenance, and making the best use of the company's resources. The level of vibration is quite sensitive to the degree of damage within the machine. Catastrophic events are often preceded by a detectable change in vibration, sometimes months in advance.
- The collection of data should not interfere with the normal operation of the machine. Generally the data must be collected on line. It is also desirable that the analysis be performed in real-time, so that up to date information is immediately available to the operator. This is especially important in critical situations, such as in monitoring turbines and aircraft systems. The collection of vibration data is usually made using an accelerometer fixed to the outside casing of the machine being monitored, and is generally unobtrusive to the normal operation of the machine.
- The diagnostic system must be sufficiently accurate to detect the presence of faults without signalling unnecessary false alarms. The system must also be robust in nature, so that minor fluctuations in the signal, due to noise, do not degrade the performance of the system. Unfortunately, vibration signals are susceptible to interference from outside sources. Other components within the machine, or even other machinery in the working environment can propagate unwanted vibrations that can potentially mask the presence of the bearing under surveillance. Changes in the operating environment can also provoke a change in the vibration characteristics of the machine. For example, a rebuilt machine may display noticeably different vibration characteristics. For these reasons, the diagnostic system must allow sufficient leeway for such variations in machine vibration.

The process of fault diagnosis is usually performed by transforming the vibration signal into the frequency domain. There are number of reasons why this is performed. Firstly, machinery faults are indicated in the spectrum by peaks at characteristic frequencies. Since each component or fault emits a vibration of unique frequency, the level of the peak provides indication of the presence or severity of such a fault. Also, weak signals can often be hidden in the time domain waveform, however, transformation into the frequency domain clearly reveals the presence of the fault. This means that faults can be identified in the presence of noisy environments, or developing faults can be detected giving sufficient warning of an impending breakdown.

Figure 1. A Damaged Rolling Element Bearing

3. ARTIFICIAL NEURAL NETWORKS

Neural computing is a rapidly expanding field in computing and artificial intelligence research. Since the publication of *Parallel Distributed Processing* by Rumelhart and McClelland[2] in 1986, the interest in artificial neural networks (ANNs) has grown significantly. Their book presented the Backpropagation algorithm; a powerful and general-purpose training algorithm for multi-layer neural networks.

The traditional philosophy of artificial intelligence has been to model the human thought process, such as capturing knowledge in a set of rules in an expert system. Alternatively, a new method of creating intelligent behaviour may be achieved if the actual biological structure of the brain could be imitated. This approach has spawned the development of so called artificial neural networks. It is important to understand that the development in neural networks has been a product of both increasing computing power over the decades and discoveries in neurobiology and the structure of the human brain.

An artificial neural network can be defined as a mathematical model of the human brain, and consists of many simple processing elements interconnected in a parallel network. Perhaps the most desirable aspect of neural networks is their ability to learn to solve a problem, rather than having to be preprogrammed with a precise algorithm. Neural networks posses powerful pattern recognition capabilities, which is not surprising considering that humans excel at such tasks as reading messy hand-writing or recognising faces in a crowd, tasks where a traditional computing approach fails dismally. Neural networks are often employed in situations where traditional techniques would be extremely difficult or impossible.

A neural network consists of an interconnected number of simple processing elements (nodes) which are analogous to neurones in the brain (Figure 2). The "knowledge" stored within the network is represented in the variable-strength connection weights between the processing elements. The adaptive learning process operates by varying the strengths of these connections. The most popular learning algorithm is called the backpropagation learning rule.

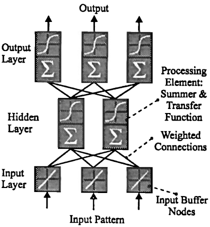

Figure 2. A Backpropagation-Type Artificial Neural Network

The function of each processing node is to combine the incoming signals and to transform them through a nonlinear transfer function.

$$y_j = f\left\{\sum w_{ij} . x_i\right\} \quad (1)$$

where, y_j is the output of the jth node. x_i is the *i*th input (or the output of the preceding layer node), w_{ij} is the connection weight between the *j*th node in the current layer and the *i*th input,

The nonlinear sigmoidal transfer function is a popular choice for the backpropagation network (Equation 2).

$$f(x) = 1/(1+\exp(-x)) \quad (2)$$

The processing nodes are typically arranged in functional groups, called layers. The input layer acts as a buffer for the incoming vector, and distributes the signal to the adjacent processing layers. The hidden layer is involved in the intermediate processing stage, while the output nodes combine the internal signal and communicate the solution to the external world. Each node in a layer sends its output to adjacent nodes in the next layer. This way, a network of dense parallel interconnections is built up.

The backpropagation learning algorithm is a supervised training rule for multi-layer feed-forward networks. The training process is classed as supervised, because both the input vector and the desired output are presented to the network during the learning phase. The backpropagation training algorithm has become the most widely used learning rule for neural network development. The reasons for its success are:

- It was the first technique allowing non-linear, multi-layered neural networks to be trained.
- The algorithm uses the concept of minimisation of squared errors, and is easy to understand and implement in computer code.
- It is a general purpose algorithm suitable for almost any application.

The backpropagation algorithm can be summarised as four sequential operations:

1. Present the input pattern to the input layer of the neural network and propagate it forward to obtain the output pattern from the output nodes.
2. For each node in the output layer, calculate the local error and subsequently, the required adjustment to the weights.
3. For each hidden node, starting at the layer beneath the output layer, calculate the local error and the required adjustments to the weights.
4. After the error has been propagated backwards through the network, simultaneously update all the weights by adjusting them accordingly.

These steps are carried out until the error converges to some desired level of tolerance. The network can then be tested for its performance. If the performance is not satisfactory, it may be necessary to change the network architecture (ie, add more nodes in the hidden layer) and retrain it, otherwise the network is ready to be employed. In the normal operation of the neural network, the preprocessed data is presented to the input layer of the network. The signal is propagated forwards through the network layers. The processed result appears on the nodes in the output layer.

The backpropagation algorithm provides a simple procedure that can be easily implemented in computer software. It generally behaves in a predictable manner, making it a powerful general-purpose tool for training neural networks. However, the backpropagation algorithm is notorious for its lengthy training times, and its occasional susceptibility of falling into local error minima. Several modifications are available for improving the rate of convergence, probably the most effective being the inclusion of a momentum term.

The robust nature of neural networks has been widely recognised in the literature. If trained correctly, neural networks can accept data corrupted by noise without any significant degradation of classification performance. This feature is known as the network's ability to generalise; which is the ability to make informed interpolations on the patterns it has been trained on.

3. FAULT DIAGNOSIS WITH NEURAL NETWORKS

Neural networks have been recently applied in the field of machine condition monitoring and mechanical fault diagnosis. One of the most important steps in building any pattern classification system is the selection of the appropriate parameters for classification. Three approaches have been proposed for the diagnosis of vibration signatures using neural networks:

1. Classification of vibration indices
2. Model-based classification of time domain vibration signals
3. Classification of vibration spectra

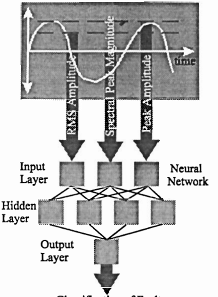

Figure 3. Liu and Megels' Neural Network Classifier. The vibration indices are fed into the input layer of the neural network, and a single number is output denoting the class of fault present.

Liu and Mengel[3] presented a technique of training a neural network using three vibration indices. The three parameters chosen were the vibration peak amplitude, RMS level, and the peak amplitude of the vibration spectrum, and were processed by a two-layer backpropagation neural network (Figure 3). The neural network acted as a "black box" pattern recognition system. The neural network had one output node, and depending upon its activation level, indicated the presence of either an inner race, outer race or rolling element fault, or a combination of faults. Success rates for the system were claimed to range from 77% to 97% correct classification, depending upon the number of hidden layer nodes employed in the network. Despite this success, their approach had a few short comings. Firstly, they discarded useful diagnostic information by only using the amplitude of the highest peak in the frequency spectrum. Other parameters could have easily been extracted from the spectrum for the network to classify. Secondly, the use of a single output node to classify the signal into one of a number of possible faults is questionable. For example, a new type of fault in the bearing would certainly be misclassified, and combination of faults could not be adequately classified. The logical solution is to use an output node for each class of fault to be identified.

A novel method of model-based fault detection in rolling element bearings using neural networks has been proposed by Baillie and Mathew[4]. The system consisted of a collection of parametric time series models, one for each class of bearing fault to be identified (Figure 4). Backpropagation neural networks were trained as the nonlinear time series models (it should be noted that the neural network is employed here to approximate a mathematical mapping function, rather than a pattern classification tool). The incoming vibration waveform was presented to each of the neural network models, and the network that best approximated the signal was declared to indicate the type of fault present. The primary advantage of fault diagnosis using the time domain vibration signal is that a diagnosis can be performed using very short lengths of data, and can be suitable in certain applications such as the monitoring of varying speed machinery. The drawback is that it is quite difficult to build a model robust enough to accept noise or small changes in the vibration signal without misclassifying the fault. Despite this shortcoming, encouraging results have been obtained by paying particular attention to pre and post processing of the waveform. Classification accuracy of up to 100% was achieved for the detection of certain faults in the bearings.

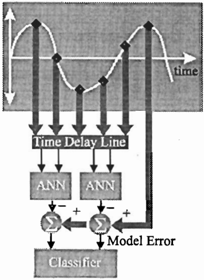

Figure 4. Baillie and Mathews' Model-Based Fault Diagnostic System. The internal neural networks act as "one-step-ahead" predictors of the vibration time series. The classifier determines which neural net most accurately models the signal, hence classifying the fault.

Perhaps the most intuitive and reliable method of presenting vibration data to a neural network for fault diagnosis is in the frequency domain. Since the human expert looks for clues in the peak components of the frequency spectrum, these features are ideal as inputs to neural network classifiers. A number of researchers have used this technique for successful diagnosis of mechanical faults in rotating machinery. For example, Kim et al[5] have used backpropagation networks to diagnose faults in gears and rolling element bearings, and Kuczewski and Eames[6] have used them to diagnose faults in helicopter transmissions. A similar system developed by the author will be discussed in detail.

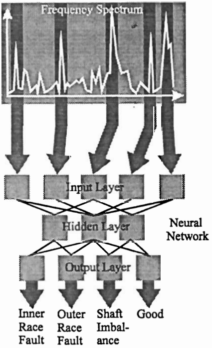

Figure 5. A Vibration Spectrum Neural Network Classifier. The magnitude of the vibration signature at certain characteristic frequencies are fed into the neural network. A high activation level on an output node classifies the class of fault present.

4. CARNEA

A demonstration bearing fault diagnostic system based on a neural network pattern classifier has been developed by the author called Carnea[7] (Carnea was the ancient Roman Goddess of good health). The system is designed to illustrate the concepts of using neural networks for fault diagnosis.

The neural network can be taught to diagnose any fault as long as the appropriate vibration data is available for training the network. In this case a number of faults associated with the bearing and its mounting were selected. These include:

1. Imbalance. Imbalance is the most common cause of excessive vibration in rotating machinery. Imbalance can usually be diagnosed by an excessively large amplitude of the vibration at the frequency corresponding to the rotation of the shaft.
2. Outer Race Faults. In a radially loaded bearing, damage usually occurs in the loaded zone of the outer race. Damage may be as a result of natural fatiguing, or premature failure for some particular reason. The fundamental frequency of roller impacts in an outer race spall can be calculated from the geometry of the bearing.
3. Inner Race Faults. Damage on the inner race of rolling element bearings is another common cause of failure. The fundamental frequency of roller impacts in the inner race can also be calculated from the bearing geometry.
4. Normal Condition. It is useful to have the neural network classify the state of a normal condition bearing. In the case of an unanticipated fault occurring in the bearing, the system will fail to indicate a normal condition, thus alerting the operator that further investigations should be carried out. Thus the fault will not go undetected.

The diagnostic system operates by firstly collecting and preprocessing the vibration data. In this case, a SKF 2209K self-aligning ball bearing was mounted in a test rig. The bearing was radially loaded to 9 kN, and the piezo-electric accelerometer was mounted on the bearing housing. Due to the radial loading of the bearing on the test rig, the inner race and rolling element fault vibrations were amplitude modulated by the rotating shaft. In the case of an inner race fault, when the inner race was in the vicinity of the load zone, the rollers passing through the defect created a large impact. However, when the inner race passed through the unloaded zone, the resulting impacts were much smaller in amplitude. Thus preprocessing involved the amplitude demodulation of the vibration signal.

In order to demodulate the bearing vibration signal, the high resonance envelope detection method was utilised[8]. This involved band-pass filtering the bearing resonant frequencies that were excited by the passage of the rollers over the fault. These structural resonant frequencies are strongly dependent upon the geometry of the bearing and its mounting configuration, but are usually found somewhere in the range from 1 kHz to 10 kHz. Inspection of the spectrum indicated that in this case the region of interest was between 3 and 5 kHz. After band-passing the signal, it was half wave rectified, and the envelope was detected by low-pass filtering the signal (which also served as an anti-aliasing filter) prior to digital sampling at a rate of 2000 Hz. Demodulation was found to be invaluable for the detection of bearing damage amongst low frequency noise.

A fast Fourier transform was computed on the bearing vibration signal, and the amplitude of the characteristic frequencies were extracted. The characteristic frequencies had been determined from the shaft speed of the test rig and the geometry of the test bearings. In total, there were ten input frequencies to the neural network, including the shaft frequencies and harmonics, and the calculated bearing ball-pass frequencies and harmonics. The amplitude of each characteristic frequency was fed into the trained neural network classifier. The neural network classified the vibration signal into one of the four classes of faults. The neural network was built with four output nodes; one for each class of fault it was trained to identify. A high activation level of a particular output node indicated the presence of the associated fault condition. For example, Figure 6 illustrates the response of the system to an outer race fault.

The network was trained by a presentation of a set of patterns for each class of fault. The backpropagation training algorithm with momentum was employed, and it took 10,000 iterations through the training set (156 minutes on a 16MHz 80386 Personal Computer) for the network to converge to an accuracy of 99.4%. Upon completion of training, the system was tested on a new set of data. The system was found to perform quite adequately on the test patterns presented to it, accurately classifying 95% of the test data. This clearly demonstrates the robust and reliable nature of neural network classifiers for mechanical fault diagnosis.

5. CONCLUSIONS

Neural networks have the ability to be trained for complex pattern recognition tasks, such as diagnosing faults in the vibration spectrum. Thus artificial neural networks are ideally suited to the automated diagnosis of faults in vibrating rotating machinery. This performance is combined with the network's tolerance to noisy data, and provides superior accuracy and reliability compared to other methods of automated fault diagnosis. Future work may also involve the combining of machine condition monitoring techniques for even more reliable and extensive diagnosis of machine condition. For example, temperature measurements may be combined with vibration measurements to diagnose faults such as loss of lubrication.

Arguably, a significant drawback of using neural networks is the requirement of a large archive of historical data required for training. However, for common machinery components such as rolling element bearings, there is sufficient reason to justify the expense of collecting training data from seeded faults in test rigs.

Perhaps the biggest attraction of neural networks is that low-cost microelectronic chips of these robust pattern classifiers are now becoming available. In the future, a low-cost hand-held electronic device could be manufactured to enable technicians to quickly and reliably check the condition of rolling element bearings. For example, after mounting a bearing on a shaft, the technician could check the machine for misalignment or out of balance faults. At a later stage in bearing life, the bearing could be periodically checked for the presence of inner or outer race faults. This proposed "black box" instrument will provide the operator with a rapid and inexpensive assessment of bearing condition, without requiring any specific expertise to analyse and interpret the results.

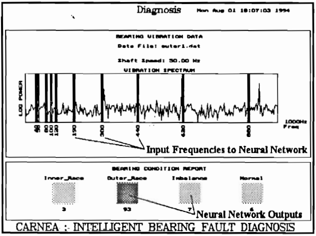

Figure 6. Output from Carnea for an Outer Race Fault. The top of the screen shows the vibration spectrum and inputs to the neural network. The bottom of the screen shows the activation levels for the output nodes of the network.

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EXPERT SYSTEMS FOR MACHINE FAULT DIAGNOSIS

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Abstract: Expert systems for the diagnosis of faults in rotating and reciprocating equipment are reviewed and one particular system intended for use with diesel engines is discussed in detail. Some of the unique features of the system , including adaptive cancellation to isolate valve event signatures as well as the use of multiple sensor types are explained.

1. INTRODUCTION

Because of their ability to mimic thought processes used by trained fault diagnosis personnel, computer based expert systems are being developed and applied in machine fault diagnosis at an exponentially increasing rate. Part of the reason for the rapid surge in interest in the use of expert systems for this purpose is the availability of powerful personal computers and high level software languages and shells designed specifically for the purpose of expert system development. Expert systems can act as excellent training tools for inexperienced maintenance fitters, but they should never be thought of as replacing the fault diagnosis specialist because sometimes there are unique unanticipated problems and corresponding thought processes used on them which are outside the domain of the expert system knowledge base. Nevertheless, an expert system can act as a valuable assistant to the human expert because it does not suffer from memory problems and because it always organises a diagnosis session in a logical and repeatable way. An intelligent, automated diagnostic expert system which uses sensor data as well as data input by the human operator will not only perform at a level comparable to a human expert in most cases, but will expedite fault diagnosis when used by less experienced personnel, leading to an overall reduction in maintenance costs. In addition, much of the "over repairing" activity resulting from poor fault diagnosis will be eliminated and experienced fault diagnosis personnel will be relieved from the more mundane equipment repair and maintenance tasks and left to work on the more difficult tasks, thus alleviating problems associated with a shortage of such personnel. Fault diagnosis is a step by step process that attempts to ascertain the internal characteristics of a physical system. What makes diagnosis difficult is the large amount of knowledge and experience it requires. First, it requires knowledge of equipment and how it operates normally. Second, it requires the gathering of information about failed equipment and their fault symptoms. Third, it requires knowledge of the type of equipment information it is necessary to gather that is relevant to the fault. Fourth, it requires an ability to use the knowledge about the equipment and the information gathered to explain how the fault could have occurred. Fifth, it requires the ability to form a hypothesis and perform some tasks to provide further information that either confirms or refutes the hypothesis. The process of gathering information and formulating and testing hypotheses may need to be done several times if the hypotheses formulated turn out negative. Only at the end of this process, when a positive diagnosis is reached, can the diagnostician repair the fault or replace the malfunctioning part.

Most of the expert system development to date for fault diagnosis in machinery has been directed at gas or steam turbines[1-6], although more recently, some work has also been directed at diesel engines[7,8]. Although many proprietary diagnostic tools are available from manufacturers of diesel engines, most of them only provide information which requires further interpretation before a diagnosis can be made. One exception to this is the SIS (Service Information System) software recently released by Caterpillar which can be used in a manual mode for fault diagnosis and automatic parts ordering, or in conjunction with a VIMS on-board monitoring system to make diagnoses based on sensor data. Unfortunately, the diagnostic part of SIS is only available for more recent Caterpillar engines and certainly not for engines produced by other manufacturers. It is not the intention of this paper to describe any of this previous work in detail; rather, attention will be focussed on a detailed description of an expert system for diesel engine fault diagnosis (CAMODE) which is the subject of a development project currently being undertaken by the authors. CAMODE is available in two versions; the manual and the automatic. The manual version is a knowledge based expert system which requires the manual input of symptoms exhibited by, and the results of specific tests on, diesel engines for the purpose of fault diagnosis in the maintenance workshop. Fault diagnoses are made by testing various hypotheses in a logical way by using an extensive set of rules which incorporate the knowledge usually contained in workshop manuals and in the heads of expert mechanics. The symptoms, which are input manually by the operator, must be observable (such as the presence of smoke in the exhaust) or the results of tests suggested by the system (such as fuel pump pressure) or readings from engine mounted gauges. As a result, the manual system is very good at diagnosing relatively simple faults but has only a limited ability in the diagnosis of more complex faults.

The advantage of the sensor based automatic version of CAMODE is its ability to diagnose complex faults which may have symptoms which are difficult or impossible to detect by an operator or diesel mechanic. A disadvantage is that a data base of fault conditions for each engine type must be acquired before the automatic system can be considered reliable and effective. A significant advantage of CAMODE is that it is useful for all makes of diesel engine and end users do not need to familiarise themselves with a new system for each make of engine they use.

Before discussing CAMODE in detail, it will be useful to provide some background information on expert systems in general and how they are applied particularly to fault diagnosis work.

2. EXPERT SYSTEM BACKGROUND

An expert system has been defined as computer software which uses knowledge and inference procedures to solve problems that are sufficiently difficult to require significant human expertise for their solution. Thus, the intention of an expert system is to solve problems, which normally require a human expert or specialist, by simulating human problem solving behaviour.

In constructing an expert system, the knowledge of one or more experts must be captured and incorporated in the program in such a way that it can be accessed easily by the program for use in a decision making process. Unlike traditional computer programs that attempt to solve problems by clearly defined and rigidly structured procedures, expert systems attempt to solve problems by using deductive reasoning, and are potentially capable of solving problems that are unstructured and poorly defined. Indeed, an expert system should be able to provide a problem solution even when input information is missing or uncertain. However, the assertion that human knowledge about a particular skill or entity can be incorporated into a program should not be taken to imply that the program can even faintly rival the common sense knowledge of a human about that skill or entity. At the current state of understanding, expert systems are almost always designed to solve problems in a restricted region of knowledge, referred to as the domain of the expert system. Indeed, all the current expert systems that have practical application operate in very narrow domains, operating on severely restricted regions of knowledge and lacking the broader human understanding that we call common sense.

Machinery fault diagnosis and maintenance is an important and growing area of application of expert systems. Systems constructed for this purpose also lend themselves for use as a training tool because once the symptoms and corresponding fault conditions have been linked, knowledge of either one can be used to derive the other. Thus an inexperienced fitter could interrogate the system to provide information about symptoms which would characterise a particular fault, or alternatively to provide a fault diagnosis consistent with certain symptoms.

In trying to diagnose a fault in a complex machine, an expert will first try to identify the defective subsystem using conscious or sub-conscious rules and knowledge and then try to identify the faulty component within the sub-system. When developing an expert system, it is important that the developer incorporates all of the information used by an expert to reach a conclusion, which means incorporating as much of this sub-conscious knowledge and reasoning as possible. The extent to which this is done is directly related to the perceived reliability of the resulting expert system.

Computer languages suitable for expert system development are different from traditional languages such as FORTRAN, PASCAL or C. These traditional languages are designed to implement a tightly specified procedure or algorithm to solve a particular type of problem. On the other hand, an expert system language is required to use symbolic, rather than numerical processing. That is, it must use known facts about a problem domain and the relationships between those facts to find both a procedure for solving the problem as well as a solution to the problem.

Two common symbolic languages used in the past for expert system development are PROLOG and LISP. In addition to these, a number of expert system shells have been developed which include inbuilt ways of inferring new facts from known facts and prescribed ways of controlling the inference process. Theoretically, one need only add the appropriate domain knowledge and the system is ready to use. However such shells or tools are usually configured to suit a particular knowledge domain and it is not always easy to manipulate the knowledge from another domain into a form that is easily added to the shell. As a consequence, in selecting a suitable shell one needs to start with the particular problem the expert system is required to solve and then work backwards to a definition of the features required. In many cases it is preferable to use commercial software which is more like a symbolic language than a shell, thus providing the advantage of greater flexibility and control albeit at the expense of simplicity for the developer. Newer expert systems are being based on IBM 386 or 486PC platforms and use Windows operating environment.

3. CAMODE ARCHITECTURE AND FUNCTIONALITY

CAMODE (Computer aided maintenance of diesel engines) is an expert system for providing maintenance advice as well as fault diagnosis. It has been developed at The University of Adelaide using the high level programming language EGERIA which is not an expert system shell but which is a higher level language than the traditionally used PROLOG language. CAMODE is intended as a workshop based tool, although it could be used for continuous engine monitoring if used with an on-board data logging facility which continuously samples engine data and then transmits it back to a central site where the expert system is based.

Of primary importance in determining the performance of a diagnostic expert system is understanding what knowledge is actually to be used and how that knowledge should be formalised, represented and integrated. Many cases of equipment diagnosis have been demonstrated successfully through the development of first generation systems which use only the shallow or heuristic knowledge of human experts in the form of production rules. The first generation of expert systems for hardware diagnosis was based primarily on the largely empirically derived knowledge of the human expert. The manual diagnostic system in CAMODE is primarily based on this type of knowledge. The automated system of CAMODE uses deep reasoning, relying on explicit fault-symptom relationships that are characterised by the signals generated by the engine components. Heuristic reasoning is used together with the qualitative physics governing the operation of the engine components to establish the operational state of the engine.

CAMODE software is configured in a layered fashion and can therefore be used to perform diagnosis either on a specific engine sub-system, such as the cooling system, or on the complete engine. Although CAMODE's primary function is to diagnose engine faults, other functions, such as advising on appropriate service and repair procedures, parts and tools requirements to carry out these service and repair procedures, testing and adjusting procedures, and specifications data, are also included in the system and may be accessed during a consultation. Educational and training facilities in the form of a Symptoms Evaluator, which may be used to assess the troubleshooting capabilities of less experienced personnel, and a Systems Operation Guide, which describes functional details and operating characteristics of engine components, are also incorporated in the system. The system is implemented on IBM personal computers and compatibles. Comprehensive on-line help and explanation facilities are available on the system to maximise ease of use. Graphical and text data for knowledge transfer, primarily whilst advising on repair procedures, are utilised extensively.

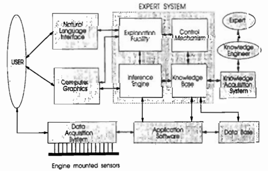

Figure 1. System Architecture of CAMODE

The automated version of CAMODE uses additional features which are linked to the manual version to form a complete system (see Figure 1). These additional components, principally the data acquisition system and the signal processing and signal analysis software linked with the knowledge base, form the heart of the system. The data acquisition system comprises engine mounted sensors and a software driven analogue-to-digital (A/D) converter. The signals acquired by the acquisition system are processed by applications software which also acts as a data reduction system, by getting rid of unnecessary information and only post-processing useful data. The information thus gathered is stored in a data base system for use by the expert system in the diagnosis of faults. All the necessary information relating to fault detection and classification are stored as rules in the knowledge base of the system. The system utilises engine surface vibration, lubricating oil pressure and temperature, engine coolant temperature and pressure, exhaust temperature and pressure, inlet manifold pressure and noise levels, fuel delivery pressure, crankcase pressure, exhaust gas composition, and instantaneous engine speed, obtained from the following types of sensors:

1. Accelerometers
2. Pressure transducers
3. Thermocouples
4. Exhaust gas analysers
5. Microphones
6. Engine speed encoder
7. Engine cycle reference encoder (optical or magnetic tachometer)

Faults detectable with the various sensors are listed in Table 1.

Table 1. Faults detectable by various sensors

Sensor	Faults Detected
Accelerometer	Combustion faults - fuel knocks, unbalanced combustion, misfiring Valve faults - seat defects, incorrect tappet clearances, mechanism wear
Pressure transducers	Oil filter blockage, fuel filter blockage, restricted aircleaners, restricted exhaust system, turbocharger turbine seizure, manifold leaks, unbalanced combustion, excessive blowby, engine misfire , excessive wear in big-end bearings
Thermocouples	Oil cooler defects, exhaust restriction, inferior fuel quality, injection timing errors, manifold leaks, under/over fuelling of cylinders, misfire
Exhaust gas analyser	Injection timing errors, inferior fuel quality, manifold leaks, restricted aircleaners
Microphones	Inlet/exhaust valve leakages
Engine speed sensor	Combustion/fuel injection fault evaluation, unbalanced combustion

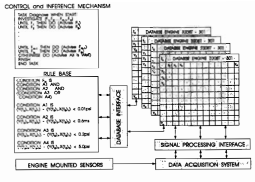

Figure 2. Schematic of operational details of CAMODE

A schematic of operational details of the system is shown in Figure 2. Data acquired from the different engine mounted sensors during the diagnosis or a service period are processed and stored in databases. These data or signatures are compared to those that were acquired when the engine was commissioned and changes are evaluated by the expert system. The changes in the different signatures reflect the condition of the different engine components and are compared against the rules that are encapsulated into the knowledge base of the system. Any abnormalities are reported and the actions to be taken are recommended.

Here, methods of analysis used to interpret vibration signals from engine mounted accelerometers will be discussed in detail. Space does not permit detailed discussion of the use of data from other sensors. Although vibration signals provide more information about the internal engine condition than other sensors, the other sensors are still needed to diagnose some faults and to confirm some diagnoses made using vibration sensors.

The use of as many source signals as possible to identify a particular malfunction helps to ensure positive identification of the root-cause for the malfunction. However, where all the associated signals cannot be accessed, the system relies upon "diagnosis by a process of elimination" for fault diagnosis. An example is the diagnosis of partial power loss due to a slight leak at one of the valves. Very slight defects causing a valve to leak might not be sufficient to alter the vibration signal appreciably; however, the faulty valve can still be diagnosed by a process of elimination where all the other associated signals, (that is, compression event, blowby past the piston rings, and fuel injection) are found to be within the acceptable range. Then from this information it can be concluded that the malfunction is due to a valve leakage since no other component can be linked to this problem.

4. DECISION ANALYSIS AND CLASSIFICATION SYSTEMS

Decision analysis and classification are major components of a diagnostic system and are built into the knowledge base of CAMODE. Machinery operating variables are usually not sufficiently well defined when the machine is operating near the "normal-failure" margin, and therefore there is always a likelihood of classifying a normal machine as having failed. The assignment of the engine to one category or the other, that is, normal or failure mode, is weighted not only by the likelihood of its being in that category based on past statistics, but also by the cost of possible diagnosis errors termed Type I or Type II. A Type I error occurs if system is classified as having failed when it has not. In this case an unnecessary cost is incurred for prematurely repairing the engine. A Type II error occurs, when a system is classified as normal when it has in fact failed. In this case the possibility of unwarranted expenses can be faced if the system breaks down and causes other damage to the engine systems. Fault decision systems in CAMODE are multi-dimensional; that is, measures on several associated signals on the malfunctioning component are available to determine its state.

The cost of diagnosis errors is most important and decisions in CAMODE are based upon the cost of, any consequential expenses due to, breakdown failure resulting in downtime and labour and materials costs. It must be appreciated, however, that the selection and setting of the decision levels may not be absolute across a range of engines even in the same organisation, but will vary from machine to machine depending on their operational environment and conditions. The decision levels may also differ for different organisations as a result of different economic and other policies. The selection of the decision levels is generally a long and tedious process which requires enormous amounts of data that also has to be analysed to extract the statistical quantities that are usually required for such exercises.

5. VIBRATION SIGNATURE ANALYSIS IN CAMODE

In the analysis of vibration signatures, the idea is to compare the vibration signature acquired from a malfunctioning engine with a time or frequency domain template signature which was acquired when the engine was commissioned and known to be in "good" condition. Differences between the two lead to identification and diagnosis of faults.

The application of vibration analysis to fault detection and diagnosis in rotating machinery is fairly well established due to the simple nature of the signals generated. Fault detection and diagnosis in rotating machinery usually requires signal analysis at the rotational frequencies or their harmonics, and analysis of faults is therefore very straightforward. However, with reciprocating machinery such as diesel engines, the events involved generate trains of vibration; each cylinder superimposes its own excitations with a delay depending on the firing sequence. The vibrations of an engine are in fact similar to a succession of transients. These transient signals are variable from cycle to cycle and much random noise is present. Time synchronous averaging (TSA) of the signals over a number of engine cycles results in a statistically stable signal and randomly occurring noise averages to zero. TSA utilises an engine cycle encoder to synchronise signal acquisition to a specific point in the engine cycle. A one per cycle event marker from the camshaft gear wheel is used as a cycle reference encoder which is also used as a trigger for signal acquisition. Although the events occurring in one cylinder's cycle are widely separated in time, events can overlap with other events from the cycle of a different cylinder or events can have only marginal separation making specific event analysis difficult. This phenomenon is common in small and compact multi-cylinder engines where it is not unusual for the combustion event of one cylinder to corrupt signals due to another source like piston slap or a valve closing event of some other cylinder. A typical case is shown for the Caterpillar 3208T marine engine (Figure 3) where one of the valve events (inlet valve no.8) acquired from the cylinder head of the engine, is seen to be in close proximity to a combustion event (combustion no.5). In this case it is difficult to analyse the valve event in the frequency domain for comparison with a template because of contamination by the combustion event.

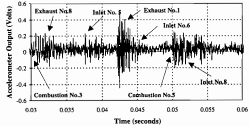

Figure 3. Part of a Vibration signature (time domain) of a CAT 3208 engine showing a valve event running into a combustion event.

The effect of a combustion event on a valve event vibration signature can be drastically reduced by using adaptive noise cancelling (ANC) incorporating a second accelerometer located at a sufficient distance from the valve (on the sump for example) so that only the combustion signature appears in its signal. An adaptive noise canceller (shown schematically in Figure 4) is then used to remove the signal correlated with the second accelerometer from the first accelerometer signal. In this way most of the combustion event contamination is removed from the first accelerometer signal leaving a valve signal which can be analysed and compared to a template representing a valve in good condition. A similar technique has been used by Tan and Dawson[9] to extract rolling element bearing defect signals contaminated by other noise in a gearbox.

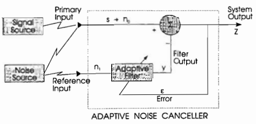

Figure 4. Schematic of an adaptive noise canceller.

The principles underlying adaptive noise cancellation can be explained with reference to Figure 4. A desired signal, denoted s, is transmitted together with unwanted noise n_1 from an engine mounted sensor to form the primary input to the noise canceller. A second sensor detects noise n_2 uncorrelated with s but correlated in some unknown way with n_1 and provides the reference input to the noise canceller. The noise n_2 is adaptively filtered to provide an output y which is as close as possible to n_1. This signal is subtracted from the primary signal to produce the system output z. The component of z correlated with n_2 is minimised by using an adaptive algorithm to optimise the weights of the adaptive filter, in much the same way as is done for an active sound control system. An adaptive rather than a fixed filter is necessary because of the continually varying nature of the vibration signal transmission paths.

An example of the results achieved using ANC is illustrated in Figures 5 to 8 which represent accelerometer signals measured on the cylinder head of the engine. Figure 5 shows an inlet valve closing event completely swamped by a combustion event. The frequency analysis of the corresponding time synchronous averaged time domain signal is shown in Figure 6. Figure 7 shows the frequency domain signature of a valve closing event measured on the cylinder head of the engine in the absence of any combustion signal and any related noise. (i.e., the valve was actuated pneumatically). The large amount of energy centred at 13kHz in the spectrum of Figure 7 can be seen clearly. In contrast, Figure 6 shows a spectrum dominated by combustion event related energy between 9 and 12kHz with little apparent energy at 13kHz. Figure 8 shows the same signal as in Figure 6 except that active noise cancellation has been used to remove the combustion event related signature leaving just the valve event with its dominant spectral energy centred at 13kHz. Thus it may be concluded that ANC was successful in removing the major part of the combustion event related contamination, thus allowing proper analysis of the valve closing event in isolation.

5. CONCLUSIONS

The application of expert systems to fault diagnosis and maintenance of mechanical equipment is becoming more widespread as equipment manufacturers and users realise the significant potential for maintenance cost savings. Earlier systems were developed exclusively for rotating equipment and particularly for gas turbines, but more recently systems have been developed for reciprocating equipment such as diesel engines. With the increasing emphasis on efficiency in industry to maintain a competitive edge, and with new techniques in signal processing making automated systems more reliable, it can be expected that the application of expert systems to equipment maintenance and fault diagnosis will become more widespread at a rapidly accelerating rate.

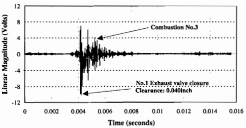

Figure 5. Inlet valve closing event swamped by a combustion event from another cylinder.

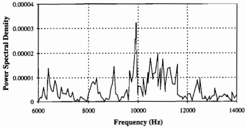

Figure 6. Frequency analysis of the combined combustion and valve event shown in Figure 5.

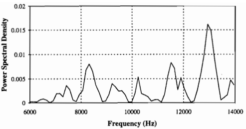

Figure 7. Frequency analysis of the event shown in Figure 5 after using ANC to cancel the combustion event.

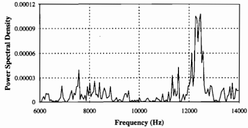

Figure 8. Frequency analysis of a valve closing event measured with the cylinder head removed from the engine and with the valve operated mechancially.

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VIBRATION ANALYSIS TECHNIQUES USED IN MACHINERY FAULT DETECTION

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ABSTRACT: To some extent machine vibration will be the result of the forces that are generated by the various mechanisms within the machine itself and then reacted by the machine's structure. Consequently it might be expected that by analysing these vibrations we may learn something about the state of the machine and in particular any faults or impending faults. Techniques used in the analysis of machine vibration will often depend on the nature of the machine itself. For example signal spectra are likely to prove useful where rotating machinery is concerned but less useful in the analysis of vibration from machines that are not cyclic in their operation. This paper describes several techniques that are used in the analysis of repetitive signals. All of the techniques described are likely to be available on modern spectrum analysers.

1. INTRODUCTION

'For every force there is an equal and opposite reaction force'. Newton's simple statement explains why machine structures will vibrate as they are loaded and unloaded by the internal forces they serve to constrain. Many machines are repetitive in their action and consequently we might expect that the external surfaces or members of these machines will also vibrate in some repetitive or cyclic manner. This periodicity may lead to distinct peaks in the frequency spectrum of the vibration and provide valuable information regarding the machine's 'health'. For example, if we were to place an accelerometer on the block of a car engine, we would expect to see a periodic impulsive acceleration corresponding to the combustion process in each of the cylinders. Furthermore, we may also expect that the nature of the block vibration will change as the engine wears due to changes in both the combustion forces and the dynamic response of the engine structure to those forces. These changes will manifest themselves in the engine's block vibration spectrum which in turn will provide a basis for monitoring the engine's health.

This paper discusses several frequency analysis techniques and one time domain technique that are used in the analysis of rotating machinery vibration signals - be they measurements of displacement, velocity or acceleration. Each of these techniques is first explained and then illustrated using a measured machinery vibration signal. The basic building block of frequency analysis - the Fourier Transform is first discussed. Following this the zoom Fourier transform, signal enveloping and time synchronous averaging are described. The zoom transform is used in digital data processing systems where the nominal 'baseband' spectral resolution is inadequate. Applications using the zoom transform include the analysis of gearbox vibrations in which several sets of harmonics each with attendant sidebands may be closely interleaved. Signal enveloping is a technique used where the signal's overall outline is of interest rather than the detailed oscillations that occur within that outline. Signal enveloping finds application in the analysis of rolling element bearings. Time synchronous averaging allows the detection of weak periodic vibration signals that are buried in asynchronous vibrations from much stronger sources. This technique is used in the detailed examination of gear teeth and mesh.

Other common techniques used in machine fault detection and diagnosis that are not discussed in this paper include RMS acceleration measurements, shock pulse methods, phase measurements, orbit analysis and cepstrum analysis. These techniques are described in reference 1.

2. THE FOURIER TRANSFORM

A vibration signal is usually transformed from the time domain to the frequency domain by the Fourier Transform [2]. The result of the Fourier Transform - the frequency 'spectrum', can be interpreted as a density function representing the magnitude and phase of the harmonic content of the time signal at a particular frequency. The Fourier Transform is shown in block diagram form in Figure 1a. The action of the search vector (which rotates clockwise in the complex plane at the frequency of interest) is to halt the rotation of frequency components in the signal that rotate anticlockwise at the same frequency as the search vector (Figure 1b). The integrator then acts to accumulate these stationary vectors. Signal frequency components rotating at other frequencies are not halted by the search vector and do not contribute to the long term output of the integrator. Consequently, the integrator output is a measure of the signal's spectral components rotating at the frequency of the search vector.

The action of the Fourier Transform is to detect and accumulate signal components at a given frequency whilst

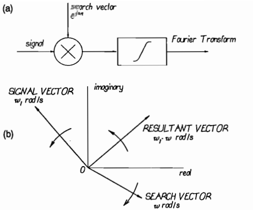


Figure 1. The Fourier Transform. (a) Block diagram representation (b) Product of the search vector and the signal component in the complex plane.

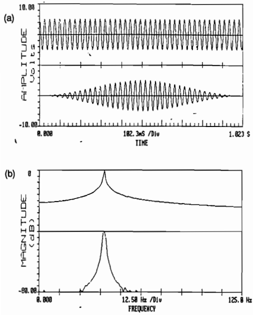


Figure 2. (a) 40 Hz sine wave truncated in time using a rectangular window (upper curve) and a Hanning window (lower curve), and (b) the corresponding Fourier transforms (magnitudes only).

eliminating all others. However, this result only holds when the integration is carried out over the entire length of the signal. This presents no difficulty for signals of finite duration such as transients. However for signals of infinite duration (such as the periodic vibrations produced by rotating machinery), we are faced with a practical difficulty as we must necessarily truncate the integration process. The result of truncating the Fourier integral is that the rotating vector resultants of the search-vector signal multiplication do not completely integrate out to zero within the integration time available. Consequently the spectrum shows spectral components that don't really exist. This effect is commonly known as spectral leakage and is illustrated in Figure 2b (upper curve) which shows the Fourier Transform magnitude of a 40 Hz sine wave that has been truncated in time (Figure 2a upper curve). Notice that most of the spectral leakage occurs in the immediate vicinity of the true frequency component at 40 Hz. This is because the slowest rotating vector multiplication products are those for which vector rotational frequency almost equals that of a signal component. It is these slowly rotating vector products that take the longest time to integrate out. By tapering the truncated sine wave smoothly to zero at both ends using a window function (fig. 2a lower curve), the spectral leakage is generally reduced (fig. 2b lower curve) although the actual width of the center lobe at 40 Hz is broadened. This tradeoff between spectral resolution and spectral leakage is a consideration made in the selection of window functions.

2.1 The Spectrogram

A common application of the Fourier Transform is the calculation of spectrograms that show how a signal's frequency spectrum changes with time. The spectrogram shown in Figure 3 represents the acceleration of a bench grinder's tool rest during a run down test. At the beginning of this test, the bench grinder was switched off and consequently began to slow from its steady rotational speed of 3000 RPM (50 Hz). Various structural resonances were excited by the rotating grinding wheel out of balance force as the grinder slowed. At any time, the periodic grinding wheel out of balance force appears in the spectrogram as a fundamental frequency component and a series of harmonics that converge with time. The fundamental component begins at 40 Hz (2400 RPM) and the second harmonic begins at 80 Hz etc. Other speed dependent frequency components are also evident. Structural resonances are intermittently excited by the harmonics of the out of balance force and appear as horizontal line segments.

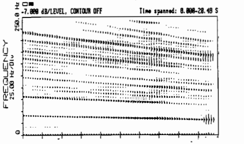


Figure 3. Bench grinder tool rest run down acceleration spectrogram showing the variation in spectral magnitude (in dB) with time. The spectrogram was formed by dividing the 20.48 s run down accelerometer record into eighty 2.048 s records, each of which overlapped its predecessor by 1.79 s. Each of the 2.048 s records was then tapered using a Hanning window and transformed using a 1024 point FFT. The magnitudes of the corresponding spectra were then displayed chronologically to form the spectrogram.

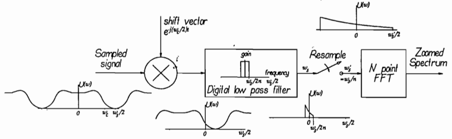


Figure 4. Digital Real Time Zoom - zoom factor = n. Initially the center frequency of the bandwidth to be zoomed is shifted to the frequency origin using a complex heterodyning process (shift vector). Next, the signal is low pass filtered. The passband of this filter just encompasses the desired zoom bandwidth. It is now possible to resample the signal at a lower rate commensurate with the reduced bandwidth. Following the resampling, an N point FFT is performed. Because the sampling rate has been reduced, the resolution of the N point FFT is n times greater than that of the unzoomed N point FFT spectrum.

3. THE ZOOM TRANSFORM

The frequency resolution of the Fourier Transform of a truncated signal is of order 1/T (Hz) where T is the signal record length. Although minor improvements in resolution may be achieved by the use of different window functions, to significantly improve the frequency resolution it is necessary to increase the signal record length. This presents no difficultly for continuous time analysis systems, (assuming the longer record length is available). However, discrete time implementations of the Fourier Transform which process fixed sample length records must make use special techniques to increase frequency resolution. One of these techniques known as the real-time zoom transform [3] is now described.

3.1 The Real Time Zoom

Many commercial digital spectrum analysers make use of the Fast Fourier Transform (FFT) algorithm [4] which processes fixed size records - typically 1024 or 2048 samples in length. Because sample record sizes are fixed, as the data sampling rate is increased, the record length T reduces and the resolution in frequency falls. However, the situation may arise where a high sampling rate is required (where the user wishes to examine high frequency vibrations) and a relatively high frequency resolution is required (that is higher than 1/T). In cases such as this, it is possible to 'ZOOM' the FFT around a particular range of frequencies using real time zoom processing. The result of 'zooming' is an increase in frequency resolution at the expense of increased processing time. For example, if it is desired to increase the frequency resolution by a factor of four, the time interval over which data is collected will increase fourfold.

Figure 4 shows the sequence of operations that make up the real time zoom. Key points are: (1) the frequency origin of the zoomed spectrum must be interpreted as the center frequency w_c of the selected zoom frequency band; (2) the frequency resolution of the zoomed spectrum is *n* times higher than that of the unzoomed (baseband) spectrum; (3) the bandwidth of the zoomed spectrum is $w_s \div n$, where w_s is the sampling rate in rad/s. (Note that due to memory limitations, some spectrum analysers only provide a real time zoom frequency resolution of *n*/2.)

Because of the resampling process used in the real time zoom (Figure 4), the total number of samples processed to produce the zoom spectrum is *n* times more than the number of samples processed in producing the baseband spectrum. Consequently processing times increase with increasing zoom factors and reducing sampling rates. For example, the processing time using a zoom factor of 10 and a sampling rate of 500 Hz is approximately 40 s for a 2048 point FFT analyser.

An example of real time zoom processing is given in Figures 5a and 5b which show the baseband and zoomed spectral magnitudes of the accelerations measured on a structural member of a large centrifugal air fan rotating at 250 RPM. The zoomed spectrum resolves the broad spectral peak in the baseband spectrum around 40 Hz into three harmonic components. Note that in this particular case, the zoom region extends from the frequency origin to 200 Hz (Figure 5b). Consequently, the same result could have been achieved by sampling the fan vibration signal at a lower sample rate. This has the effect of increasing the record length T and therefore the spectral frequency resolution for a fixed sample number FFT.

4. ENVELOPE ANALYSIS

Signal enveloping is an amplitude demodulation process in which a curve representing the signal's overall envelope or 'outline' is extracted from the signal One signal processing method used in signal enveloping known as complex demodulation [5] is shown in figure 6. Other enveloping methods include signal rectification followed by smoothing (low pass filtering) and the use of the Hilbert transform [6].

4.1 The High Frequency Resonance Technique

An application of envelope analysis in machine fault analysis is the detection of faults in rolling element bearings using the 'high frequency resonance technique' [7]. This technique involves the detection of high frequency (>15 kHz) structural resonances in a bearing housing that are periodically excited by the passage of a rolling element over a surface defect within the bearing. This defect may exist in either the inner or outer race of the bearing or on the rolling element itself. Using the bearing's geometry and rotational speed, the repetition frequencies corresponding to defects in any of these elements are readily calculated. It is these repetition frequencies (usually of order 50 Hz to 500 Hz) that are used to diagnose bearing faults. The high frequency resonances repetitively excited by the passage of a fault are used to detect the basic repetition rate itself.

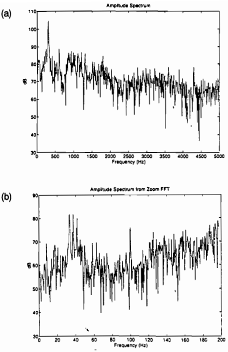


Figure 5. Analysis of centrifugal fan vibration using the real time zoom transform. (Fan rotational speed 250 RPM.) (a) base band spectrum showing 300 Hz peak due to electric drive current pulsations (6 x 50 Hz), (b) real time zoom centred on 100 Hz with a zoom factor of 25. The zoom spectrum resolves the broad spectral peak in the baseband spectrum at 40 Hz into three spectral peaks at 33.5 Hz, 37.5 Hz and 41.8 Hz. These peaks represent harmonics of the fan's rotational speed (4.17 Hz) which coincide with structural resonances of the sheet metal fan housing.

An example of the application of the high frequency resonance technique is given in Figure 7 the technique is implemented by first bandpass filtering the bearing housing acceleration signal around a structural resonance to eliminate unwanted signal components (Figure 7a lower curve). The resulting signal includes the high frequency resonance which is periodically excited at the bearing defect repetition rate. Because it is the periodic excitation rate that is of interest rather than the high frequency oscillations resulting from this excitation, the bandpass filtered signal is enveloped (Figure 7b). The spectrum of the enveloped signal is then examined for evidence of frequency components at the bearing fault repetition rates (Figure 7c).

5. GEAR ANALYSIS USING TIME SYNCHRONOUS AVERAGING

Vibration signals that are periodic but embedded in vibration from other asynchronous vibration sources may be extracted using time synchronous averaging. This technique relies on the availability of a trigger source that is synchronous with the periodic signal of interest. With each trigger pulse, a fixed length record is recorded and accumulated with previous records. In this way, only the signal components that are synchronous with the trigger are re-inforced in the accumulated sum. Synchronous averaging finds application in the analysis of gear faults where the tooth mesh vibrations caused by the meshing of individual gear teeth on a given gear can be compared.

Figure 8 shows an example of the time synchronous averaging of an acceleration signal measured on the baseplate of a gear driven lathe. An optical trigger was attached to the shaft of one of the lathe's drive gears. The synchronously averaged signal (Figure 8b) clearly shows the passage of each of the gear's individual teeth although in the latter part of the record there is a region in which this is less distinct. This indicates some change in the gear mesh occurs which may warrant further investigation. Also evident in this record are the effects of gearmesh modulation with shaft position.

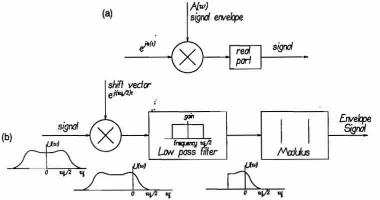


Figure 6. Signal enveloping using complex amplitude demodulation. (a) The signal is represented as the product of an instantaneous amplitude A(t) and the real part of a vector $e^{j\phi(t)}$ rotating in an anticlockwise sense in the complex plane. A(t) represents the signal envelope and $\phi(t)$ is the signal's instantaneous phase angle in radians (fig. 6a). The rate of change of $\phi(t)$ with time is interpreted as the signal's instantaneous frequency which is always positive. This analytic representation of the signal has only positive frequency components in its spectrum. (b) The analytic signal is found by filtering out the signal's negative frequency components using the shift vector $e^{-j(wb/2)t}$ and low pass filtering. The modulus of the resulting signal representing A(t) gives an estimate of the signal envelope. Note that it is not necessary to shift the signal spectrum rightward after filtering as this operation only affects the phase of the filtered signal but not its amplitude.

(a)
(b)
(c)

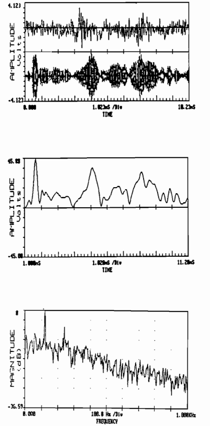
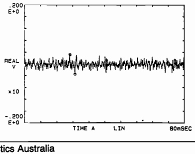


Figure 7 Bearing fault detection using the high frequency resonance technique. (a) The measured acceleration of bearing housing (upper curve) for a double row self aligning ball bearing driven at 1750 RPM under radial load. The lower curve shows the signal after bandpass filtering about a measured bearing housing structural resonance at 24 kHz, (filter bandwidth 3 kHz). This resonance serves to amplify the broadband bearing defect impacts. (b)The envelope of bandpass filtered signal. The envelope was calculated using the complex demodulation technique. (c) The spectrum of the envelope signal showing a peak at 224 Hz corresponding with the repetition frequency for a known inner race fault in this bearing.

8 (a)



8 (b)

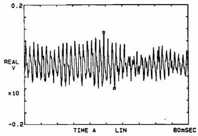


Figure 8. Synchronous averaging of gear vibration measured on the baseplate of a gear driven lathe. Figures a and b represent acceleration records accumulated without and with synchronous averaging respectively. Both records represent 1024 averages. Triggering was synchronised to the position of a 44 tooth gear rotating at 675.6 RPM. The records shown represent nine tenths of one revolution of the gear.

6. CONCLUSION

This paper has described a number of common techniques used in the detection and diagnosis of faults in rotating machinery. Many other techniques are used that have not been discussed such as the use of the Cepstrum in the analysis of gear faults and signal phase comparisons for the detection of misaligned couplings. Again, the reader is referred to reference 1 for further information.

It is important to understand that although many of the techniques described in this paper are readily available on modern spectrum analysers, the user is likely to be disappointed if he or she expects to simply 'plug in the analyser and diagnose the fault'. The user must be aware of which techniques are appropriate for the investigation of particular faults and how to interpret the results that he or she has attained. Furthermore, the diagnosis of machine faults is often a matter of detective work which requires the use of not one but several techniques and a good deal of perseverance.

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Note

Ultrasonic Foetal Videos?

As a result of the repeated and pointed criticism by the American Institute of Ultrasound in Medicine (AIUM) and members of the diagnostic ultrasound profession, the Food and Drug Administration (FDA) is working in conjunction with states to stop the recent outcropping of businesses which are using diagnostic ultrasound equipment to produce a prenatal videotape for entertainment purposes. "They're essentially making an entrepreneurial event out of a medical procedure," said Lennard Greenbaum, M.D., from AIUM.

In a letter addressed to AIUM and ten other professional organizations in the USA, the FDA states, "Persons who promote, sell, or lease ultrasound equipment for making 'keepsake' fetal videos should know that we view this as an unapproved use of a medical device, and that we are prepared to take regulatory action against those who engage in such misuse of medical equipment. '

AIUM has confirmed with the FDA's Office of Compliance that the equipment at two of these operations in Texas has been embargoed, Peek-a-Boo Inc. and Baby Images, in what likely is the beginning of equipment seizures to follow in other states. The FDA and the Texas Department of Health are engaged in an ongoing joint investigation of businesses who use foetal diagnostic ultrasound in this manner. According to the two agencies, this use of ultrasound is contrary to what the equipment was approved for and contrary to the standards and uses defined by the FDA for foetal diagnostic ultrasound equipment.

Across the country, these companies are advertising their service of performing ultrasound examinations to produce a videotape of the foetus as part of a new type of family album. AIUM is concerned about this exploitation of a technology designed for medical purposes: "To state things simply and bluntly, diagnostic ultrasound is a valued medical tool, not a device for casual entertainment and exploitation," Michael S. Tenner, M.D., President of AIUM said. "The use of videotape as an archival form of a medical ultrasound study is an accepted and common practice. However, this in no way condones the practice of videotaping or filming an obstetrical ultrasound without a medical indication."

AIUM's viewpoint is shared by the Society of Diagnostic Medical Sonographers (SDMS). In a statement issued on March 12,1994 the society stated "Diagnostic medical sonography is a medical procedure that is requested by a physician, performed by a sonographer, and interpreted by a sonologist.... Because of our dedication to professionalism, and our commitment to the use of ultrasound as a diagnostic procedure, SDMS does not condone the use of ultrasound solely for entertainment purposes."

Another concern is the level of experience acquired by the person performing the ultrasound service. Although ultrasound is a safe and effective diagnostic tool and to date there are no known bioeffects, it is a medical test to be completed by trained sonographers or sonologists. Still another concern is expressed by Leon Frizzell, Ph.D., Chairperson of the AIUM Bioeffects Conference, an in-depth review of bioeffects of ultrasound by leading experts in the field, and Professor of Electrical and Computer Engineering at University of Illinois. "It is wise to be conservative and to limit human ultrasound exposure to situations which provide a physician with valuable clinical information. Thus, it is acceptable to provide the patient with a copy of a videotape acquired as part of a normal medical examination, but it is not appropriate to use ultrasound solely for the purpose of creating a videotape of the fetus."

Extracted from AIUM Newsletter Sept 1994

News...

I-INCE Board Meeting

The 1994 meeting was held in Yokohama in August. At the previous meeting of the Board in Leaven in 1993, two Working parties were formed - "Noise emission of road vehicles - the effect of regulations" convened by Ulf Sandberg and "Upper noise limits in the workplace" convened by Tony Embleton, Canada. Draft reports of these WP's were presented and they will be published in the December and March issues of Noise News International. The Member Societies of I-INCE (which includes AAS) will be asked to comment on the drafts and to vote on their publication as official I-INCE documents. It is hoped that they could then be circulated to the different countries' bureaucrats who may be able to influence relevant politicians.

Four new topics were suggested for investigation, they will be published in NNI for comment and, if agreed, Member Societies will be requested to nominate experts to take part in the Working Parties. Work is carried out mainly by correspondence and fax, and meetings take place in conjunction with Internoise meetings. The proposed topics are "Building envelope noise reduction, "Consumer information and labelling", "Noise walls (roadside barriers)" and "Community noise criteria (engineering aspects of a WHO draft)".

Tor Khilman, a member of the I-INCE Board, is the new Chairman of the ICA and he discussed the role of the Commission and expressed the need to revitalise the ICA Congresses. The I-INCE Board agreed that it is important to support ICA because of its broad coverage of all aspects of acoustics. The next ICA will be held in Trondheim, Norway June 26-30th 1995, followed by Seattle, June 20-27th 1998 and Rome in 2001.

Inter-noise 95 will be in Newport Beach, California, July 10-12 and it will be immediately preceded by "Active 95". Arrangements for Inter-noise 96, to be held in Liverpool, England were described. The Board also decided to accept the invitation of Hungary to hold Inter-noise 97 in Budapest.

Noise News International, I-INCE's journal which is distributed to all Member Societies was also discussed, and methods of increasing its circulation were suggested - including encouraging individual society members to become subscribers.

Anita Lawrence

WESTPRAC & INTERNOISE

It always seems to be a good idea to attend a conference when the first "Call for Papers" appears in the mail. There is usually not too much effort required to compose an Abstract once the theme for the conference has been noted and the Technical Areas have been identified. (Research goes on all the time). The deadline for submission of the papers always approaches too rapidly, and seems to coincide with other important deadlines. But the real hassle begins about 2 weeks before departure for the conference when the pressure to resolve all outstanding matters starts to mount. Things are much worse after the return from the conference, and the question arises, "Was it worthwhile?" I am happy to report that on this occasion it was definitely worth the effort. There were two conferences (three actually, although it was impossible for me to attend the third).

The "Fifth Western Pacific Regional Acoustics Conference", WESTPRAC for short, was held in Seoul, Korea from the 23rd-25th August. In all there were about 170 papers from 22 countries giving rise to 4 parallel sessions during the 3 days. All the normal areas in acoustics were covered to some extent. The 2 areas which attracted the greatest number of papers were those that dealt with Underwater Acoustics, and Speech Analysis. The papers in these sessions were largely from the Asian contingent, and some were quite advanced. The Koreans in particular were heavily into speech analysis. The overwhelming impression of the conference was one of fine organisation and good attention to detail. The Conference Dinner was the best I had attended despite the unexpected "Red Faces" session in which Marion Burgess, Bob Hooker and I did the best we could with "Waltzing Matilda"..it wasn't very good! The next WESTPRAC Conference will be held in Hong Kong in 1997.

If it was possible to improve the standard of organisation for a conference, that happened at "Internoise 95" which was held in Yokohama, Japan from the 29th-31st (The exception was the Conference Dinner but no more will be said about that!). There were about 40 countries represented including a group of 24 from Australia. By far the largest group was of course from Japan although the USA and Europe were well represented as well. The sessions needed to be well organised! Typically there were 10 parallel sessions apart from those given over to the distinguished lectures.

All the usual topics were covered and if there was some frustration it was due to the difficulty in choosing which one of the 10 sessions to attend each 20 minutes. Inevitably there was a wide variety of standard in the papers, both from a technical and presentational point of view. That applies equally to the Invited papers, Contributed papers and the Distinguished Lectures. It is a pity some authors did not give more thought to the quality of their visual aids used in their presentation. An undergraduate student is advised about how much information can be absorbed in a single slide. Not very much!It would have been beneficial too if more time could have been given to discussion. But these are minor points and are not intended to distract from the vast amount of insight and enlightenment that occurred at this conference.

So, the conferences were very productive and stimulating. It was gratifying to see that the work that is being done in Australia was comparable to that of the best anywhere in the world. I look forward to the next "Inter-noise" conference to be held in USA in 1995.

Robin Alfredson

AAS Annual Conference November 1995 Freemantle, WA

The WA Divisional Committee has been actively involved in the early stages of the organisation of the 1995 Conference, to be held in Perth, 15-17 November 1995. The Conference theme will be "Acoustics Applied", and it is hoped that papers will point to practical applications, whether it be noise or vibration assessment or control, architectural acoustics, physiology or noise legislation or any other related area of acoustics.

The venue will be the superbly restored Esplanade Hotel in historic Freemantle, 20 km from Perth. The Hotel is a centre for easy walks through the art galleries, specialty shops. historic spots and harbourside areas of this unique city. So there will be lots for both delegates and accompanying persons to do outside the conference. It is definitely worth considering combining the conference with an Asian holiday - the extra cost can be minimal!

Now is a good time to start planning to attend the Perth Conference in 1995 and deadline for papers abstracts is 12 May 1995.

For further details: Dr Graeme Yates, Dept of Physiology, University of WA, Hackett Drive, Crawley, WA, 6009, Tel (09) 380 3321, Fax (09) 380 1025.

ACTIVE CONTROL

There have been a number of activities associated with active control - two in the ACT and one in WA.

For many people, the area of active noise control remains shrouded in mystery. Certainly, the notion of introducing a sound to cancel an unwanted sound is an appealing one, but the practicalities are not so simple. So it was perhaps not surprising that about 50 assembled at UWA on 11 August to hear an enlightening technical presentation by **Dr Pan Jie** from the Dep. of Engineering on this topic.

Those of us who had followed (at a distance) the debate as to the basic mechanism involved in active noise control were assured by Pan Jie that it is now generally accepted that the superposition principle is the one which explains the phenomena observed in active noise control. The mystery of the "cancelled energy" was explained by it's transfer to other regions of the spatial sound field.

Thus reassured that order still prevailed in the Universe, we began to grapple with the mysteries of the control systems. The key to this is to have a thorough understanding of every aspect of the control system. Firstly one needs a good grasp of the maths involved and secondly a working knowledge of electronics and Digital Signal Processing techniques, to design a practical system. Thirdly, one needs a detailed knowledge of the electroacoustic characteristics of the microphones and loudspeakers used for detecting and cancelling the unwanted noise. Pan Jie followed the lecture with a demonstration of active noise control applied to a set of earmuffs for the mining industry and a duct system.

John Macpherson

The topic of active control was presented to a joint meeting of the ACT Group of the Society and the ACT Branch of the Institute of Physics held on 11 October. **Assoc Prof Joseph Lai** from the Acoustics and Vibration Centre at the Australian Defence Force Academy gave a very comprehensive explanation of the principles of active control as well as its limitations. He also discussed various applications. Demonstrations in the lecture room complemented the presentation and was followed by a short tour of the facilities of the Centre. Such joint meetings are usually well attended and provide an opportunity for discussions between those who may not otherwise meet.

A two day short course on Basics of Active Control for Noise and Vibration was held by the Acoustics and Vibration Centre at the Australian Defence Force Academy in early November. The main presenters were **Dr Colin Hansen** and **Dr Scott Snyder** from Mechanical Engineering at Adelaide University. **Assoc Prof Joseph Lai** presented an introductory session and assisted with the practical exercises. The registrants came from a range of areas including defence, industry, university researchers and consultants. The presenters coped well with the mixed group and ensured that all went away knowing more about active control and anxious to apply it in their work areas.

Marion Burgess

PUBLICATIONS

Journal of Technical Acoustics

Publication of this new journal by the East European Acoustical Association (formerly the Soviet Acoustical Association) began in English in 1994. It will initially be published with four issues each year, each issue containing about 70 pages. The journal will be of interest to scientists and engineers involved with aircraft, vehicles, ships, industry and buildings. The price is $US 95 per year. There is an additional fee per year of $US 15 for overseas airmail from Russia. Subscriptions to International Scientific Publications, PO Box 13, Auburn AL 36831, USA.

Noise Abstracts and Reviews

This new journal is being published in Russia by the Noise and Vibration Control Society in cooperation with the Russian Institute of Scientific and Technical Information. Each issue will contain a feature article and will survey major research and developments in noise and vibration control and contain abstracts of at least 1500 to 2000 papers, reports, patents and books per year, plus announcements of international meetings, new developments, recent studies and a calendar of upcoming events. Both theoretical and applied noise control topics will be covered. The journal will be published in English and Russian. Beginning in July 1994, there will be 6 issues per year. Annual subscription rate is $US 120 postpaid for institutions and libraries and $US 90 postpaid for individuals. Enquiries or subscriptions to International Scientific Publications, PO Box 13, Auburn AL 36831, USA.

Noise-Con 94 Proceedings

Noise-Con 94, the 1994 National Conference on Noise Control Engineering, was held in Florida in May. The theme was Progress in Noise Control for Industry. The Proceedings contains 1088 pages and 165 papers devoted to a wide variety of topics on noise control engineering of interest to industry. The Proceedings are available for $US95 from Noise Control Foundation, PO Box 2469 Arlington Branch, Poughkeepsie, NY 12603, USA. The price includes surface mail; airmail is an additional $US 25.

STANDARDS

Quality Manual

The Quality Manual Toolkit from Standards Australia takes the mystique out of writing a quality manual and is aimed at smaller business firms.

Catalogue on Disk

Having the Australian Standards catalogue on disk is a useful resource for any regular user of standards. Purchasers are able to make unlimited installations of the software on stand alone or network systems restricted only to the registered site of purchase

Handbooks

"Guide to the expression of uncertainty in measurement" and "Vocabulary of basic and general terms in Metrology" are invaluable handbooks wherever accuracy in the expression of scientific measurement is required. The former establishes general rules for expressing and evaluating uncertainty in measurement. The latter is a comprehensive guide concerned with vocabulary used in all branches of science and technology. Both handbooks are aimed at creating uniformity and ease of understanding.

Contact: Standards Australia Information Centre Tel (02) 746 4748.

ARUP ACOUSTICS

Arup Acoustics are now operating in Australia. The Australian practice is led by **Peter Griffiths** who has returned after 3 years with Arup Acoustics in London. The practice is part of a global network with offices in the UK, Hong Kong and the US. The group has been responsible for the acoustic design of many landmark projects of a variety of sizes, over a wide range of building types and environmental situations. Contact details: Arup Acoustics, 477 Kent St, Sydney 2000. Tel (02) 261 1633, Fax (02) 261 2181.

New Products...

BILSOM

Hearing Protection + FM Radio

Bilsom Australia have released a comfortable hearing protector with built-in high quality FM stereo radio. Workers in high noise environments can enjoy radio reception in perfect stereo without compromising hearing protection. The Bilsom 797 Radio earmuff can motivate workers to always wear their hearing protection when in noise hazard environments. It has been tested to AS1270-1988 and has an SLC rating of 27 dB. The unit is equipped with a unique sound limiting circuit to avoid the emission of harmful sound levels from the FM radio within the ear cups, which are limited to 82 dB Leq8. Two standard 1.5V alkaline batteries provide a life of 140 hours, and battery replacement is a quick and simple operation. Bilsom's Radio earmuffs are a practical solution to the complex problem of selecting the correct hearing protection in high noise environments.

Further information: John Read, Communication Products Manager, Bilsom Australia, tel (02) 450 1544.

ACADS BUILDING SERVICES GROUP

WOMBAT Acoustical Analysis Program

The computer program WOMBAT performs acoustical calculations for various sound transmission problems in and around buildings. The program was developed by ACADS and may be licensed for use on a micro computer. The program currently performs the following functions, and additional functions will be the subject of future updates: barrier wall attenuation, transmission loss of a wall made up of a number of components, room acoustical properties, sound ratings and summations, air conditioning duct attenuation, and duct breakout noise. WOMBAT is a menu driven fully interactive program. The methods on which the various functions in the program are based are described in the AIRAH/ACS Noise Control Application Manuals and A/C Duct Design Manual. The program runs under MSDOS and can be supplied on 3.5" or 5.25" diskette.

Further details: ACADS, 16 High Street, Glen Iris, Vic 3146. Tel (03) 885 6586, Fax (03) 885 5974.

VIBRAMETRICS

Accelerometers

New versions of the popular 8000 series accelerometers have been released. The 8000 Guardian Series is a small, centre hole mount accelerometer certified to be sensor highway compatible. Now available in a high temperature, intrinsically safe and general purpose versions.

The 6036 and 8000 Century are high temperature accelerometers (350 deg F) and offer extraordinary specifications such as 10 kHz frequency response. Both are sensor highway compatible.

Sensor Highway

The number of sensor points on the popular sensor highway "one wire" system has been expanded from 250 to 4,500. The controller is now available in a version which plugs into your computer. The number of simultaneous outputs has been increased from 3 to 4 with an option for 6.

Further information: Int Scientific Instruments, 40 Chomley St, Prahran, Vic 3181. Tel (03) 529 3660, Fax (03) 529 7524.

New Members...

The following are new members of the Society, or members whose grading has changed.

New South Wales

Member: Mr M Warpenius, Mr M Harrison, Mr M Palavidis, , Mr J Caley

Subscriber: Mr D Mazlin, Mr K Williams, Mr P Banks,

Student: Mr K Burgemeister,

Queensland

Subscriber: Mr S Pugh,

South Australia

Student: Mr M Simpson, Mr J Woolley, Mr C Howard

Victoria

Member: Dr M Kierzkowski, Mr T M Marks

Subscriber: Mr A Tattersall, Mr R Nicholson, Mr P De Bruin

Student: Mr M Butyn, Ms K Wakeham

West Australia

Subscriber: Mr A Mills

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Volume 22, 1994

A. ARTICLES

B. REPORTS

Cumulative index for Volumes 11-21 listed in 22(1) 29-31

Books...

Basic Music Industry Skills

AUSMUSIC, series of training modules, PO Box 307, Port Melbourne VIc 3207, Tel (03) 696 2422, Fax (03) 696 2879. Price A$45 to $80 per module.

AUSMUSIC has developed an extensive training package which, if satisfactorily completed, can lead to an accredited Certificate in Basic Music Industry Skills. The package is aimed at those involved with contemporary music. The main streams of the package deal with Music Industry Studies, Music Performance, Music Business Management,Music Technology, Marketing and Promotion. The complete package has been designed for the use by some form of educational provider such as school, TAFE or private organisation in the music industry. Over 100 modules are available and the time for completing each module ranges from 3 to 48 hours. Each module is essentially self contained, can be purchased individually, and comprises a trainers manual, student workbook and video. Thus individuals or small groups, who do not wish to obtain the Certificate, can work through just the modules in which they are interested.

The two modules inspected were "What did you say?" from the Occupational Health and Safety study area in Stream 1 and "Getting to know your gear" from the Live Sound study area in Stream 4. Both of these are considered to be three hour modules.

The fifteen minute videos feature interviews with those in the music industry such as performers, technicians, managers etc. These respond very naturally to the questions and the style is particularly relevant for the module on protecting your hearing. Comments from performers from well known groups who have hearing damage which affects their lifestyle, even to the extent that they can no longer perform, should really reinforce the importance of hearing protection. Unfortunately, insufficient emphasis was given to the simple option of reducing the volume! The explanations on basic acoustics and equipment were kept very simple and any essential technical terms were explained.

The student workbook makes great use of graphics to make each page look interesting and keep the attention of the reader. Obviously the main users of this package would be young people who would consider this layout very "user friendly". There are small tasks and questions to be answered and a crossword at the end which even I found interesting to complete. The trainers manual is well set out and provides sufficient background material on relevant points without excessive explanations. A reference list includes books and contact details for AUSMUSIC for further support information.

The complete package appears to cover all the important aspects for those wishing to work in the music industry. I would recommend that any young person interested in performing in the contemporary music area would gain much knowledge from working though selected modules. I would also recommend they start with the module dealing with hearing protection although perhaps this shows my bias.

Marion Burgess

Marion Burgess is a research officer at the Acoustics and Vibration Centre, Australian Defence Force Academy, Canberra and is involved with educational activities.

Diary...

CONFERENCES and SEMINARS

• Indicates an Australian Activity

1995

January 11-12, SINGAPORE
Society of Acoustics (Singapore)
Annual Conference - Noise
Details: Dr W S Gan,Acoustical Services Pty Ltd., 209-212 Innovation Centre, Nayang Avenue, NTU, Singapore, 2263, Republic of Singapore. Tel 65-791 3242. Fax 65-791 3665

February, SUSSEX
Opera and Concert Hall Acoustics
Details: IOA, Agriculture House, 5 Holywell Hill, St Albans, Herts AL1 1EU, UK. Tel +44 727 848195, Fax +44 727 850553.

March 21-23, LYON
Euronoise 95 - Software for Noise Control
Details: CETIM, Acoustical Dept, BP 67, 60304 Senlis, France. Tel +33 4 458 3217, Fax +33 4 458 3400

March 22-25, CINCINATTI
Hearing Conservation Conf
Details: Michele Johnson, Nat Hearing Cons Assoc, 431 East Locust St, Suite 202, Des Moins, IA 50309 USA. Tel +1 515 234 1588, Fax +1 515 234 2049

March 26-29, SAN FRANCISCO
39th AIUM Convention
Details: AIUM , 14750 Sweitzer Lane, Suite 100, Laurel, MD 20707-5906, USA. Tel +1 301 498 4100, Fax +1 301 498 4450

April 3-5, BIRMINGHAM
Sonar Transducers 95
Details: Mr J R Dunn, School of Electronic & Elect Eng, Uni Birmingham, Edgbaston, Birmingham B15 2TT, UK. Tel +44 21 414 4312, Fax +44 21 414 4291, email jdunn@ee_admn.bham.ac.uk

April 5-7, SOUTHAMPTON
Int Conf Computational Acoustics
Environmental Applications
Details: Jane Evans, COMACO 95, Wessex Institute of Technology, Ashurst Lodge, Ashurst, Southampton SO4 2AA, UK.Tel +44 703 293223, Fax +44 703 292853, email CMI@ib.rl.ac.uk

April 20 - 22, LISBON
8th Int Conf on Low Frequency Noise & Vibration
Details: Conference Secretariat, 107 High Street, Brentwood, Essex, CM14 4RX, UK. Tel +44 277 224632, Fax +44 277 223453

April 25 - 27, VENICE
Vibration & Noise 95
Details: MJ Goodwin, School Eng, Staffordshire Uni, PO Box 333, Beaconside, Stafford ST18 0DF, UK. Tel +44 785 275242, Fax +44 785 227741

May 9-11, LIVERPOOL
Environmental Noise and Vibration
Details: IOA, Agriculture House, 5 Holywell Hill, St Albans, Herts AL1 1EU, UK. Tel +44 727 848195, Fax +44 727 850553

May 15-18, TRAVERSE CITY
SAE Noise and Vibration Conf
Details: Mone Asensio, SAE Int, 3001 West Big Beaver Rd, Troy, Michagan USA. Tel +1 313 649 0420

May 31 - June 4, WASHINGTON
129th Meeting Acoustical Society of America
Details: ASA, 500 Sunnyside Boulevard, Woodbury, NY 11797, USA Tel +1 516 576 2360, Fax +1 516 349 7669

June 12-16, ABERDEEN
Symp on Fisheries and Plankton Acoustics
Details: J. Simmonds, Marine Laboratory, PO Box 101, Victoria Road, Aberdeen AB9 8DB, Scotland. Fax +44 224 295511

June 20-22, WARSAW
Noise Control 95: Noise - a civilization hazard
Details: Noise Control 95, Central Institute for Labour Protection, Czerniakowska 16, 00-701 Warsaw, Poland. Fax +482 623 36 95

June 26-30, TRONDHEIM
15th International Congress on Acoustics
Details: ICA'95, SEVU Congress Department, N-7034, Trondheim, Norway. Fax +47 7359 5150, email ica95@sevu.unit.no

July 2 - 6, PARIS
Int Symp on Musical Acoustics
Details: ISMA'95 Secretariat, IRCAM, 1 Place Igor Stravinsky, 75004 Paris FRANCE. Tel (331) 44 78 47 60, Fax (331) 42 77 29 47, email: isma@ircam.fr

July 6-8, NEWPORT BEACH, CALIF
Active 95: Int Symp on Active Control
Details: Noise Control Foundation, PO Box 2469 Arlington Branch, Poughkeepsie, NY 12603 USA. Tel +1 914 462 4006, Fax +1 914 463 0201

July 10-12, NEWPORT BEACH, CALIF
INTERNOISE 95
Details: INCE/USA, PO Box 3206 Arlington Branch, Poughkeepsie, NY 12603 USA. Fax +1 914 473 9325

August 1-9, STOCKHOLM
Int. Congress Phonetic Sciences
Details: ICPhS 95, Dept Linguistics, Stockholm Uni, 106 91 Stockholm Sweden Fax 46 816 2347

August 16-18, AUCKLAND
Conf of NZ Acoustical Society
Details: Secretary, PO Box 1181, Auckland, NZ. Fax +64 9 6233248

September 3-7, BERLIN
1995 World Congress on Ultrasound
Details: J. Herbertz, Gerhard-Mercator-Universitat, 4708 Duisburg, Germany

September 19-22,
• Asian Pacific Conf on OH&S
Details: OH&S Conference, PO Box 515, Sunnybank, Qld 4109. Tel (076) 312 438, Fax (076) 345 4892

November 15-17, PERTH
• AAS Annual Conference "Acoustics Applied"
Details: Dr G Yates, Dept Physiology, Uni WA, Hackett Drive Crawley, WA 6009 Tel (09) 380 3321, Fax (09) 380 1025, email gyates@uniwa.uwa.edu.au

November 27 - Dec 1, ST LOUIS
130th Meeting Acoustical Society of America
Details: ASA, 500 Sunnyside Boulevard, Woodbury, NY 11797, USA, Tel +1 516 576 2360, Fax +1 516 349 7669

December 4-7, HONG KONG
SDVNC 95 Int. Conf. Structural Dynamics, Vibration, Noise & Control
Details: Prof De Mao Zhu, Nanjing Uni Aeronautics & Astronautics, Nanjing, Tiangsu210016, China, Tel +86 254492492, Fax +86 25 4498069

1996

February 19-21, MELBOURNE
• 1st Australasian Cong on Applied Mechanics
Details: AE Conventions (ACAM 96), PO Box E181, Queen Victoria Terrace, ACT 2600. Tel (06) 270 6562, Fax (06) 273 2918

April 1 - 4, ANTWERP
Forum Acusticum 96
1st Conv. European Acoustics Association
Details: Forum Acusticum, Technological Institute KVIV, Desguinlei 214, B-2018, Antwerpen, Belgium, Tel +32 3 216 0996, Fax +32 3 2160689

June 24-28, HERAKLION, CRETE
3rd European Conf on Underwater Acoustics
Details: Conference Secretariat, Institute of Applied and Computational Mathematics, PO Box 1527, 711 10, Heraklion, Crete, Greece. Tel +30 81 210034, Fax +30 81 238868, email conference@iesl.forth.gr

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COURSES

1995

February 6-9 MELBOURNE
Linear & Nonlinear Systems - visiting lecturer, Dr Julius S Bendat
Details: Margaret Keegel, Office of Continuing Education, Monash University. Tel (03) 903 2808, Fax (03) 903 2805, or Dr Len Koss, Mech Eng.Tel (03) 905 3551

AUSTRALIAN ACOUSTICAL SOCIETY ENQUIRIES

*** Notification of change of address**

*** Payment of annual subscription**

General Secretary
AAS– Professional Centre of Australia
Private Bag 1, Darlinghurst 2010
Tel (02) 331 6920 Fax (02) 331 7296

Enquiries regarding membership and sustaining membership should be directed to the appropriate State Division Secretary as under:

AAS - NSW Division
Professional Centre of Australia
Private Bag 1, DARLINGHURST 2010
Sec: Mr Ray Piesse
Tel (02) 969 6668

AAS - SA Division
C/–Department of Mech Eng
University of Adelaide
GPO Box 498, ADELAIDE 5001
Sec: Mr A C Zander
Tel (08) 228 5698 Fax (08) 224 0464

AAS - Queensland Division
C/– Ron Rumble Pty Ltd
PO Box 29,
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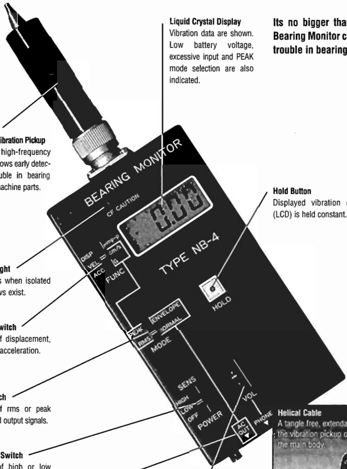
NSK·RHP BEARING MONITOR
MODEL NB-4

Its no bigger than your hand, but the NB-4 Bearing Monitor can give you early warning of trouble in bearings and other machine parts.



Liquid Crystal Display
Vibration data are shown. Low battery voltage, excessive input and PEAK mode selection are also indicated.

Hand-held Vibration Pickup
Superior high-frequency response allows early detection of trouble in bearing and other machine parts.

Hold Button
Displayed vibration data (LCD) is held constant.

Warning Light
LED flashes when isolated bearing flaws exist.

Function Switch
Selection of displacement, velocity, or acceleration.

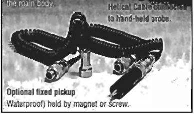
Mode Switch
Selection of rms or peak readings and output signals.

Sensitivity Switch
Selection of high or low sensitivity or power off.

Output Terminal
Either the vibration wave form or waveform envelope signal is output.

Earphone Output
Vibrational sound may be heard using earphones and the volume controller.

Helical Cable
A tangle free, extendable cable may be used to connect the vibration pickup or it can be connected directly to the main body.



Optional fixed pickup
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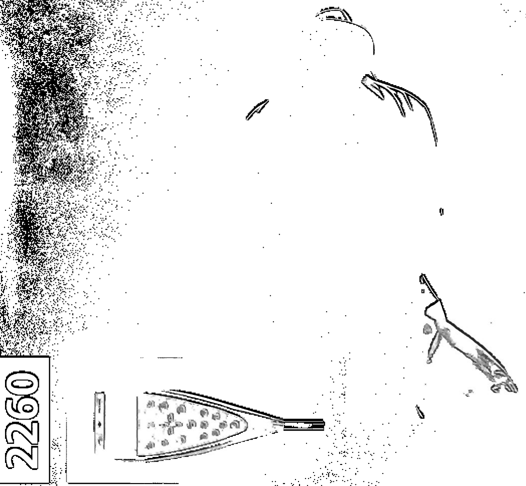

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