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Radiation efficiency of planar structures- a case study on its application for estimation of radiated sound power

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ABSTRACT

Identification of the contribution from multiple noise sources is critical for suggesting potential noise mitigation measures. Structural noise radiation of planar structures located on industrial sites frequently provides significant contribution to noise levels measured at affected receivers. One of the methods to estimate sound power (SPW) radiated from walls, enclosure roofs, or industrial buildings is the measurement of vibration over the radiating surface.

Theoretically the SPW emitted by a planar structure is proportional to product of the squared vibrovelocity averaged over the radiating surface, area of the surface, the radiation efficiency, and a few other ancillary parameters. Radiation efficiency of simple plates has its peak at a critical frequency and tends to be unity at higher frequencies. Industrial enclosures and building are frequently built from reinforced concrete, brick, and mortar. They represent inhomogeneous structures, and the radiation efficiency of these structures is more complex than it is for metal plates.

Sound intensity measurements of planar structures installed in an electrical substation site were undertaken using a sound intensity probe. Vibrovelocity estimates were also obtained to compute indirect estimates of the radiated sound power. Radiation efficiency was analysed in third octave frequency bands using the SPW and vibrovelocity estimates. It was shown that radiation efficiency has a more complex character in comparison with metal plates, showing that vibration measurements of these types of structures and materials for estimation of radiated sound power may not always provide good representation of such complex structures.

1 INTRODUCTION

Task of noise mitigation at an industrial site frequently involves analysis of noise contribution from multiple noise sources. In situ measurements of sound power can be performed accurately by using a sound intensity probe and other relevant measurement techniques. Where radiation from structures such as walls, roofs of buildings or enclosures is important, measurement of vibration can be considered as an appropriate technique to estimate SPW radiated from the surface. Sound intensity instruments may not always be available or sound intensity measurements may not be considered practicable at times.

Theoretically, the sound power radiated by a vibrating surface can be estimated from the mean square vibration velocity averaged over the surface (Chertok, 1964; Takatsubo et al.,1983). The mean square vibration is linked to the radiated sound power through radiation efficiency. This parameter is reasonably documented for a limited number of materials and less defined for more complex structures. The radiation efficiency is commonly assumed to be unity for many calculations where identification of dominant noise sources or estimate of radiated sound power is required.

Sound intensity measurements were performed for planar structures located in an industrial site including a brick and concrete walls. Simultaneous surface vibration measurements were undertaken for the same structures. The results have provided a good ground for comparison of direct (via sound intensity) and indirect estimates of SPW radiated from vibrating surfaces. This paper details comparison of SPW estimates obtained by both of the methods and calculations of the radiation efficiency based on the sound intensity measurements as the reference method.

2 THEORETICAL BASIS FOR ESTIMATION OF SOUND POWER

2.1 Radiated sound power based on vibration measurements

Vibration measurements can be used for indirect estimation of sound power radiated from the surface. Generally, indication of few measurement points distributed over the vibrating surface are sufficient to give a reasonable estimate of the radiated sound power (Bies and Hansen, 2009). The sound power W is given by:

$$W = \langle v^2 \rangle_S S \rho c \sigma, \qquad (1)$$

where *S* is the area of the surface, $\langle v^2 \rangle_S$ is the averaged mean square velocity and σ is the radiation efficiency determined for relevant 1/3 octave bands; ρ is the density of the air and *c* is the speed of sound. Equation (1) can be expressed as sound power level L_w under standard environmental conditions (Bies and Hansen, 2009) given by:

$$L_w = 10\, Log_{10}\langle v^2 \rangle_S + 10\, Log_{10}S + 10\, Log_{10}\sigma + 146\,, \;(dB\; re\; 10^{-12}W) \tag{2}$$

The radiation efficiency is difficult to predict for composite or complex structures. This parameter peaks at the critical frequency for a metal flat panel and tends to be unity at higher frequencies (Wallace, 1972; Laulagnet,1998). Radiation efficiency at lower frequencies may be substantially less than one (Sablik, 1985, Kou et al., 2015). Frequently the radiation efficiency is considered unity for approximate evaluation of radiating sound power from vibration measurements. Sometimes it is also suggested to apply A-weighting to the measured vibration levels to identify A-weighted SPW and reduce uncertainty brought by unknown radiation efficiency at the low frequencies.

2.2 Radiation power determined by intensity measurements

Computing SPW levels using intensity measurements has become popular since relevant measurements can be performed in situ and does not require specific acoustic environment such as an anechoic or semi- anechoic chamber. There is a number of national and international standards that provide recommendations on relevant measurement procedures. Reference can be made to ISO 9614 series of standards (International Organization for Standardization, 1996) or similar. Sound power radiated from a surface, or a segment of the surface can be computed as follows (Fahy, 2000):

$$W = I_n S, \tag{3}$$

where I_n is the time and area averaged acoustic intensity measured normal to the surface. Sound power estimates obtained via intensity are considered to be accurate and they are adopted as reference magnitudes in the current work.

3 ESTIMATES OF SOUND POWER- CASE STUDY

Vibration and sound intensity measurements were performed as part of noise mitigation assessment for an electrical substation site. Sound power estimates were necessary to identify dominant contributing noise sources to enable suggestions of practical ways to reduce noise emission from the site.

Surface vibration was measured at grid points positioned on the radiating surfaces as shown in Figure 1. A SVAN 958A noise and vibration analyser equipped with SV84 accelerometer was utilised for vibration data acquisition.

Sound intensity measurements were undertaken using Brüel & Kjær sound intensity probe kit Type 3654 and Type 2270 sound level analyser.

The noise investigation program was also accompanied by many SPL measurements and elaborate modelling of the site. Sound intensity measurements were performed directly at the radiating surfaces when they were dominant noise sources. Analysis of available data and results of contribution from other sources show negligible influence of other noise sources on sound intensity measurements.

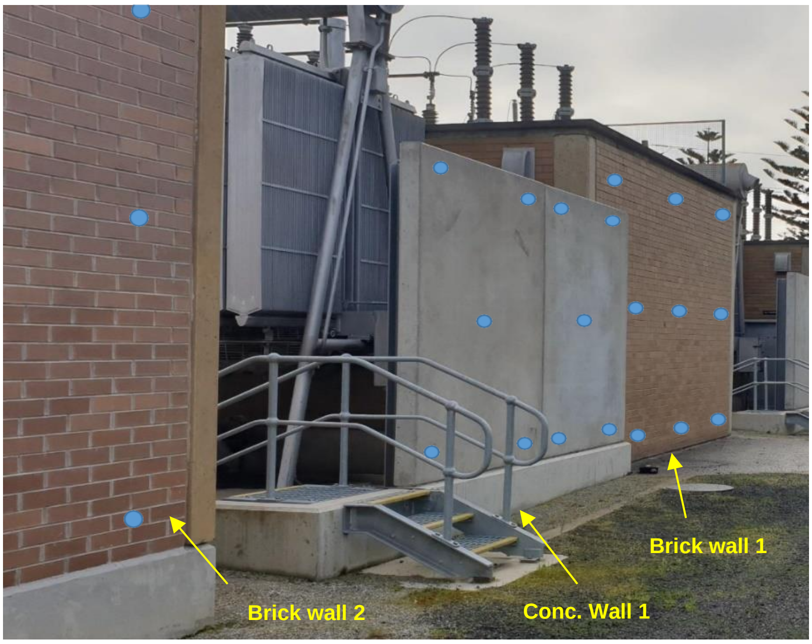

Figure 1: Example of planar structures where vibration and sound intensity measurements were performed

3.1 Determining SPW by vibration measurements

Surface vibration levels from the radiator bay oil splash concrete barrier and transformer enclosure brick walls were used to estimate sound power radiated from different structural elements in an electrical substation site. The transformer enclosure wall was a double brick construction with a total thickness of about 230 mm. The radiator bay oil splash barrier was made from approximately 130 mm thick precast concrete panels.

The average surface vibration levels for each wall element were calculated and converted to an overall sound power level (L_w) radiated by the wall surface as follows:

- The 1/3 octave RMS surface vibration levels were processed to obtain the mean velocity square of the points measured on each wall element for each frequency band.
- Each averaged 1/3 octave band was then converted from RMS vibration level to a radiated airborne sound power level (L_w) using equation (2) with assumption that the radiation efficiency σ=1.
- The calculated sound power level for each 1/3 octave band was then converted to an A-weighted sound power level.
- The overall A-weighted sound power level for the relevant 1/3 octave bands was then calculated using energetic summation across all frequencies to provide an overall level across the relevant band width.
- Note the band width analysed for the purposes of this paper was from 25 Hz through to 2000 Hz and sits comfortably within the frequency response of the SV84 accelerometer (0.2 Hz to 3,700 Hz) and the sound intensity probe (less than 5 KHz for a 12 mm spacer) used for this assessment.
- The spectral range selected covered all frequencies expected to be relevant in assessing the noise from the site under investigation while making an allowance for the known limitations of magnetically coupling an accelerometer to a base plate, namely decreased response to frequencies higher than approximately 2,000 Hz.

Table 1 provides a summary of overall SPW estimates of different planar structures located on site based on the measured surface vibration levels.

Table 1: Estimated total SPW levels based on surface vibration levels, (re 10^{-12} W)

Planar Structure	Total, dB	Total, dB(A)
Brick wall 1	80.6	63.2
Brick wall 2	77.0	61.0
Brick wall 3	97.9	78.9
Brick wall 4	86.9	70.3
Conc. wall 1	72.8	56.3
Conc. wall 2	70.4	54.1

3.2 SPW calculated by sound intensity measurements

Sound intensity measurements were undertaken at the same time as of the vibration measurements over the planar structures noted above. The sound power level for each element of planar structures were then calculated based on spatially averaged sound intensity levels using the scanning surface method in accordance with procedures outlined in ISO 9614–2: 1996 *Determination of Sound Power Levels of Noise Sources using sound intensity – Part 2: Measurement by Scanning*.

The calculated overall sound power levels based on the measured sound intensity levels for each of the planar elements assessed are provided in Table 2. One can see that the highest and lowest SPW levels for the structural elements differ in approximately 27 dB. The highest measured sound power levels corresponded to the transformer enclosure radiator bay wall where a structural coupling of the transformer and enclosure wall resulted in significant re-radiated noise. These results obtained enabled a more accurate modelling of the complex site noise emissions and development of specific mitigation measures to address dominant sources of noise on site.

Table 2: Calculated SPW levels based on sound intensity measurements, (re 10^{-12} W)

Planar Structure	Total, dB	Total, dB(A)
Brick wall 1	85.1	65.2
Brick wall 2	85.6	64.5
Brick wall 3	102.2	83.2
Brick wall 4	93.3	74.0
Conc. wall 1	83.8	64.6
Conc. wall 2	76.6	56.7

Comparison of 1/3 octave SPW estimates based on the surface vibration levels and sound intensity measurements are also shown in Figure 2 to Figure 4. It can be seen that the most prominent 1/3 octave component corresponds to 100 Hz for all tested planar structures. Another multiplier of the electrical frequency of 50 Hz also has local maximum at 200 Hz. This is common for industrial high power transformers.

Comparison of SPW estimates show notable differences in the 1/3 octave estimates at low and high frequencies (below 80 Hz and above 1000 Hz) and, while a reasonable agreement is observed at upper range of low frequencies and mid frequencies (100 Hz – 800 Hz). Overall, it appears that the sound power estimates using the surface vibration levels and assumption of σ=1 across all frequencies provides a lower estimate compared to that calculated using the sound intensity measurements.

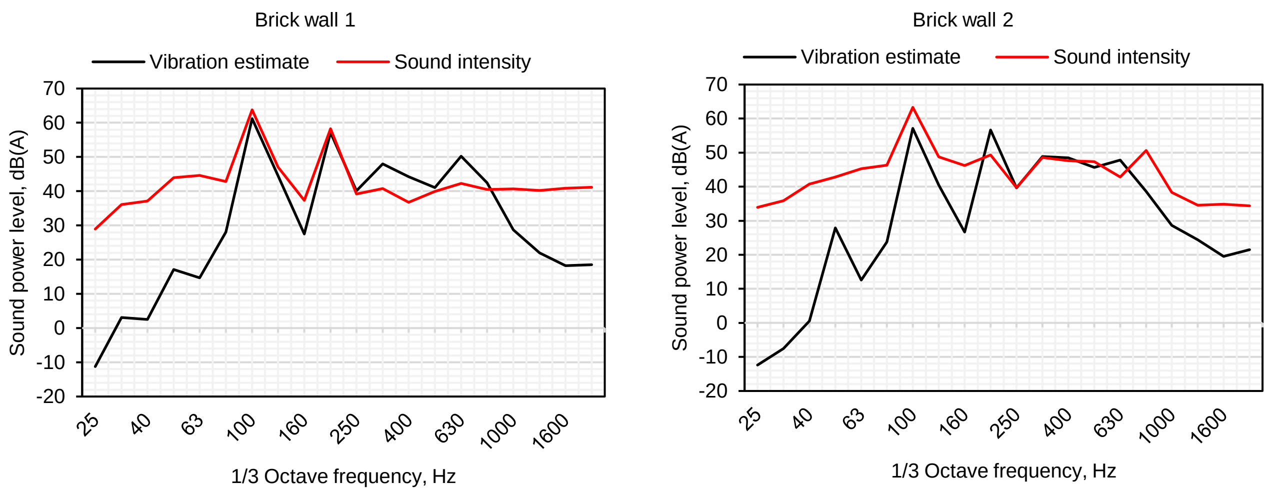

Figure 2: Comparison of estimated A-weighted sound power levels – Brick wall 1 and 2

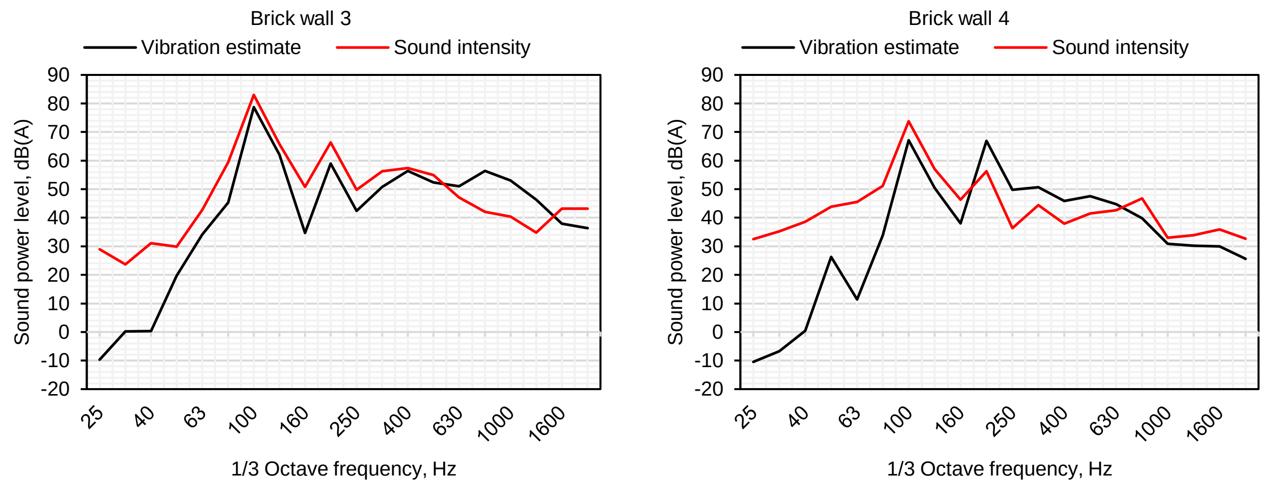

Figure 3: Comparison of estimated A-weighted sound power levels – Brick wall 3 and 4

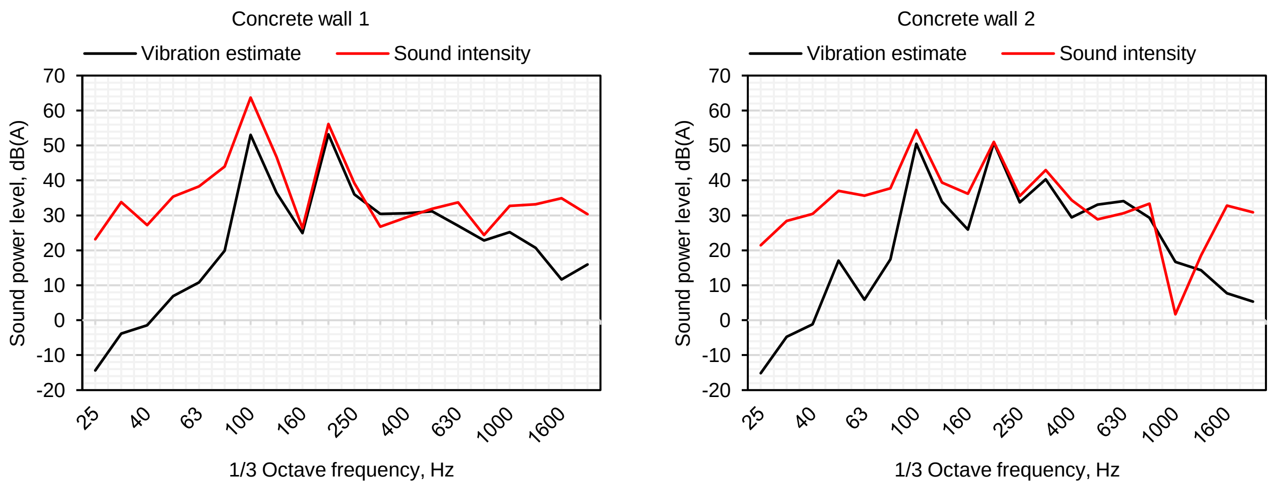

Figure 4: Comparison of estimated A-weighted sound power levels – Concrete wall 1 and 2

4 SOUND RADIATION EFFICIENCY

It may be expected that sound radiation efficiency of planar composite structures is different from that of a metal plate, which is characterised by substantial peak at the critical frequency and unity at higher frequencies. Critical frequency of a flat panel can be defined as (Bies & Hansen, 2009):

$$f_c = \frac{c^2}{2\pi}\sqrt{\frac{m_{eff}}{B_{eff}}}, \tag{3}$$

where m_{eff} is the effective surface mass of the panel and B_{eff} is the effective bending stiffness. Even if the computation of the surface mass of the structures can be done accurately, bending stiffness of brick and mortar walls or reinforced concrete structures scarcely can be made without knowledge of the details of design and correct representation of boundary conditions. For a 110 mm brick panel a critical frequency of about 250 Hz is estimated (based on ρ =1600 kg/m^3, Young Modulus of 8.9 GPa, $\vartheta = 0.1$) while for a 130 mm precast concrete a critical frequency of 225 Hz is estimated (based on ρ =2340 kg/m^3, Young Modulus of 11 GPa, $\vartheta = 0.2$). Taking into account that SPW estimates in Table 1 were obtained using an assumption that the radiation efficiency is unity, actual σ can be computed as follows:

$$\sigma = \frac{W_{int}}{W_{vib}}, \tag{4}$$

where W_{int} is sound power calculated using the sound intensity method and W_{vib} is sound power calculated using vibration measurements. It is reminded that W_{vib} is calculated with assumed radiation efficiency being unity. This formula can be applied both to 1/3 octave SPW levels and overalls. By taking logarithms of equation (4), the expression can be written as:

$$10\ Log_{10}\sigma = L_{Wint} - L_{Wvib}, \tag{5}$$

where L_{Wint} is the sound power level calculated using the sound intensity method and L_{Wivib} is the sound power level calculated using vibration measurements in dB (or dB(A) if A-weighted levels are considered).

4.1 Radiation efficiency of structures

Radiation efficiency of structural elements noted above were calculated based on the comparison of data obtained via surface vibration measurements and that of the sound intensity measurements discussed in section 3. The estimates of the radiation efficiency term for the 1/3 octave bands are shown in Figure 5. The overall calculated radiation efficiency corresponding to the difference between the sound power level estimates using surface vibration measurements and that of the sound intensity measurements are also summarised in Table 3.

Table 3: Calculated radiation efficiency ($10\ Log_{10}\sigma = L_{Wint} - L_{Wvib}$)

Planar Structure	Total, dB	Total, dB(A)
Brick wall 1	4.5	2.0
Brick wall 2	8.6	3.5
Brick wall 3	4.3	4.3
Brick wall 4	6.4	3.7
Conc. wall 1	11.0	8.3
Conc. wall 2	6.2	2.6

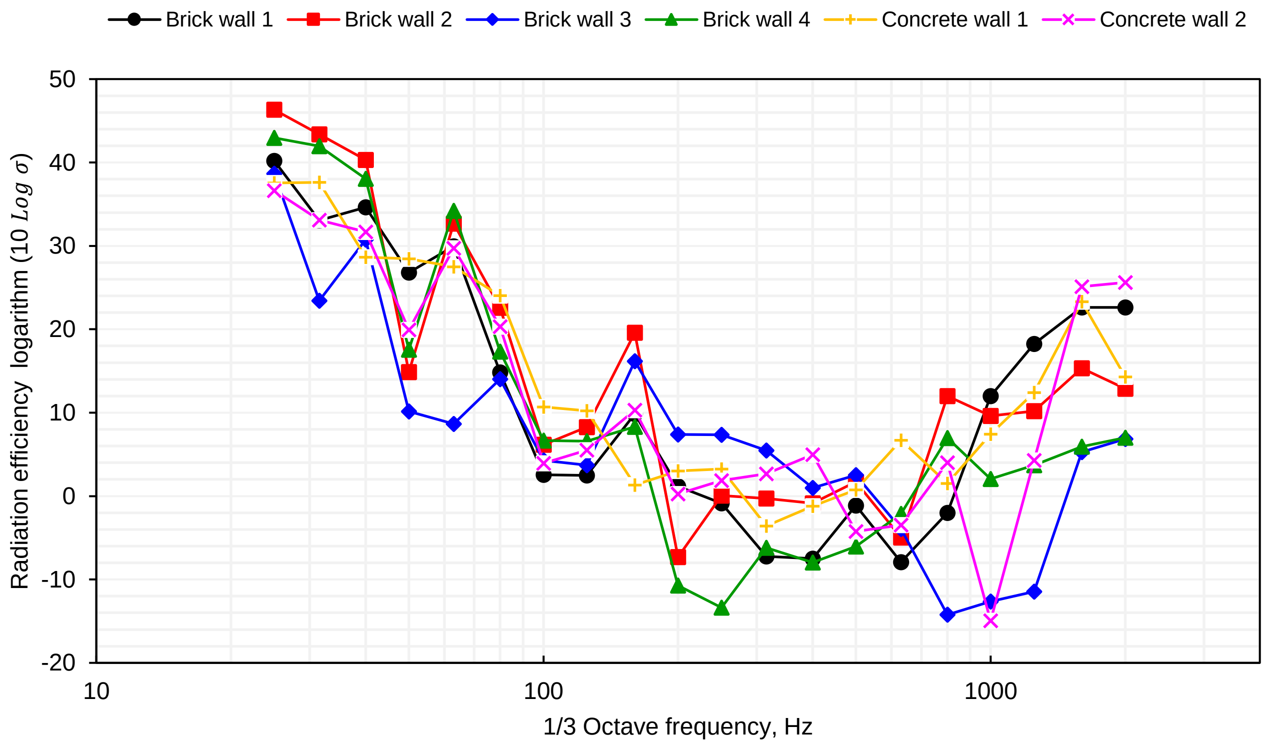

Figure 5: The radiation efficiency of planar structures $(10\ Log_{10}\sigma)$

Figure 5 shows that the radiation efficiency of the composite planar structures such as brick and precast concrete walls is different from that of the theoretical radiation efficiency for metal plates and has a more complex character. The typical expected peak at the critical panel frequency is not evident (around 230 – 250 Hz) and at higher frequencies the calculated radiation efficiency does not appear to follow the expected trend to unity.

The estimated overall un-weighted sound power levels indicate a 4 – 11 dB difference between the estimates with surface vibration levels assuming σ=1 and those calculated using sound intensity. However, this difference is less noticeable for A-weighted overall SPW ranging between 2 – 4 dB, with exception of Concrete wall 1 where an 8 dB difference is observed. Additionally, results indicated that the estimated 1/3 octave sound power levels at lower frequencies (typically below the estimated panel critical frequency) using the surface vibration levels assuming σ=1 appear to notably underestimate the sound power levels compared to that measured using sound intensity.

Overall, the results indicate that although the A-weighted SPW calculated from surface vibrovelocity levels assuming radiation efficiency being unity were found to be lower, they did not differ from the reference magnitudes calculated using sound intensity measurements by more than about 4 dB(A). Therefore, the radiated sound power estimation method based on the surface vibration measurements can be used as a reasonable screening method to identify dominant sound sources from planar structures and identify approximate magnitudes to characterise sound radiation from vibrating surfaces.

5 SUMMARY

Use of surface vibration measurements to estimate sound power levels radiated from planar structures is considered in this paper. Estimates of radiated sound power levels were obtained by measurements of vibrovelocity levels over the surface of various planar structures assuming a radiation efficiency of unity across all frequencies (σ=1) including brick and concrete walls. Results were compared to the calculated sound power levels from the same structures using sound intensity measurements. The results indicate that overall A-weighted sound power estimates using the vibrovelocity levels and assuming the radiation efficiency of one across all frequencies may provide a lower estimate compared to the sound intensity measurements by about 4 dB. The results also indicate that the assumption of radiation efficiency of unity for low frequencies typically below that of the expected panel critical frequency notably underestimated the sound power levels compared to the reference values calculated using sound intensity.

Considering SPW levels obtained by the sound intensity measurements as reference values, analysis of radiation efficiency for planar structures was carried out. The results showed that the typical radiation efficiency of planar structures such as brick and concrete walls has more complex character than for thin metal plates. However, a reasonable agreement was still achieved between the calculated overall A-weighted sound power levels using surface velocity levels and assumption of radiation efficiency being unity compared to that of sound intensity measurements.

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