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INTENSITY MEASUREMENTS FOR BUILDING ACOUSTICS

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1. Introduction

It is commonly accepted that sound intensity measurement offers a potentially powerful diagnostic tool in the field of building acoustics. However, despite the continual improvement in measurement instrumentation, there has been a lack of guidance and procedural information available for transmission loss measurements. This will be partly rectified by the publication of the revised ISO 140-5 which concerns 'Field measurements of airborne sound insulation of facade elements and facades'. Annex E describes a sound intensity measurement method for the determination of the sound reduction index for a building element which is to be used when flanking transmission affects the accuracy of the traditional method or when the intensity method is deemed to be preferable.

This paper looks at the practicalities of sound intensity measurements in typical rooms in dwellings and for facade elements with reference to the revised ISO 140-5. An extension of this approach to sound power measurement for separating and flanking elements is also described to allow sound power rank ordering.

2. Intensity measurements in reverberant fields

The ability to accurately measure sound intensity in enclosed spaces is affected by the reactivity of the sound field. This is described by the pressure-intensity indicator or field indicator F which is defined as 'the difference between the time and surface averaged sound pressure level, L_p, and the normal sound intensity level, L_I on the measurement surface'. Reverberation times can be simply related [1] to an average value of the field indicator F, to give an indication of problems obtaining accurate intensity measurements in a reverberant room.

$$F = 9 + 10lg\left(\frac{S}{A}\right) = 9 + 10lg\left(\frac{ST}{0.16V}\right)$$

where
S is the element surface area (m^2)
A is the absorption area of the receiving room (m^2)
V is the room volume (m^3)
T is the reverberation time (s)

In the above expression it is assumed that there is a doubling of mean square pressure approximately 150mm from the radiating surface where the intensity probe is commonly placed. Waterhouse [2] quotes the increase in the sound pressure level at a perfectly reflecting surface to be 2.2dB in a reverberant field hence the assumption used in the above equation gives worst case values.
(NB The rule of thumb quoted in the revised ISO 140-5 to achieve F<10dB with S/A <1.25 is inferred from the above equation.)

The draft European Standard describing a survey method for field measurements of sound insulation (also referred to as the 'short test method') [3] contains average reverberation times in octave bands (125Hz - 2kHz) for common room constructions using European measurement data. These data can be used to indicate when the average field indicator F is likely to exceed 10dB in typical rooms in dwellings, leading to potential intensity measurement problems. Average values of field indicator F are shown in **Table 1** assuming an average room dimension of 3.5m perpendicular to the separating wall for measurement of the sound power radiated by the separating wall. The data indicate that unfurnished rooms are likely to present measurement problems in the building acoustics frequency range without the introduction of absorbent material into the room. In furnished rooms, accurate measurements without additional absorbent are more likely to be feasible. The average reverberation times all have values greater than or equal to 0.4s whereas a value of 0.3s which is common in many furnished living rooms in the UK would give an average field indicator of 6.2dB.

3. Waterhouse correction

The energy density in enclosed spaces is not uniformly distributed as assumed in the diffuse field model. At the boundaries of a room, the phase relationships between waves at a single point are no longer random which causes an increase in the energy density near the boundaries. Waterhouse [2] introduced a correction term for sound pressure measurements made in the central region of a reverberant room to calculate the total sound energy in the room. Use of the Waterhouse correction must be considered whenever sound pressure measurements made in the centre of a reverberant room are to be related to radiated sound power. The Waterhouse correction W in dB is defined as

$$W = 10\,lg\left(1 + \frac{S_T \lambda}{8\,V}\right)$$

where

S_T is the total area of all the boundary surfaces in the receiving room (m^2)
V is the receiving room volume (m^3)
λ is the wavelength of sound in air (m)

Waterhouse corrections are shown in **Figure 1** for $15m^3$ and $35m^3$ rectangular rooms assuming an average room dimension of 3.5m perpendicular to the separating wall with a room height of 2.3m. The size of the correction term for rooms in typical dwellings is found to be greater than 0.5dB below 1kHz.

4. Field measurement of the sound reduction index of facade and facade elements

The principle of measuring the sound insulation of a building element is to measure the sound power transmitted through the element and compare it with the sound power incident on the element. With traditional methods of measuring sound insulation, both the incident and transmitted sound power are obtained indirectly from sound pressure level measurements. With the intensity method the incident sound power is obtained indirectly from sound pressure level measurements as before, but the transmitted sound power is obtained directly by measuring the sound intensity radiated by the element.

The use of sound intensity measurements to measure the sound reduction index of facades and facade elements in the field has several advantages. The intensity measurements can be made on the inside or the outside of a facade, depending on whether it is more suitable to place the sound source indoors or outdoors. (A disadvantage is that a steady sound source is required and therefore traffic noise is not suitable as a source). Another advantage is that the sound reduction index of a facade element (such as a window) can be measured, even when there is significant sound transmission through other parts of the facade.

4.1 Requirements of ISO 140-5

Annex E in revised ISO 140-5 sets out the test procedure that should be followed, including some recommendations and requirements on how the intensity measurements should be carried out. The most important of these are as follows:

- The measurement surface must totally enclose the test element. This means that if the test element is not in a niche, the measurement surface must be box-shaped to enclose it.

- The time and space integrated sound intensity level shall be measured by scanning the intensity probe across the measurement surface with a scanning pattern of parallel lines. The arithmetic average of two scans should be taken; one carried out horizontally and one vertically. The difference between the two measurements should be less than 1.0dB for every frequency band. The results may still be used if the requirement cannot be met, having attempted to change the scanning pattern or sound field, but the deviation from the standard must be stated in the test report.

- The field indicator F shall be no greater than 10dB.

4.2 Practical considerations for scanning sound intensity measurements

Small facade elements, such as windows mounted in a niche, can often be treated as a single area and scanned with a single sweep of the intensity probe across the surface defined by the niche opening. However, due to the large surface area of most walls, or in cases where a box-shaped surface is used, it is generally more convenient and practical to split the wall surface into sub areas to be scanned individually. (Scanning a large area requires physical repositioning of the operator and probe during the scan, which increases the chance of operator movement noise causing negatively signed intensity or overload.)

The disadvantage of using sub areas is due to the fact that the field indicator F is defined for the complete measurement surface. If a single scan area is used for the whole surface, a straightforward check on the measurement validity can be made by ensuring that F<10dB for each scan. If F is too high, attempts can then be made to reduce it by increasing the distance of the probe from the wall surface, or adding extra absorbent to the room and repeating the scans. If multiple sub areas are used, the field indicator, which is calculated from all sub area measurements, is not instantly available to be checked in the field unless the measurement equipment is computer controlled. This means that a judgement has to be made, on the basis of individual sub area measurements, whether attempts need to be made to reduce F. In the field, the time available on site effectively sets the limit on the amount of repeat data that can be gathered to try and improve the field indicator.

Time constraints in the field also restrict the ability to meet the requirement of achieving less than 1.0dB difference between the horizontal and vertical scans. In the field it is often difficult to satisfy this requirement, especially at the upper and lower limits of the building acoustics frequency range. To be certain of meeting the requirement, scans must be compared as the measurements are carried out, so that repeat scans can be made until the requirement is satisfied. This is too time-consuming in the field, and it has been found that a practical solution is to carry out two horizontal scans and two vertical scans for each sub area and take the average of the horizontal and vertical scans with the smallest difference in each frequency band [4].

4.3 Example field measurement

The intensity technique was used to measure the sound reduction index of a single glazed, wooden-framed window, set in a 230mm thick solid brick facade facing a residential road.

To avoid disturbing the neighbours, the noise source was placed inside the room and the sound intensity measurements were made on the outside of the facade. The measurement surface was a box-shape enclosing the window. The main surface of the box was parallel to the window and approximately 150mm in front of it. The measurement surface was divided into sub areas, the main surface being divided into eight sub areas, and each side of the box being a separate sub area. (It was necessary to make the sub areas quite small in order to reduce the measurement time for the individual scans. Noise from traffic on the residential road affected the intensity measurements, which therefore had to be made in the quiet periods when no vehicles were passing).

Each sub area was scanned four times (twice horizontally and twice vertically) and the mean intensity level for each sub area was obtained from these measurements as described above. The time and space averaged sound intensity level over the whole measurement surface (L_I) was then calculated, taking account of the different sizes of the various sub areas.

The sound pressure level in the source room (L_P) was obtained from measurements at six positions in the centre of the room, and the sound reduction index of the window was calculated using the following equation:

$$R_I = L_P - 6 - \left(L_I + 10lg\left(\frac{S_m}{S} \right) + 10lg\left(1 + \frac{S_T \lambda}{8V} \right) \right)$$

where

L_P is the average sound pressure level in the source room (dB re 2E-5Pa)
L_I is the average normal intensity for a measurement surface enclosing the window (dB re 1E-12Wm^{-2})
S_m is the area of the measurement surface (m^2)
S is the area of the window (m^2)

Figure 2 shows the sound reduction index of the window as measured using the intensity technique and compares it with the sound insulation of the whole facade, as obtained by the traditional sound pressure measurement method (with road traffic as the source). An initial comparison of the sound intensity levels radiated by the window and the wall of the facade had suggested that the sound insulation of the facade would be dominated by the window, so it would be expected that the two measurements give similar results. It can be seen that on the whole the agreement between the two sets of results is good. The weighted sound reduction indices obtained with the intensity technique and the traditional method were 23dB and 22dB respectively.

5. Measurement of sound transmission between dwellings

5.1 Example measurement analysis and discussion

Intensity measurements made in the BRE flanking laboratory can be used to illustrate measurement analysis in a situation where sound is radiated by two flanking surfaces and a separating surface. A wide band noise source was placed in one of the first floor rooms with intensity measurements taken in the adjacent first floor room. The two flanking surfaces included a 100mm aerated concrete flanking wall leaf (70kgm^{-2}) and a 12.5mm plasterboard ceiling (10kgm^{-2}) supported by a wooden lattice. The separating surface was a 100mm concrete separating wall leaf (166kgm^{-2}). Radiation into the receiving room was dominated by the plasterboard ceiling with a predicted critical frequency in the 2.5kHz third octave band. Below the critical frequency, non-resonant transmission across the plasterboard between the room and roof void is dominant, whereas above the critical frequency, resonant transmission between room and plasterboard as well as roof void and plasterboard dominates.

Measured sound power levels for each of the three surfaces are shown in **Figure 3**. The primary check on this data is made using the field indicator values for each measurement surface shown in **Figure 4**. The field indicator is dependent upon the position of the probe in the sound field and is non-zero if the sound field is not that of a plane progressive wave or inter-channel phase mismatch exists. The normalised error due to phase mismatch can be quantified using the difference between the residual pressure-intensity index and the measurement field indicator. ISO 140-5 specifies that the residual pressure-intensity index is greater than (F+10)dB so that the maximum error in the intensity measurement due to phase mismatch is less than 0.45dB. Assuming that the phase mismatch is known to be negligible compared to the actual phase difference that exists in the sound field, the field indicator for a measurement made in a reverberant field can only indicate that the sound intensity value may not be accurate because it is not a progressive plane wave field. The revised ISO 140-5 requires that F<10dB which in this example is only satisfied for all surfaces between 400Hz and 1.25kHz although the separating and flanking walls had field indicators below 10dB between 160Hz and 1.6kHz. The reason for higher field indicator values with the ceiling measurements is partly due to the difficulty in damping the room modes between the ceiling and the floor without the operator standing on absorbent material whilst scanning the ceiling. Intensity measurements on walls are simplified by the fact that absorbent material can be stacked behind the operator to damp the room modes at each measurement position. (NB Measurement problems are also encountered when scanning a floor surface where it is awkward to hang absorbent material above the operator and operator movement noise must be avoided.)

If field indicator values greater than 10dB can not be resolved on site, a secondary check should be made to ensure that the measured receiving room sound energy corresponds to the predicted sound energy from the intensity measurements using all the significant radiating surfaces in the receiving room. The measured receiving room sound energy is found from sound pressure measurements in the centre of the room with the addition of the Waterhouse correction. The difference between the calculated energy from the intensity measurements and the measured energy using sound pressure is calculated as shown in the equation below.

$$\Delta E = 10lg\left(\Sigma 10^{L_{wi}/10}\right) + 10lg\left(\frac{4}{A}\right) - L_p - 10lg\left(1 + \frac{S_T \lambda}{8V}\right)$$

where

L_{wi} are the measured sound power levels for each of the i radiating surfaces

L_p is the average sound pressure level in the receiving room (dB re 2E-5Pa)

Zero values for ΔE indicate the inclusion of all significant radiating surfaces and accurate sound intensity measurements for the dominant radiating surfaces. The use of intensity measurements with F≥10dB in rank ordering of the sound power rating for different surfaces can with caution be justified by referring to values of ΔE.

Figure 5 shows the energy level difference ΔE using measured receiving room sound energy with and without the Waterhouse correction. The receiving room volume V was 51.2m^3 with a total surface area S_T of 87.6m^2. These room parameters give rise to Waterhouse corrections that cause a significant increase in the accuracy of the receiving room sound energy at low frequencies. Between 400Hz and 1.25kHz where F<10dB for all three surfaces, ΔE is seen to be less than 1.1dB.

6. Vibration measurements for sound power estimation

As an alternative to sound intensity measurements, surface vibration measurements combined with predicted radiation efficiencies can be used to estimate the sound power radiated by each surface. However, this approach can be impractical and inaccurate for the following reasons. Prediction of the radiation efficiency at and below the critical frequency is often inaccurate. Above the critical frequency, the radiation efficiency tends to unity and the results are more reliable. At present, the preference of the construction industry appears to be a move away from wet trades like plastering towards the use of dry finishes such as plasterboard linings. These linings are commonly 12.5mm thick with critical frequencies in the 2.5kHz or 3.15kHz 1/3 octave bands, therefore, this approach will be of negligible use due to the restricted frequency range where the assumption of unity for the radiation efficiency is valid. It should also be noted that lightweight materials excited by a sound field will have measurable vibration below the critical frequency which is due to non-resonant transmission, hence the vibration levels measured at these frequencies are not appropriate for use with predicted radiation efficiencies. Measurement of wall vibration also requires that sufficient measurement positions are used to account for the spatial variation in vibration.

1. **F.J Fahy.** Sound Intensity. Elsevier Science Publishers Ltd.

2. **R.V Waterhouse.** Interference patterns in reverberant sound fields. Journal of the Acoustical Society of America (1955) **27**(2) 247-258.

3. **CEN/TC 126/WG 1 N181.** Building Acoustics: Field measurements of airborne and impact sound insulation and of sound pressure level from equipment - Survey method. 10th draft October 1995.

4. **T Emmanuel.** Measurement of the sound insulation of facades and facade elements - A comparison of the intensity technique with the traditional method. Proceedings of the Institute of Acoustics Vol. 15: Part 8 (1993).