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MEASUREMENT OF THE AVERAGE SOUND PRESSURE LEVEL IN A ROOM AT LOW FREQUENCY

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Abstract
The problem of how to measure the average sound pressure level in a room at low frequencies with a few microphone positions is investigated. An alternative to the current ISO140 standard microphone positions is proposed where microphones are spaced equally along a room diagonal rather than randomly in the diffuse field. The proposed placing is tested mathematically, by simulation and by measurement. Results indicate improved accuracy and reduced variance at low frequency compared with the ISO140 method. The method also gives good results at higher frequencies.

INTRODUCTION

The background to this paper is the increasing need for accurate measurement of sound insulation at low frequencies (loosely defined to be below about 160Hz). This paper focuses on the specific problem of optimum microphone placement in order to obtain a reliable measurement of the average sound pressure level in a room. Other known sources of error, such as reverberation time measurements are not considered here. In the current standard measurement procedure (ISO140) the microphones are distributed evenly, but randomly throughout the room volume, avoiding positions close to reflecting surfaces and (for the source room) close to the loudspeaker source. The hypothesis to be investigated in this paper is that a more accurate and repeatable room-averaged sound pressure level can be obtained by distributing microphones along a room diagonal (by diagonal is meant any of the four longest diagonals of a rectangular room). The rationale for this hypothesis will be presented in the next main section, but first some previous work in this area is reviewed.

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Literature review

In recent times, the development of home audio, hi-fi systems, computer audio and television audio have resulted in an incresed acoustic power output at frequencies below 100Hz [1,2]. As a result there is more need for good low frequency sound insulation, and the recent changes to the Building Regulations in the UK reflect this need by placing more emphasis on low frequency performance through use of the C_{tr} (traffic noise correction). Unfortunately, it has been found that the greater emphasis on low frequency performance has resulted in a considerable widening of the variance of the rated sound insulation. This is problematic when attempting to guarantee the minimum performance of a given construction through a number of sets of test results. Therefore, there is a need for a measurement technique that is both accurate and reproducible while at the same time being easy to understand and implement.

It is known that the accuracy and reproducibilityof ISO 140 measurements below 100 Hz is far from satisfactory [2-6] and although the situation improves as frequency increases, the 100, 125 and 160Hz third octave measurements often show wide variance, particularly for smaller rooms. One of the main reasons is the breakdown of the diffuse field assumption on which ISO140 is based. Room modes become significant at frequencies where the room dimensions become comparable to an acoustic wavelength, as a result of which the sound pressure level throughout the room may vary significantly. Thus, it is difficult to obtain a reliable average sound pressure measurement from a few microphone positions.

The low frequency problem has previously been addressed by several authors. An iintensity method, specified in BS 15168-2 [8] is said to provide better reproducibility especially in the 50 – 160Hz octave bands [2, 6]. However, the method is time consuming and complicated, as it requires the surface of the test partition to be divided into sub-areas and sound pressure and sound intensity measurements to be made separately on each. It is also not suitable for field measurements.

Lubman, [9] provided expressions for variance of the sound pressure in a reverberant field. He also pointed out that, even in a perfectly diffuse field, the sound pressure at a point may differ significantly from the room average value. Pederson et al [6] proposed a new method to obtain improved reproducibility using corner source loudspeakers, microphone positions close to the test object, an absorbing back wall in the receiving room (to reduce the dependence on geometry) and sound intensity measurements in the receiving room. Standard deviation values associated with reproducibility were found to be lower than those using the ISO 140 method in the low frequency region (<100 Hz). However, the method is time consuming and requires significant treatment to be added to the room.

Gibbs and Maluski investigated a diffuse field correction term using finite element analysis of the modal fields in rectangular rooms [10] but did not provide a concrete proposal for a measurement method. Simmons [3, 4] compared existing methods of obtaining the average sound pressure levels pertaining to low frequency environmental noise [3]. Most methods gave unsatisfactory performance in the low frequency region, and Simmons suggested improvements. More recently, Hopkins and Turner [5] proposed a measurement technique for sound insulation. They proposed that ISO recommendations should be used in the range 100 Hz – 5KHz, supplemented by additional corner measurements for the 50, 63 Hz and 80 Hz 1/3rd octave bands. They employed an empirical weighting factor and recommended further verification work.

ROOM-AVERAGED SOUND PRESSURE LEVEL: THEORY

The problem addressed is how to obtain a reliable averaged sound pressure level in a room using a finite number of microphone positions. In practical terms this means establishing the optimum placement for a fixed number of microphones. It is assumed that the sound pressure in a room excited by a single frequency source is given as an infinite sum of modal contributions [11]:

$$p(r, r_0, \omega) = iQ\omega\rho_0 \sum \frac{\varphi_n(r)\varphi_n(r_0)}{\left(k^2 - k_n^2\right)K_n} \quad (1)$$

where p is the sound pressure, Q the volume velocity of the source, ρ_o the air density, ω the radian frequency, $r = (x, y, z)$ is an arbitrary receiver position, and r_o the source position, and $K_n = \int_V \varphi_n^2 dV$ is a normalising factor. For illustrative purposes a rectangular room is assumed with rigid walls, the mode functions for which are given by cosine functions:

$$\varphi_n(r) = \cos(k_x x)\cos(k_y y)\cos(k_z z) \quad (2)$$

where $k_x = n_x \pi / l_x$ is the modal wavenumber in the x direction, where $n_x = 0,1,2...$ is the number of nodal lines, and l_x the length of the room in the x direction. Similar expressions apply for y and z, and the wavenumbers are related to the eigenvalues by:

$$k_n{}^2 = k_x^2 + k_y^2 + k_z^2. \quad (3)$$

If the source position is assumed to be a corner (which is one of the positions specified in ISO140), then we will substitute $r_0 = (l_x, 0, 0)$, giving: $\varphi_n(r_0) = \pm 1$.

Average sound pressure throughout the volume

We first integrate the squared pressure throughout the volume in order to obtain an exact expression for the spatially averaged sound pressure:

$$\langle p\rangle_V^2 = \frac{1}{V}\int_V |p|^2 dV \tag{5}$$

where V is the volume, and the subscript V indicates that the average is obtained throughout the volume. Substituting equation (1) into equation (5) we get:

$$\langle p\rangle_V^2 = \frac{Q^2\omega^2\rho_0^2}{V}\iiint_V \left\{\sum_n \frac{\varphi_n(r)\varphi_n(r_0)}{\left(k^2 - k_n^{\ 2}\right)K_n}\right\}^* \left\{\sum_m \frac{\varphi_m(r)\varphi_m(r_0)}{\left(k^2 - k_m^{\ 2}\right)K_m}\right\} dV \tag{6}$$

where * indicates complex conjugate. Due to orthogonality the mixed terms ($n \neq m$) do not contribute to the integral. Therefore, for a rigid walled rectangular room the spatially averaged sound pressure squared is the energetic sum of the mode contributions:

$$\langle p\rangle_V^2 = \omega^2\rho_0^2 Q^2 \sum_n \frac{I}{\left|k^2 - k_n^{\ 2}\right|^2 K_n^2} \tag{7}$$

where $I = \iiint \cos^2(k_x x)\cos^2(k_y y)\cos^2(k_z z) dxdydz = K_n$.

Averaging along a diagonal

The average sound pressure level along the diagonal can be obtained as a line integral [12]. We start with a parametric equation for the diagonal starting at (0,0,0) and finishing at (l_x,l_y,l_z) (note that this avoids the corner with the loudspeaker). This diagonal is described by the vector equation:

$$g(t) = tl_x\bar{\mathrm{i}} + tl_y\bar{\mathrm{j}} + tl_z\bar{\mathrm{k}} \tag{8}$$

where $\bar{\mathrm{i}}, \bar{\mathrm{j}}, \bar{\mathrm{k}}$ are the unit vectors in x, y, z. The average pressure squared along the diagonal is given by:

$$\langle p\rangle_d^2 = \frac{1}{l}\int_0^1 |p(t)|^2 \left|\frac{dg}{dt}\right| dt \tag{9}$$

where $l = \sqrt{l_x^2 + l_y^2 + l_z^2}$ is the diagonal length and the subscript d indicates an average is obtained along the diagonal. Substituting Equation (2) into (10) we get:

$$\langle p\rangle_d^2 = \omega^2\rho_0^2 Q^2 \int_0^1 \left[\begin{matrix}\left\{\sum \cos(n_x\pi t)\cos(n_y\pi t)\cos(n_z\pi t)/K_n\right\} \\ \times\left\{\sum \cos(m_x\pi t)\cos(m_y\pi t)\cos(m_z\pi t)/K_n\right\}\end{matrix}\right] dt \qquad n,m = 0,1,2... \tag{10}$$

This expression can be integrated, but more insight can be gained by looking at individual terms. Below the first room mode all *m* and *n* are zero, and the volume and diagonal averages are identical. If the room response is dominated by an axial mode in the x direction (e.g. $n_y = n_z = 0$) then we have:

$$\langle p \rangle_d^2 \approx \omega^2 \rho_0^2 Q^2 \int_0^1 \cos^2(n_x \pi t) dt \qquad (11)$$

which again is identical to the volume average for the same mode (clearly, the same result applies to other axial modes). This result is important because the lowest room modes, which are most likely to be the cause of variance, are axial modes. Thus, at and below the lowest few room modes, the diagonal average is likely to give a good estimate of the true average.

If the response is dominated by tangential modes (e.g. $n_x = n_y = 0, n_z \neq 0$) then the diagonal average is a factor of 3/2 higher than the volume average. For some oblique modes the factor varies, for example for modes $n_x = n_y = n_z \neq 0$ it is 5/2. However, whereas for a volume integral the total energy is the sum of the mode energies, this is not the case for the line integral because the modal pressures along the diagonal do not form an orthogonal set of functions. Therefore, mode coupling plays a role in the diagonal average and the situation is complicated. To investigate this further a room was simulated numerically as described in the following section.

SIMULATION OF A ROOM

It has been argued above on mathematical grounds that the diagonal average is likely to give a good estimate of the room (volume) average at frequencies around the lowest room modes. The situation for higher modes is more complicated, and in order to test the hypothesis a rectangular room has been simulated using the modal summation theory as described above. The room dimensions are 2.96m x 2.08m x 2.75m which are the same as used for the measurements described in the next section. Note that there is no inherent upper limit to the validity of the modal theory. Thus, whilst we are primarily interested in the low frequency region, the model is valid at higher frequencies where the behaviour is essentially diffuse.

Figure 1 shows the true (volume) averaged sound pressure level, compared with the average along the diagonal. The trends described in the previous section are clearly seen. Below the lowest mode and close to the first three (axial) modes the agreement is almost exact. Where tangential modes become dominant, the diagonal average overestimates the true average, and at 130-150Hz, where higher order axial modes are prominent the agreement is again quite close. At higher frequencies, as more modes contribute to the response, the diagonal average may be higher or lower than the true average, but is generally quite close.

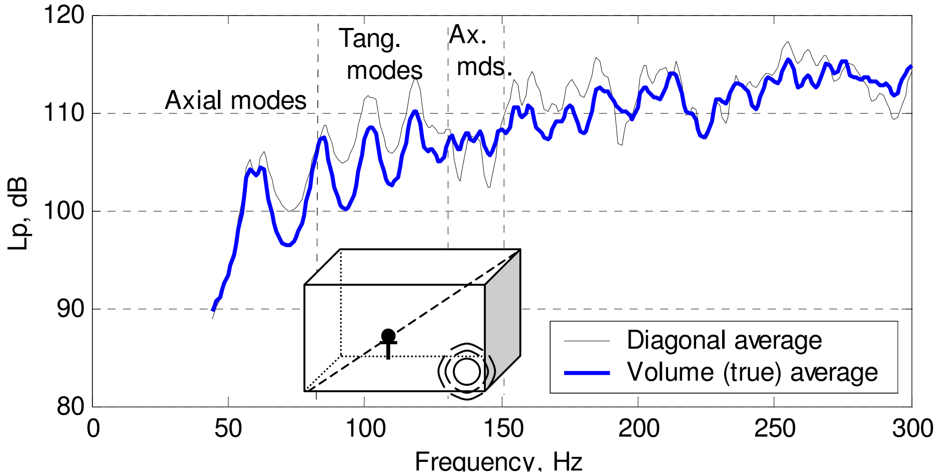

Figure 1 – Comparison of diagonal average with volume (true) average sound pressure level.

As well as the diagonal average, a standard ISO140 test was simulated, in which response positions were chosen randomly from the 'valid' ISO positions i.e. positions further than 0.5m from any reflecting surface. Twenty sets of 6 ISO 'microphone' positions were evaluated.

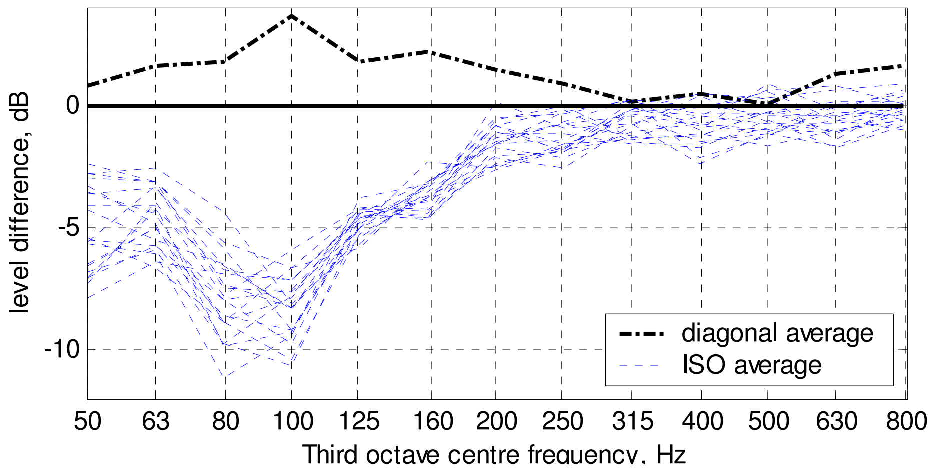

Figure 2 – Level difference between estimated and true room average sound pressure level

The diagonal average and twenty valid ISO averages are compared as third octave band levels in figure 2. The results have been normalised to the true average. It is seen that the ISO averages significantly underestimate the sound pressure levels below 200Hz. Above 200Hz the ISO measurements lie consistently about 1dB below the room average, which is expected since the ISO positions are designed to capture the reverberant field which will generally be below the room average because of increased sound pressure near the walls. The diagonal average is in close agreement over the whole range. Perhaps a more significant observation from figure 2 is that there is a wide variation of up to 7dB from the highest to the lowest ISO average in any third octave. Such variance is problematic in sound insulation measurement, particularly when a statistical guarantee of minimum performance is required (as in the UK). The diagonal average is generally closer to the true average and (for a single room) there is no associated variance, which is potentially an important advantage.

EXPERIMENTAL VALIDATION

The above result was tested by measuring the sound pressure level over a grid of points in a small rectangular room, following a similar procedure to Hopkins and Turner [5]. The room dimensions, 2.96m x 2.08m x 2.75m high are fairly typical of a small bedroom. The walls were painted brick, the ceiling was plasterboard, and the floor was rigid concrete with a thin nylon carpet. A 6x6x6 grid was used and a cabinet loudspeaker, pointing into one corner, was used to excite the room. Grid positions in the nearfield of the loudspeaker were not used. An additional 7 points were placed on the diagonal in between the main grid points so as to give a total of 13 points on the diagonal. In total, 210 measurement positions were used.

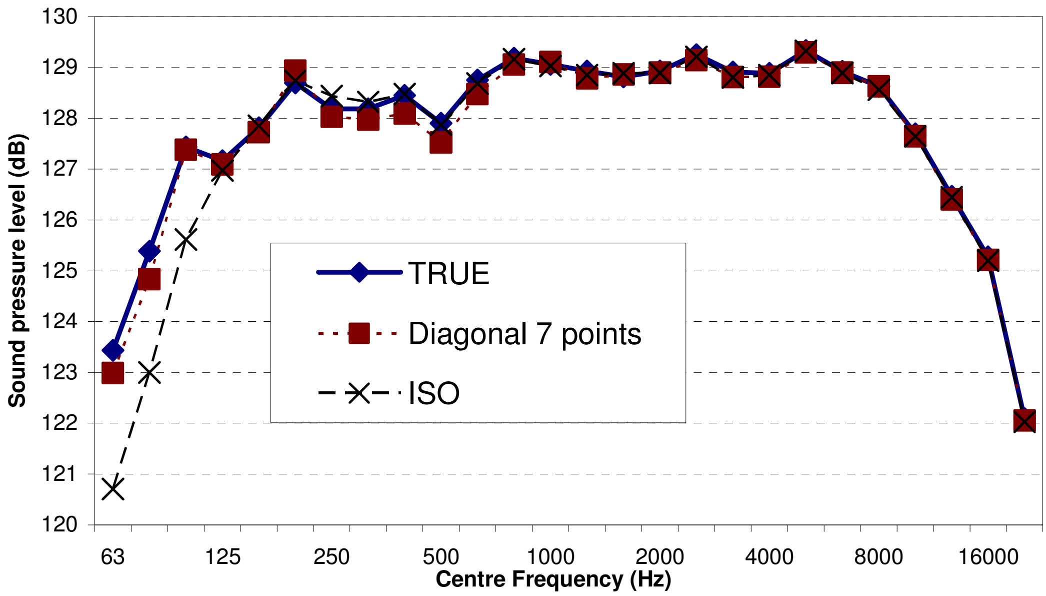

Figure 3 – Measured sound pressure level in a rectangular room showing true, diagonal and ISO averages.

The agreement between the diagonal (7 point) and true (210 point) average is remarkably good over the whole frequency range as shown in figure 3. The 13 point diagonal average was close to the 7 point average and is not shown for clarity. Also shown is a single ISO average, which also displays good agreement, except below 125Hz where it underestimates the true value by 2-3dB. These results are consistent with those from the simulation, although the deviations are smaller overall, perhaps because the damping was underestimated in the simulation making modal behaviour more pronounced than in the real room.

CONCLUDING REMARKS

The feasibility of positioning microphones along a room diagonal for sound insulation measurement has been investigated as an alternative to the current 'random' ISO140 recommended positions. It has been shown that the average sound pressure level along the diagonal is identical to the room (volume) average for the lowest room modes and below the first mode. This equality does not hold for higher order modes, but simulation and measurement both suggest that the diagonal average gives a more reliable estimate of the true average than the ISO140 positions at low frequencies. The results also indicate at least as good agreement as the ISO140 method at higher frequencies. A significant advantage of the diagonal average could be that there is no inherent variance, whereas the ISO140 positions showed significant variation even within a single room, depending on the choice of position. A practical advantage could be that the positions could be found precisely in field tests by a using a laser beam pointer to illuminate the diagonal. The results have so far been tested with a single point sound source in the corner (as in the source room), although it is believed the results will hold for distributed excitation (as in the receiver room) this has not yet been proven. The variance for different aspect ratios and for non-rigid walls also needs to be checked.

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