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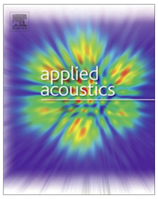

# Using transient and steady-state SEA to assess potential errors in the measurement of structure-borne sound power input from machinery on coupled reception plates

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ABSTRACT

Isolated reception plates provide an engineering approach to quantify the structure-borne sound power input from machinery through the measurement of the spatial-average velocity level and structural reverberation times. For applications in building acoustics there are practical and economic reasons to consider using coupled reception plates formed by solid heavyweight walls or floors that are structurally coupled to other building elements. This paper uses transient and steady-state statistical energy analysis to investigate how the errors depend upon the building structure to which the coupled reception plate is connected. It is shown that the problem is twofold. Firstly, in the low- and mid-frequency ranges, the steady-state velocity level on the coupled reception plate is increased by energy returning from other coupled plates. Secondly, the structural decays on the coupled reception plate have significant curvature due to returning energy; hence short evaluation ranges are needed to minimise the error when determining the total loss factor. This leads to a problematic situation where the coupled reception plate appears to give the correct answer due to the error in the energy cancelling out the error in the total loss factor. The latter error can be minimised using short evaluation ranges for the structural reverberation time.

## 1. Introduction

The prediction of sound and vibration in heavyweight buildings is commonly tackled using Statistical Energy Analysis (SEA) or SEA-based models [1]. For machinery that directly excites the building structure, these models require knowledge of the structure-borne sound power input from the machine into a building element such as a wall or floor. A practical engineering solution to quantify this power input in frequency bands is to use an isolated reception plate in the laboratory [2,3]. This requires measurements in one-third octave bands or octave bands to determine (a) the spatial-average velocity levels on the reception plate due to excitation from the machine, and (b) the structural reverberation times of the reception plate in order to calculate the total loss factors. The reception plate is usually isolated from any supporting structure using resilient material so that structural coupling is negligible. This ensures that the plate response is unaffected by energy returning to it from any other structure to which it is coupled.

In heavyweight buildings a machine acting as a source of structure-borne sound will usually be connected to a receiving element such as a brick/block wall, or a concrete floor. For many rigidly connected or resiliently mounted machines in heavyweight buildings the magnitude of the receiver mobility tends to be much lower than the source mobility, and the mass of the machine rarely has a significant effect on the vibration response of the wall or floor. This has led to a laboratory measurement standard, EN 15657-1 [4], which uses an isolated reception plate formed from concrete. The approach using an isolated reception plate is also incorporated into an informative annex in EN 12354-5 [5] which uses an SEA-based model to calculate sound pressure levels due to service equipment in a building.

Rather than use an isolated reception plate in the laboratory, there are economic and space-saving reasons to consider using a heavyweight wall or floor that is structurally coupled to other building elements to form a coupled reception plate. For example, using a concrete floor that forms part of a reverberation chamber, or a wall/floor that forms part of a source or receiving room in a transmission suite. This would allow test laboratories to make use of existing facilities to quantify the structure-borne sound power input in a highly-controlled environment. However, with laboratory installations it is not always possible to reproduce the mechanical fixings and operating conditions that exist in situ. Hence field measurement of the structure-borne sound power input is potentially useful for survey grade measurements as well as for diagnostics and noise control in existing or similar buildings.

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This could make use of coupled reception plates formed by walls or floors in a heavyweight building where the machinery has already been installed.

Recent research [6] by the authors has focussed on the errors that occur in the estimate of the total loss factor from decay measurements on heavyweight building elements, and the subsequent errors in laboratory measurements of airborne and impact sound insulation as well as structural coupling parameters such as the vibration reduction index or the coupling loss factor. This work used Transient Statistical Energy Analysis (TSEA) to assess the effect of different evaluation ranges when calculating the structural reverberation time. TSEA models were validated by good agreement with decay curves measured on concrete/masonry walls and floors in a large building. This resulted in a proposal for an evaluation procedure to determine structural reverberation times that (a) maximises the part of the early decay which can be used in the evaluation range and (b) identifies when a structural decay curve is, and is not, significantly affected by energy returning from the rest of the structure. The potential exists to use a similar approach with coupled reception plates and this is considered here in the present paper.

This paper focuses on coupled reception plates in heavyweight buildings and the systematic errors that can occur due to energy returning to this reception plate from the connected structure. SEA and TSEA are used to investigate how these errors depend upon the building structure to which the coupled reception plate is connected. The aim is to quantify the errors and give insight into their origin in order to identify potential solutions that could minimise the errors that occur with coupled reception plates.

## 2. Quantifying structure-borne sound power using a reception plate

The aim of measurements with an isolated or coupled reception plate is to quantify the structure-borne sound power input from a machine. It is primarily intended for machines that have a vibrational output which can be considered stationary over time. The reception plate method requires measurement of (a) the temporal and spatial average mean-square bending wave velocity over the plate surface and (b) the spatial-average structural reverberation time of the plate. The structure-borne sound power input, $W_{\mathrm{in}}$, can then be determined according to

$$W_{\mathrm{in}} = \omega\eta E = \omega\eta m\langle v^2\rangle \tag{1}$$

where $E$ is the bending wave energy (J), $m$ is the mass (kg) of the reception plate, $\langle v^2\rangle$ is the temporal and spatial average mean-square bending wave velocity ($\mathrm{m}^2\,\mathrm{s}^{-2}$) and $\eta$ is the total loss factor (dimensionless) determined from the structural reverberation time given by

$$\eta = \frac{6\ln 10}{2\pi f T_{\mathrm{s},X}} \tag{2}$$

where $T_{\mathrm{s},X}$ is the structural reverberation time (s) calculated using an evaluation range of $X$ dB.

For an isolated reception plate that is formed from 100 mm thick concrete, laboratory measurements on building machinery indicate that errors up to 5 dB can occur in the low-frequency range where modal overlap and mode counts are low, but that errors are typically only ±2 dB in the mid- and high-frequency ranges [2].

These errors can be attributed to the inherent measurement uncertainty and the assumptions made in the reception plate method. In terms of measurement uncertainties it is reasonable to assume that the largest components will be due to the spatial variation in vibration over the plate surface (this affects the estimate of spatial-average velocity levels) and errors in the evaluation of the structural decay curves (this affects the total loss factors). The two assumptions which tend not to be satisfied and can potentially increase the error are (1) high modal overlap, which rarely occurs due to low damping and/or low mode counts in the frequency bands of interest and (2) significant variation in the driving-point mobility over the plate surface.

This paper is concerned with investigating and quantifying systematic errors due to the use of a coupled, rather than an isolated reception plate. For this reason, numerical experiments are carried out with transient and steady-state SEA as this avoids the aforementioned measurement uncertainties and gives much greater insight into the nature of the problem. For this reason it relies on previous validations of SEA [1] and TSEA [6] with measurements in heavyweight buildings.

## 3. Numerical experiments

Steady-state SEA is used to calculate the steady-state vibration level on the coupled reception plate using matrix SEA. The use of matrix SEA is necessary for heavyweight buildings as it is rarely accurate to determine steady-state sound and vibration levels using a limited number of paths with SEA path analysis because of the importance of the many long paths [7].

Transient SEA (TSEA) is used to calculate the structural decay curves on the coupled reception plate. Previous results [6,8] indicate that when a heavyweight test element is rigidly connected to the transmission suite structure there are multiple-slope decay curves which cause significant errors in the measured total loss factor due to energy returning to the test element from the laboratory structure. Hopkins and Robinson [6] have shown with TSEA that for structural reverberation time measurements on walls and floors in transmission suites or flanking laboratories that $T_5$ or $T_{10}$ should be used to avoid significant errors in the calculated total loss factor.

The SEA and TSEA models are used to calculate one-third octave band data over the building acoustics frequency range from 50 to 5k Hz.

### 3.1. Steady-state and transient SEA models

Matrix SEA calculations to determine the subsystem energies are carried out using

$$\begin{bmatrix} \sum_{n=1}^{N}\eta_{1n} & -\eta_{21} & \cdots & -\eta_{N1} \\ -\eta_{12} & \sum_{n=1}^{N}\eta_{2n} & & \\ \vdots & & \ddots & \\ -\eta_{1N} & & & \sum_{n=1}^{N}\eta_{Nn} \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ \vdots \\ E_N \end{bmatrix} = \begin{bmatrix} W_{\mathrm{in}(1)}/\omega \\ 0 \\ \vdots \\ 0 \end{bmatrix} \tag{3}$$

where $\eta_{ij}$ is the coupling loss factor from subsystem $i$ to $j$, and $\eta_{ii}$ is the internal loss factor for subsystem $i$ and $W_{\mathrm{in}(i)}$ is the power input into subsystem $i$.

Transient SEA (TSEA) uses power balance equations in the time domain as described by Powell and Quartararo [9]. Using a finite difference approach, the decay curve for a subsystem $i$ can be calculated using

$$\begin{aligned} E_i(t_{n+1}) &= E_i(t_n) \\ &\quad + \Delta t\left[W_{\mathrm{in}(i)}(t_n) + \omega\left(\sum_{j(j\neq i)}^{N}\eta_{ji}E_j(t_n) - \eta_i E_i(t_n)\right)\right] \end{aligned} \tag{4}$$

where $E_i(t_{n+1})$ is the energy at the next time step in subsystem $i$, $E_i(t_n)$ is the energy at the current time step in subsystem $i$, $\eta_{ji}$ is the coupling loss factor from subsystem $j$ to subsystem $i$, $\eta_i$ is the total loss factor of subsystem $i$ and $\Delta t$ is the time interval.

To determine structural decay curves, the power input in TSEA is used with an arbitrary power input of 1 W into the bending wave subsystem representing the coupled reception plate over a single time interval at $t = 0$. At $t = 0$ the energy in all subsystems is zero; hence the energy in each subsystem rises and then begins to decay as would the measured velocity level on the structure after transient excitation (such as would occur with a hammer hit). However, in a TSEA model there is no need to use backward-integration as there would be with measurements using impulse excitation.

The structure-borne sound power is always injected into bending wave subsystems, however SEA and TSEA are considered for bending wave only models as well as bending and in-plane wave models. This is because in-plane waves have been shown to be important in large buildings, and particularly in the mid- to high frequency range [10]. Structural and radiation coupling loss factors are calculated as described in Hopkins [1].

### *3.2. Test constructions*

Two scenarios for heavyweight buildings are considered; a laboratory and a field situation. To facilitate comparison of these two situations the coupled reception plates form the wall or the floor/ceiling in identical rooms. The floor and ceiling are 150 mm cast in situ concrete ($\rho_s = 330$ kg/m$^2$), two of the opposite walls are 215 mm dense aggregate blockwork walls ($\rho_s = 430$ kg/m$^2$) with the other two opposite walls being 100 mm dense aggregate blockwork walls ($\rho_s = 200$ kg/m$^2$). The material properties are taken from published data [1] for the longitudinal wavespeed ($c_L$), Poisson's ratio ($\nu$), and the internal loss factor ($\eta_{int}$). For cast in situ concrete: $c_L = 3800$ m/s, $\nu = 0.2$, $\eta_{int} = 0.005$. For dense aggregate blockwork: $c_L = 3200$ m/s, $\nu = 0.2$, $\eta_{int} = 0.01$. All walls and floors are assumed to be homogeneous isotropic plates.

The room dimensions are 4 m × 3.5 m × 2.4 m with a frequency-independent reverberation time for the room of 0.5 s. In the field situation this reverberation time is typical of a furnished room in a dwelling [1]. Note that room reverberation has been shown to affect measured structural decay curves on heavyweight walls/floors when using long evaluation ranges [6]. Hence the use of 0.5 s in this paper ensures that room reverberation will have negligible effect on the structural decay curves for evaluation ranges up to 30 dB in both the laboratory and the field situation. This choice of room is therefore appropriate for the test constructions because the aim is to draw conclusions on energy returning to the coupled reception plate from other connected plates rather than the rooms.

The laboratory situation is represented by a single test room such as a small reverberant chamber. The ground floor slab can either be 'earthed' or 'unearthed'. An unearthed model assumes that the total loss factor of the ground floor slab equals the sum of the coupling loss factors plus the internal loss factor for concrete. This would represent a laboratory which was mounted on vibration isolators to reduce background noise. In the earthed model, the ground floor slabs have additional damping because they are in direct contact with the earth over their complete lower surface; this is simulated by setting the internal loss factor of each ground floor to $f^{-0.5}$ which is justified by measurements on actual concrete ground floors [1].

The field situation is represented by a large building comprising 27 rooms that are identical to the single room used for the laboratory situation. In this case the ground floors are all 'earthed'.

In practice, most machinery will directly radiate some sound into the room in which it is housed. The sound field in the room could then subsequently excite the coupled reception plate and potentially increase its measured vibration level. For this reason, it is appropriate to question whether a coupled reception plate with a resiliently-mounted machine might incur additional errors when the radiated sound power is greater than the structure-borne sound power. Numerical experiments have been carried out to address this question by building SEA models for the constructions considered in this paper. These show that the largest error incurred due to an additional sound power input from machinery is in the low-frequency range (50–200 Hz). However, this error is still less than 1 dB even for ratios of sound power input to structure-borne sound power input up to a factor of five. For this reason, the sound power radiated by the machinery into the room is assumed to be zero.

## 4. Results

The first stage is to use TSEA to predict the structural decay curves on each wall or floor after excitation has ceased. Fig. 1 shows these predicted decays at 100, 500 and 1k Hz. For the earthed and unearthed laboratories the decays become distinctly non-linear after a drop in vibration level of between 5 and 10 dB with a clear secondary decay slope due to energy returning from the coupled walls and floors. In the field situation each wall/floor is connected to many more walls and floors than the walls/floors of the single isolated room in the laboratory; hence the decays are significantly faster in the field situation. In both the laboratory and field situations, the decays have significant curvature due to energy returning to the excited subsystem from the other walls and floors in the building which results in a secondary slope. The implication for the calculation of reverberation times is that long evaluation ranges which extend across significant curvature on the decay will result in incorrect reverberation times (i.e. too long) which will subsequently lead to underestimates of the total loss factor.

The next stage is to calculate the error for the structure-borne sound power input in decibels. This is calculated from Eq. (3) by using matrix SEA to determine the mean-square velocity on the coupled reception plate with five different scenarios for the total loss factor. Scenario (1) uses exactly the same total loss factor that is used in matrix SEA; hence it is referred to as the 'exact TLF'. Scenarios (2)–(5) use TSEA to determine the structural reverberation time with evaluation ranges of (2) 5 dB, (3) 10 dB (4) 15 dB, and (5) 20 dB which are then used in Eq. (2) to calculate the total loss factor. Figs. 2 and 3 show the errors in the structure-borne sound power input for the laboratory situation where the ground floor is unearthed and earthed respectively. Fig. 4 shows the errors for the field situation.

In Scenario (1) the errors in the structure-borne sound power input in both laboratory and field situations show that use of the exact TLF leads to an overestimate in the structure-borne sound power input. This overestimate tends to be most significant in the low- and mid-frequency ranges. Hence even when the structural reverberation times correspond exactly to the total loss factor there is an error due to energy returning from other walls and floors in the building that increases the steady-state vibration level on the coupled reception plate. This is discussed further in Section 4.1 using SEA theory to give greater insight into this error.

With Scenarios (2)–(5) it is expected that the total loss factors will often be underestimated due to the evaluation of curved structural decays (refer back to Fig. 1). Figs. 2–4 show that the effect of this error on the total loss factor is smallest with $T_5$ and largest with $T_{20}$. Hence there is a general trend for the positive errors initially observed in Scenario (1) to become increasingly negative as the evaluation range is increased from Scenario (2) to (5). For models where only bending waves are considered, the errors are largest in the low- and mid-frequency ranges, and the errors reduce with increasing frequency. However, for bending and in-plane wave models the errors tend to increase at high frequencies.

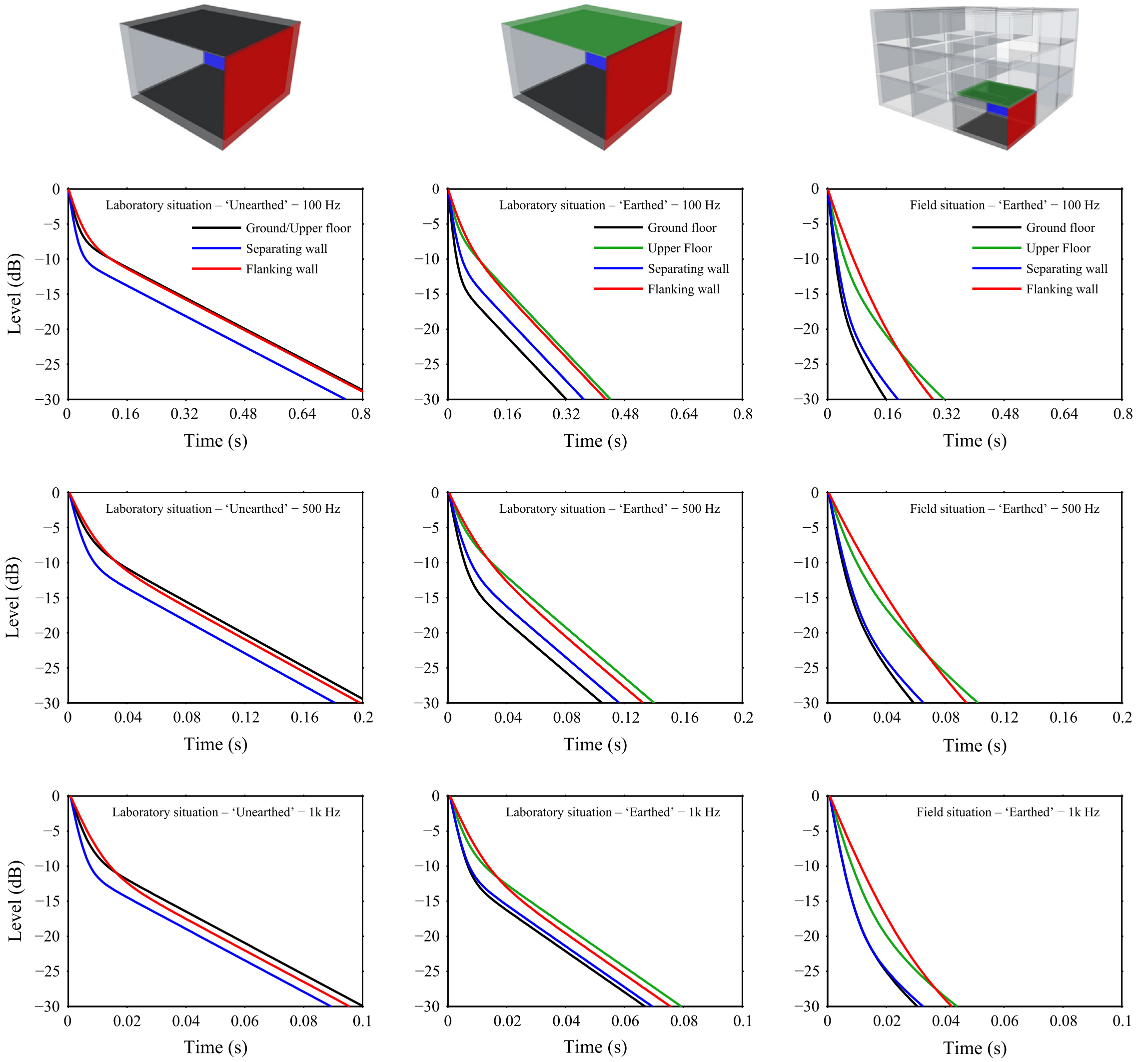

**Fig. 1.** TSEA predicted structural decay curves for the ground and upper floors, the separating wall and the flanking wall. Laboratory situation – 'Unearthed' ground floor (left column). Laboratory situation – 'Earthed' ground floor (middle column). Field situation – 'Earthed' ground floors (right column).

Scenarios (2)–(5) simulate the practical situation that would be used for measurements on coupled reception plates in the laboratory or field. Hence there will always be two errors that combine together: the overestimate in the steady-state vibration level and the underestimate in the total loss factor. These two errors will either cancel each other out at some frequencies, or combine to give underestimates or overestimates of the power input depending on the evaluation range that is used for the reverberation time.

The error in the steady-state vibration level on the coupled reception plate in the low- and mid-frequency ranges is a systematic error that is specific to the building and the choice of coupled reception plate in that building. The error in the total loss factor can be minimised by using the evaluation procedure for structural reverberation times that was recently proposed by Hopkins and Robinson [6]. This approach maximises the part of the early decay which can be used in the evaluation range and identifies when a structural decay curve is, and is not, significantly affected by energy returning from the rest of the structure.

## 5. Discussion

In this section, SEA theory is used to indicate how coupled reception plates can result in overestimates of the structure-borne sound power input. This is under the assumption that the total loss factor of the coupled reception plate that is used to calculate the power input is devoid of error.

Assume that a machine has a structure-borne sound power input, $\Pi_{in}$, on a reception plate. For a power input into an isolated reception plate (subsystem 1) as shown in Fig. 5 the power balance equation is

$$\Pi_{in} = \omega\eta_{11}E_1 \tag{5}$$

Now consider power input into the same reception plate (subsystem 1) when it is coupled to another plate (subsystem 2) so that it becomes a coupled reception plate. In this situation, the energy stored in subsystem 1 is denoted as $E_1'$ to distinguish it from the isolated reception plate. The power balance equations are now given by

$$\Pi_{in} = \omega(\eta_{11} + \eta_{12})E_1' - \omega\eta_{21}E_2 \tag{6}$$

$$0 = \omega(\eta_{22} + \eta_{21})E_2 - \omega\eta_{12}E_1' \tag{7}$$

Re-arranging Eq. (7) gives

$$E_2 = \frac{\eta_{12}E_1'}{\eta_{22} + \eta_{21}} \tag{8}$$

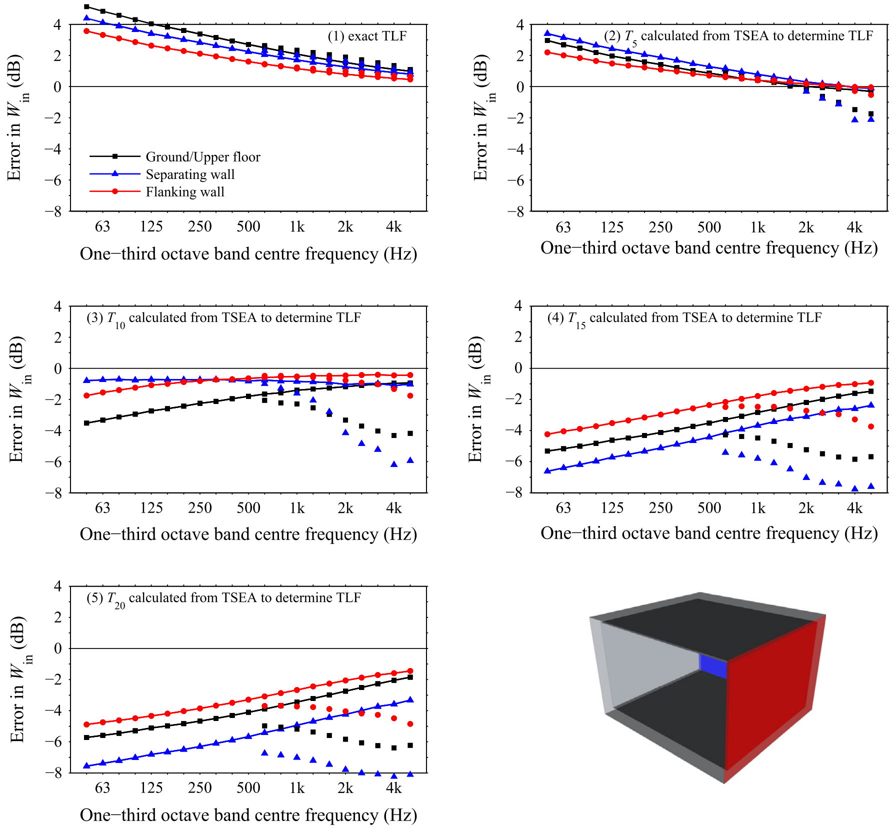

**Fig. 2.** Error in the structure-borne sound power input using walls/floors as a coupled reception plate. Laboratory situation – ‘Unearthed’ ground floor. Markers connected with solid lines represent the bending only model (50–5k Hz). Markers without lines represent the bending and in-plane model (630–5k Hz).

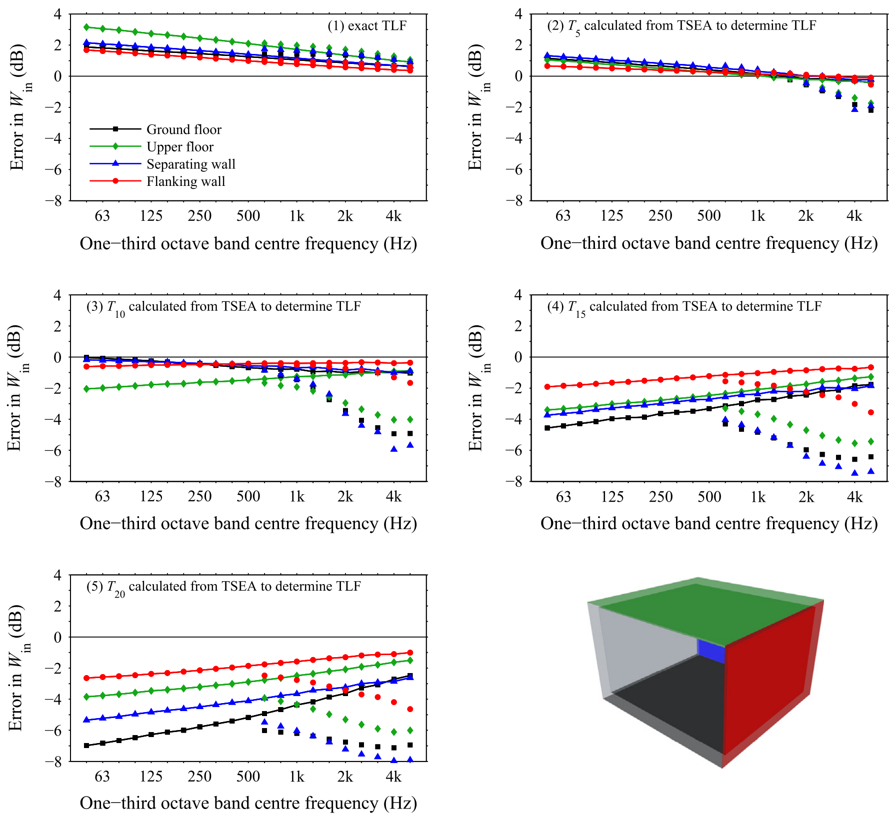

**Fig. 3.** Error in the structure-borne sound power input using walls/floors as a coupled reception plate. Laboratory situation – ‘Earthed’ ground floor. Markers connected with solid lines represent the bending only model (50–5k Hz). Markers without lines represent the bending and in-plane model (630–5k Hz).

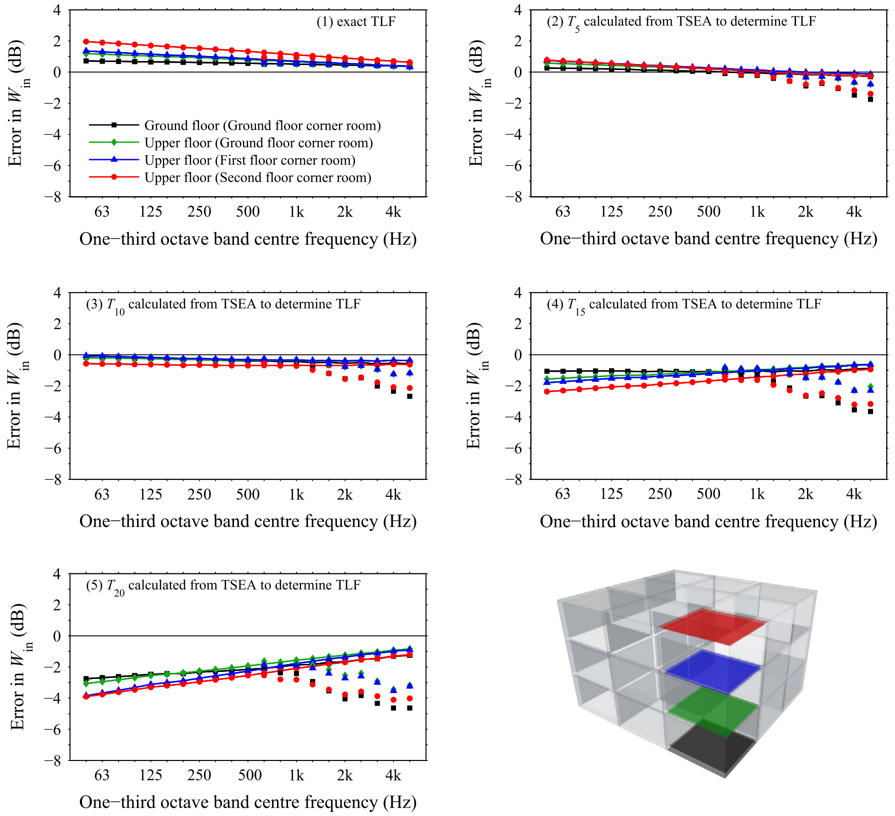

**Fig. 4.** Error in the structure-borne sound power input using walls/floors as a coupled reception plate. Field situation – 'Earthed' ground floors. Markers connected with solid lines represent the bending only model (50–5k Hz). Markers without lines represent the bending and in-plane model (630–5k Hz).

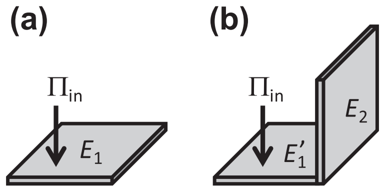

**Fig. 5.** (a) Isolated reception plate. (b) Coupled reception plate.

Combining Eqs. (6) and (8) gives

$$\Pi_{in} = \omega(\eta_{11} + \eta_{12})E_1' - \frac{\omega\eta_{12}\eta_{21}E_1'}{\eta_{22} + \eta_{21}} \tag{9}$$

Equating (5) and (9) gives the energy ratio

$$\frac{E_1'}{E_1} = \frac{\eta_{11}}{\eta_{11} + \eta_{12} - \left(\frac{\eta_{12}\eta_{21}}{\eta_{22}+\eta_{21}}\right)} \tag{10}$$

Now it is possible to calculate the power with the reception plate approach using the steady-state energy levels on the plate and the exact total loss factors used in the SEA model to give the calculated power ratio

$$\frac{\Pi_1'}{\Pi_1} = \frac{\omega(\eta_{11} + \eta_{12})E_1'}{\omega\eta_{11}E_1} = \frac{\eta_{11}^2 + \eta_{11}\eta_{12}}{\eta_{11}^2 + \eta_{11}\eta_{12} - \left(\frac{\eta_{11}\eta_{12}\eta_{21}}{\eta_{22}+\eta_{21}}\right)} \tag{11}$$

Eq. (11) shows that the coupled reception plate will overestimate the structure-borne sound power input. This overestimate tends to be most significant when the internal loss factors are very small.

Note that by solving the power balance Eqs. (6) and (7) for the coupled reception plate to determine $E_1'$, it is possible to retrieve the correct power input using

$$\Pi_{in} = \omega(\eta_{11} + \eta_{12})E_1' - \omega\eta_{21}E_2 \tag{12}$$

This is confirmed by substituting (8) into (12) as it gives the same result as Eq. (9). Hence the general equation to retrieve the correct power input for a coupled reception plate that is connected to $N$ subsystems is

$$\Pi_{in} = \omega\left(\eta_{11} + \sum_{j=1}^{N}\eta_{1j}\right)E_1' - \omega\sum_{j=1}^{N}\eta_{j1}E_j \tag{13}$$

The implication is that the correct power input can be recovered from a coupled reception plate if accurate values are available for (a) the reception plate's total loss factor (i.e. the bracket term in Eq. (13)) and (b) the coupling loss factors from all other plates that are connected to it. However, as these will be determined from measurements this is only possible if the measurement uncertainties are negligible for coupling loss factors and total loss factors with masonry/concrete walls or floors. To assess these measurement uncertainties, Fig. 6 shows typical standard deviations from measurements on a 140 mm cast in situ concrete floor that was rigidly connected on each of its four edges to a 215 mm dense aggregate wall across an L-junction. Total loss factors for the floor and two of these walls are shown in Fig. 6a; these were measured using the evaluation procedure for structural reverberation times described by Hopkins and Robinson [6]. Four coupling loss factors were measured between the floor and two of these walls (i.e. two coupling loss factors from floor to wall and two coupling loss factors from wall to floor) using simplified ESEA [1] for which the standard deviations are shown in Fig. 6b. Simplified ESEA effectively ignores in-plane wave energy even though significant in-plane wave generation often occurs at masonry/concrete plate

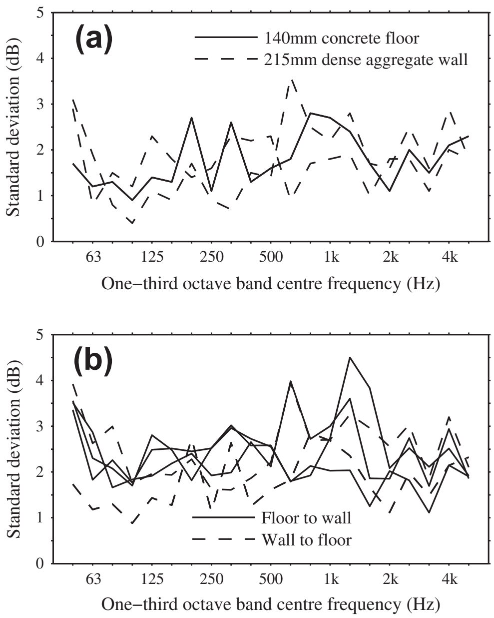

**Fig. 6.** Example measured data from a 140 mm cast in situ concrete floor that was rigidly connected on each of its four edges to a 215 mm dense aggregate wall: (a) Standard deviation for the total loss factor of the 140 mm floor and two 215 mm walls. (b) Standard deviation for four coupling loss factors between the floor and the wall determined using simplified ESEA.

junctions above 1k Hz. The importance of in-plane waves is difficult to identify with Experimental SEA and can result in unrepresentative SEA models [11]. Hence it would rarely be suitable to use measured coupling loss factors in Eq. (13) at frequencies above 1k Hz.

For all the loss factors shown in Fig. 6 the average value of the standard deviation is ≈2 dB. Therefore the uncertainty associated with these loss factors will often be similar or greater than the error in the structure-borne sound power input due to the coupled reception plate shown in Figs. 2–4. This leads to the conclusion that using Eq. (13) to improve the accuracy in the estimate of the power input is not a viable approach.

## 6. Conclusions

If coupled reception plates that form walls or floors in heavyweight buildings are used to try and quantify the structure-borne sound power input, there is the potential to incur significant errors due to energy returning to the reception plate from other connected plates. The problem is twofold. Firstly, in the low- and mid-frequency ranges the steady-state vibration level on the coupled reception plate is increased by energy returning from other coupled plates. Secondly, the structural decays have significant curvature due to the returning energy; hence short evaluation ranges are needed to minimise the error when calculating the total loss factors. This leads to the situation where the coupled reception plate can give the 'right answer for the wrong reason' because the error in the energy cancels out the error in the total loss factor. The latter error can only be minimised using an evaluation range of ≈5 dB for the structural reverberation time; note that smaller ranges would be impractical to measure and increasingly prone to error. Evaluation procedures have recently been published by the authors [6] that are suitable for doing this.

It has been shown that in principle it is possible to recover the correct power input from a coupled reception plate. However, this requires accurate values for the reception plate's total loss factor as well as the coupling loss factors from all other plates that are connected to the reception plate. This is only possible if the measurement uncertainties are negligible for the measured coupling loss factors and total loss factors. Measured data from a heavyweight building indicate that they are not negligible for typical masonry/concrete walls and floors; hence this corrective approach is not feasible in practice.

The isolated reception plate remains a valuable engineering approach to characterise structure-borne sound sources in the laboratory, but the results in this paper indicate that the method should only be extended to coupled reception plates with some caution unless an increase in the uncertainty is acceptable. An alternative approach to avoid this problem could be to determine the structure-borne sound power input on coupled reception plates using a power substitution method with a 'standard' source that has a known power input.

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