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Sound insulation in buildings: linking theory and practice

C. Hopkins

University of Liverpool, School of Architecture, Abercromby Square, L69 7ZN Liverpool, UK
carl.hopkins@liv.ac.uk

Validated theoretical models exist to predict sound and vibration transmission across some, but not all types of building element over the building acoustics frequency range. For this reason, laboratory measurements remain important at the design stage. As the sound insulation *in-situ* is determined by both direct and flanking transmission, prediction models often incorporate measured data for one or both aspects. To indicate the limitations of laboratory measurements, transient and steady-state SEA are used to illustrate how the transmission suite affects structural reverberation times of solid test elements and to quantify the inherent errors in structural coupling measurements on junctions of walls/floors. Particular problems occur with the laboratory measurement of structural coupling on junctions. Previously, prediction models have focused on steady-state sound pressure levels in buildings. However, transient sources cause significant disturbance to occupants, with regulatory requirements based on maximum sound pressure levels to protect against sleep disturbance. Recent work using transient SEA is used to illustrate the potential to predict maximum levels. With increasing emphasis on the importance of sound insulation at low-frequencies, indications are given on how the revision of field measurement Standards will seek to improve repeatability below 100Hz.

1 Introduction

In building acoustics, the unavailability of theoretical models to accurately predict sound and vibration transmission across all types of building element explains why laboratory measurements remain important at the design stage. The sound insulation *in-situ* is determined by both direct and flanking transmission, prediction models are essential tools that often need to incorporate measured data. This paper reviews the links between laboratory measurements and the prediction models that are used to design buildings to achieve the required sound insulation, as well as the field measurements used to verify the *in-situ* performance. The inability of prediction models to deal with every type of building element indicates why laboratory measurements are so important in providing information at the design stage. However, validated prediction models for simple elements are essential to illustrate the inherent limitations of many laboratory measurements.

2 Laboratory sound insulation measurements: Errors in structural reverberation times for heavyweight elements in transmission suites

Transmission suites are often used to measure the airborne and impact sound insulation of heavyweight test elements. However, in commercial laboratories it is rare for the results to be accompanied by measurements of the structural reverberation time. This is partly because of the difficulties in evaluating and measuring fast structural decays with standard equipment, but also due to reducing testing costs. Yet the structural reverberation time is essential for the comparison of sound insulation results from different laboratories [1,2] or for inclusion in prediction models to estimate the *in-situ* performance using Statistical Energy Analysis (SEA) [e.g. see 2] or SEA-based models such as EN12354 [3].

Transient SEA (TSEA) [4] is used here to illustrate the effect of idealized transmission suites on the structural decay curve of the test element when it is mechanically excited [5].

For a structure-borne sound power input into bending wave subsystem, i, in an SEA system of N subsystems, the change in energy is defined by the difference between the power gained and the power lost by that subsystem as in Eq. (1).

$$\frac{\mathrm{d}E_i(t)}{\mathrm{d}t} = \left[W_{\mathrm{in}\,(i)}(t) + \sum_{j\,(j\neq i)}^{N} \omega\eta_{ji} E_j(t) \right] - \left[\omega\eta_{ii} E_i(t) + \sum_{i\,(i\neq j)}^{N} \omega\eta_{ij} E_i(t) \right] \quad (1)$$

where $E_i(t)$ is the time-varying energy in subsystem i, $W_{\mathrm{in}(i)}(t)$ is the time-varying power input into bending wave subsystem i, η_{ii} is the internal loss factor of subsystem i, η_{ij} is the coupling loss factor from subsystem i to subsystem j.

Figure 1 shows an idealized transmission suite formed from 200mm cast in-situ concrete plates (440kg/m^2). The plate shown in red is the test element which represents a 100mm separating wall of lightweight aggregate blocks (140kg/m^2). All plates are modeled as being isotropic and homogenous with effective linings on all walls and floors of the transmission suite.

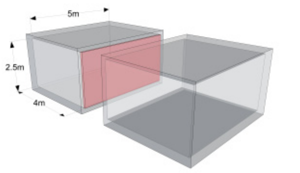


Figure 1: Idealized transmission suite

An important decision in the design of a transmission suite is whether the concrete ground floor slab should be ‘earthed’ or ‘unearthed’ (electrical analogy). An unearthed model is introduced which assumes that the total loss factor of the ground floor slabs equals the sum of the coupling loss factors plus the internal loss factor. This represents a laboratory mounted on vibration isolators to reduce background noise (primarily in the receiving room) as well as reducing flanking transmission between the source and receiving rooms. In the earthed model, the ground floor slabs have additional damping because the slabs are assumed to be in direct contact with the earth over their complete surface; this is simulated by setting the internal loss factor of each ground floor plate to $f^{0.5}$; this is justified by measurements on actual ground floors [2]. It is assumed that there is no transmission of vibration between the two floor slabs via the earth; hence no coupling via ground-borne wave motion is considered in the model. A decoupled model is introduced which assumes that the separating wall is physically decoupled from the structure but has the same total loss factor as if it were still connected. Although not physically realizable, this provides a useful benchmark from which to assess the effect of the ground floor slab being 'earthed' or 'unearthed' on the structural decay curve.

Previous work [5] indicates that the sound field in the source and receiving rooms with reverberation times of 1.5s only causes a secondary slope on the decay curve of the wall after the level has dropped by at least 30dB. Hence the curvature in the TSEA decay curves shown in Figure 2 is primarily due to the exchange of energy between the test element and the laboratory walls and floors.

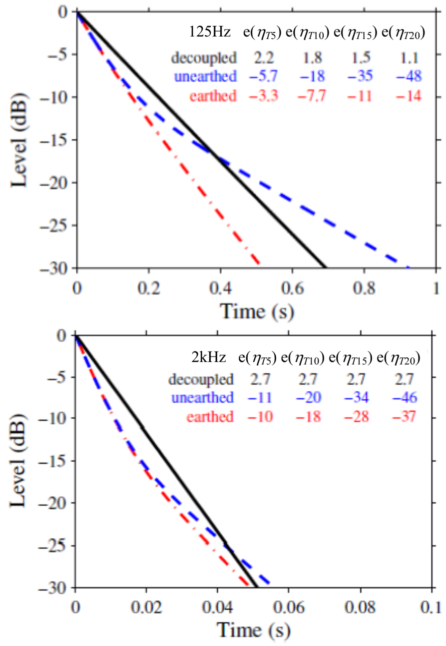


Figure 2: TSEA structural decay curves for the test element along with the percentage errors in the total loss factors.

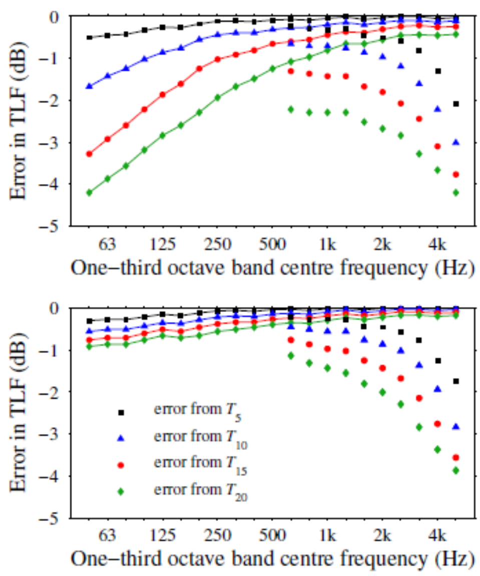


Figure 3: Error in the TLF for the test element. Unearthed (upper graph) and earthed (lower graph) ground floors.

Figure 3 shows the errors in decibels for the total loss factor over the entire frequency range when the transmission suite is earthed and unearthed. Due to multiple-slope decay curves, a smaller evaluation range for the structural reverberation time yields lower errors for the total loss factor. The errors are significantly lower when the transmission suite is earthed compared to unearthed. The earthing provides a 'sink' to dissipate energy in the ground; hence less energy is available to return to the separating wall. TSEA results and experimental experience indicate that for earthed and unearthed laboratories it is beneficial to evaluate decay curves using T_5 to avoid errors unless the decay curve is straight over a longer evaluation range.

3 Laboratory and field measurements: Vibration transmission across junctions

The prediction model in EN 12354 was introduced to standardize the estimation of *in situ* sound insulation for building products and elements hence satisfying the requirements of the European Construction Products Directive [6]. Whilst EN 12354 contains some theoretical and empirical data these requirements made it essential for manufacturers to be allowed to use measured data for their products. This required new measurement Standards for the vibration reduction index, K_{ij}, in ISO 10848 [7].

Measurements of vibration transmission across L-junctions of masonry/concrete walls and floors compare well with theory assuming diffuse incidence bending wave fields without wave conversion at the junction [2]. This is partly because separating walls and floors that form part of L-junctions tend not to be as thick, heavy and stiff as those in T- and X-junctions. However, in-plane wave generation plays a significant role in determining vibration transmission across the straight section of T- and X-junctions. For typical masonry/concrete walls and floors the effect of in-plane waves usually becomes significant above 1kHz. Unfortunately, Experimental SEA (ESEA) is not well-suited to identifying wave conversion and only simplified forms of ESEA are practical for building structures [8]. For this reason, measurements of the vibration reduction index consider only the excitation and response of bending waves; requiring velocity level differences that are normalized using structural reverberation times. This presents a potential problem with the EN 12354 model as it assumes that only bending wave energy is stored in, and transmitted between, walls and floors. The in-plane subsystems are effectively ignored as a 'black box' of unknowns.

Whilst transmission suite designs have evolved through standardization to control the variables that contribute to poor reproducibility, flanking laboratory design is still in its relative infancy. Designing a flanking laboratory to measure structural coupling parameters between heavyweight building elements is inherently awkward. Masonry/concrete elements are sufficiently heavy that they need structural support, and they ideally need to be connected to other parts of a building structure so the total loss factors are representative of *in situ* values. Idealized laboratory and field arrangements are considered in this section using prediction models to gain insight into the measurement errors. SEA is used to determine the velocity level difference with TSEA to determine the structural reverberation times as T_5 to minimize errors from double-slope decays. As EN 12354 is the same as first-order SEA path analysis, K_{ij} is simply related to the SEA coupling loss factor, η_{ij}. The errors are shown in terms of the predicted value (from simplified ESEA using SEA and TSEA) minus the actual value.

Errors with a masonry T-junction are shown in Figure 4. To assess the effect of the laboratory it is initially useful to consider arrangement (a) where the test junction is isolated. The junction could be considered as being suspended in space but as this is clearly not possible in practice, it essentially corresponds to the situation where each wall in the junction is built off strips of resilient material. The largest error occurs in η_{2B3B} due to the indirect path 2B→1B→3B being stronger than the direct path 2B→3B below 1kHz. This illustrates that isolating the junction from all other structures to minimize unwanted flanking transmission introduces other problems due to low total loss factors. Arrangement (b) is a more practical realization of a flanking laboratory where each wall in the junction is rigidly connected to an individual, concrete ground floor with high damping due to the earth underneath. Whilst η_{2B3B} still has significant errors at low-frequencies, the coupled ground floor plates significantly increase the errors in the high-frequency range due to the existence of in-plane wave energy. Arrangement (c) represents an *in situ* measurement in a large building. Errors in η_{2B3B} are similar to the isolated junction, but η_{1B2B} and η_{2B1B} errors are higher due to flanking transmission via the rest of the building.

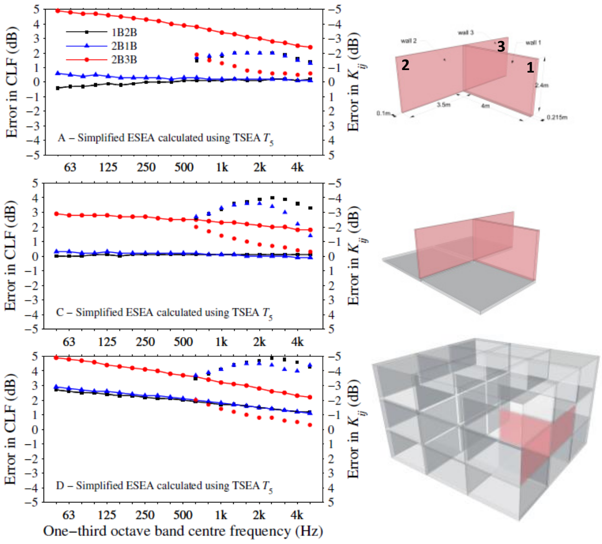


Figure 4: Error in the coupling loss factor or vibration reduction index for a T-junction of walls: (a) when isolated in the laboratory (upper), (b) when each wall of the junction on individual highly-damped concrete floor slabs (middle) and (c) when measured *in situ* in a large building (lower).

The largest errors come from the velocity level differences due to the connections (or lack of connections) to the flanking laboratory or building, and not the evaluation of the structural decay curves.

The results indicate that for heavyweight walls and floors there are problems in measuring structural coupling both in flanking laboratories and *in situ* using simplified ESEA. Whilst structural intensity could be used to solve the problem, the results only tend to be valid below 1kHz on typical masonry/concrete walls and floors.

4 Prediction: Incorporating coupling parameters from isolated heavyweight plate junctions in models of complete buildings

Section 3 indicates problems in laboratory and field measurements of structural coupling parameters for heavyweight junctions. This needs to be considered in the context of EN 12354 in which the measured values can be incorporated. Although EN 12354 was originally intended for adjacent rooms in heavyweight buildings it has subsequently been shown to be ill-suited for this purpose as it uses only first-order SEA path analysis [2,9,10]. In practice there are so many higher-order paths of collective significance that matrix SEA is needed for accurate prediction. Hence it is also needed when considering structure-borne sound transmission from service equipment (or machinery) to non-adjacent rooms.

Two issues are illustrated by the example [11] in Figure 5 (upper graph); firstly, that matrix SEA with coupling loss factors from wave theory is inadequate for non-adjacent rooms and secondly that even if 160 of the strongest paths are summed, these are significantly different to matrix SEA, showing that path analysis is not a practical or accurate solution. However EN 12354-5 (which applies to structure-borne sound transmission from machinery) currently promotes path analysis but does not account for in-plane wave generation. This is not problematic because noise problems from machinery over long distances in buildings only tend to be in the low- and mid-frequency ranges. However, in the low- and mid-frequency ranges, heavyweight walls and floors have low modal density and low modal overlap. Hence it is worth considering whether there would be any advantage in including measured or predicted values into prediction models in order to overcome any inherent errors in using wave theory. The example in Figure 5 (lower graph) using a global mode approach [12] gives an indication that significant improvements in the accuracy of SEA can be made for non-adjacent rooms.

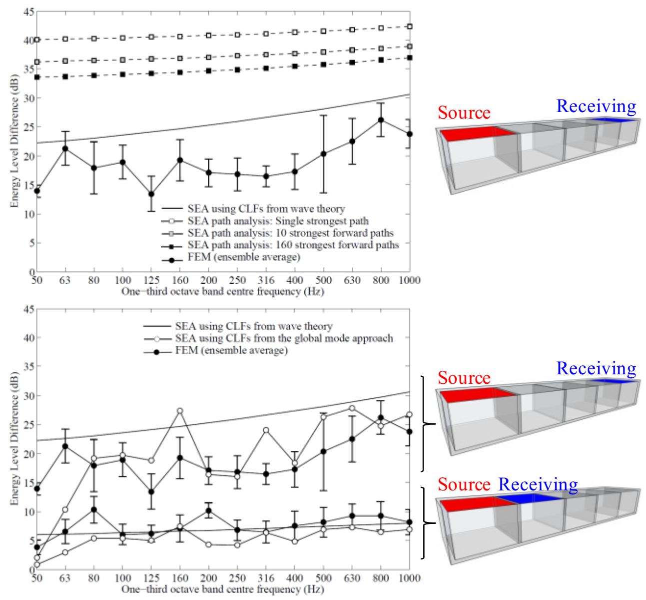


Figure 5: Energy level difference between floors predicted using FEM and SEA. Upper graph shows SEA with coupling loss factors from wave theory for matrix and path analysis. Lower graph includes SEA when calculating coupling loss factors from a global mode approach.

5 Prediction: Using Transient SEA to estimate maximum sound pressure levels from excitation by single impacts

For several decades the measurement of impact sound insulation in the field has primarily used the ISO tapping machine. This is effectively a steady-state source for which L_{eq} measurements are convenient. In contrast, Japan and Korea measure impact sound insulation using a single heavy impact from the ISO rubber ball. However, to-date there has been a lack of validated prediction models in building acoustics to estimate maximum sound pressure levels with Fast time-weighting, $L_{p,Fmax}$, in rooms. A potential application occurs with a single impact from the ISO rubber ball when testing heavyweight buildings.

SEA has been used with considerable success to predict steady-state sound and vibration transmission in heavyweight buildings; hence TSEA is a logical starting point to predict $L_{p,Fmax}$ with Transient SEA in masonry/concrete buildings [13]. Positive indications that TSEA could work well with heavyweight buildings where walls/floors have relatively low mode counts and low modal overlap can be gleaned from work on two coupled beams with similar features [14].

In this example a force plate is used to measure the input force from the ISO rubber ball dropped from a 1m height. This is converted into a 'transient power input' using the driving-point mobility for the floor. This power input is then applied to the TSEA model by uniformly distributing it over a number of consecutive time steps equivalent to the time of the applied force.

Validation of the TSEA approach to predict maximum levels is shown in Figure 6 using measurements in a heavyweight laboratory structure with a 140mm concrete floor excited by the ISO rubber ball.

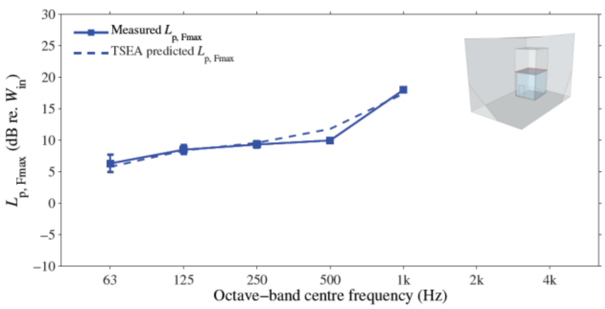


Figure 6: Measured and TSEA predicted maximum sound pressure level (normalized to 'transient power input') due to an impact from the ISO rubber ball on a concrete floor.

6 Field sound insulation measurements: Improving repeatability and reproducibility at low-frequencies

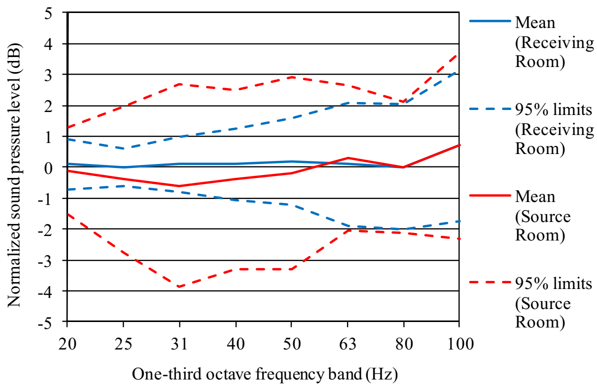
Regulatory requirements on airborne sound insulation between dwellings are usually specified in terms of a single-number quantity calculated using the frequency range between 100Hz and 3.15kHz. This range is suitable for sources such as speech, however, hi-fi, computer audio, home cinema, and television equipment often has a significant sound power output at frequencies below 100Hz. Hence there is a need to measure the airborne sound insulation below 100Hz. From a regulatory viewpoint this is only appropriate if the measurement method has suitable repeatability, reproducibility, and relevance (i.e. there is a link between the insulation that is measured, and the insulation experienced by the building occupants). However, a problem arises at low frequencies where the sound field cannot be considered as diffuse because many habitable rooms (particularly bedrooms) have small volumes. Strong modal room responses typically occur in volumes <25m^3 where there are often less than five modes below 100Hz. Maximum differences between the lowest level in the central zone of the room and the highest level that is ≈0.5m from the room boundaries can be 17–28 dB.

Repeatability and reproducibility can be improved by making use of additional microphone positions to sample sound pressure in the corners of rooms below 100Hz. A similar approach is used in ISO 10052 for low-frequency noise measurements from service equipment in buildings. The aim of the low-frequency method is to use the central zone SPL measurement, L, and the corner SPL, L_{Corner}, to estimate the average SPL for the entire room volume. This can be achieved using an empirical weighting according to

$$L_{LF} = 10\lg\left[\frac{10^{0.1L_{Corner}} + (2.10^{0.1L})}{3}\right] \tag{2}$$

Sound pressure level measurements were taken in regular grids in a source room (29m^3) and receiving room (18m^3) in a timber frame dwelling [15]. Figure 7 (upper graph) shows that the mean for different sets of five microphone positions in the central zone is ≈0dB but that the 95% confidence intervals are large below 100Hz. Figure 7 (lower graph) shows that the low-frequency method has a mean value that is within 1dB of the average SPL for the entire room volume with 95% confidence intervals that are significantly smaller below 100Hz.

Figure 8 shows results from 37 field tests in lightweight building constructions indicating that this low-frequency measurement protocol (which should improve repeatability and reproducibility) will change one-third octave band values by -7dB to +4dB although single-number quantities will typically only decrease by a few decibels [15].



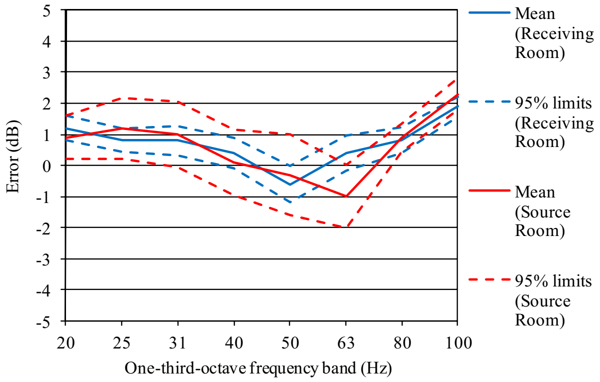


Figure 7: (Upper graph) Normalized sound pressure level showing the variation due to different sets of five microphone positions normalized to the average of all central zone positions. (Lower graph) Error between L_{LF} and the average of all grid points in the entire volume.

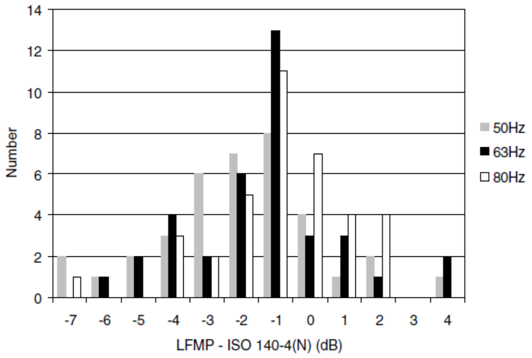


Figure 8: Differences between D_{nT} calculated using the low-frequency measurement protocol (LFMP) and ISO140-4(N) in the 50, 63 and 80 Hz one-third octave bands.

7 Conclusions

This paper sought to demonstrate the interplay in building acoustics between laboratory measurement and prediction models that are primarily based around the SEA framework of analysis.

TSEA has been used to quantify the effect of transmission suites on the measured structural reverberation time of heavyweight walls or floors. This indicates that 'earthing' one of the rooms is beneficial and that T_5 is often needed to calculate the total loss factor. TSEA has also been used to predict the maximum sound pressure level in rooms due to impact excitation, and has been validated against laboratory measurements with the ISO rubber ball.

Laboratory and field measurements of structural coupling parameters on junctions are fraught with errors, but if this could be overcome, prediction models do indicate the potential to improve predictions in the low- and mid-frequency ranges.

In addition, a proposal is described to improve the repeatability and reproducibility of field measurements of sound insulation in the low-frequency range.

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