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Prediction of maximum Fast time-weighted sound pressure levels from time-varying structure-borne sound sources in heavyweight buildings

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ABSTRACT

At present the prediction model in EN 12354-5 for sound transmission due to structure-borne excitation from building machinery is limited to sources running under steady-state conditions. As machinery noise also needs to be assessed under time-varying conditions, building regulations on installation noise in some European countries set requirements based on the maximum Fast time-weighted sound pressure level in the receiving room. This paper proposes an approach that could predict this information at the design stage and validates it using idealised time-varying signals applied via a shaker into a concrete floor. A heavyweight reception plate is used to quantify the structure-borne sound power using equivalent continuous levels over 125ms time periods from which the highest value can be used as the power input into an SEA or SEA-based prediction model. An empirical correction (developed in previous work by the authors) is then applied to the output from this model to estimate the maximum Fast time-weighted sound pressure level. This approach is validated with measurements in a room below a concrete floor (where there is suppressed flanking transmission) from which the results show close agreement between predictions and measurements for one-third octave bands and A-weighted values.

Keywords: machinery, structure-borne sound power, time-varying signals, Fast time-weighted levels

1. INTRODUCTION

The structure-borne sound power from a high-mobility source injected into a low-mobility plate can be determined according to EN 15657 (1) by using the reception plate method when the source operates under steady-state conditions. This can then be used as input data to estimate the steady-state sound pressure level in a receiving room using the SEA-based prediction model described in EN 12354-5 (2). However, building machinery does not always operate in a 'steady-state' and often has time-varying operating conditions. At present there is no standardised procedure with the reception plate to quantify the structure-borne sound power from time-varying sources. In addition, EN 12354-5 is not able to predict the maximum Fast time-weighted sound pressure level (L_{Fmax}) in the receiving room which is required in some European regulations on installation noise e.g. VDI 4100 (3) in Germany.

In heavyweight buildings it is possible to predict the impact sound insulation due to transient excitation in terms of maximum Fast time-weighted sound pressure levels using Transient Statistical Energy Analysis (TSEA) (4,5). This requires measurements of the blocked force from the transient excitation for which the approach has been validated for heavy impacts from the ISO rubber ball and the bang machine on heavyweight floors with and without floating floors (6,7). However, there has been a move through the EN 12354 series of standards to simplify the prediction process for the building industry, such that it is not feasible to incorporate TSEA calculations in these Standards. Hence the aim in this paper is to identify and validate a simpler procedure than TSEA which could be used in an SEA-based prediction model like EN 12354-5 to estimate the maximum Fast time-weighted sound pressure level from building equipment. This would require input data for time-varying structure-borne sound power and ideally this would be based on a modified approach to the reception plate method described in EN 15657.

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The underlying principle to this new approach for time-varying structure-borne sound sources is that building machinery such as boilers, washing machines, pumps tends to have different operating cycles between which an approximately broadband, structure-borne sound power input ramps up and down. However, such machinery rarely introduces very short, high level transients in the power input like an impact from a dropped object such as the rubber ball which has ≈20ms contact time (6,7). For this reason, it is proposed that the reception plate could be used to identify $\max\{L_{\mathrm{eq,125ms}}\}$ and that this could be used as input data in an SEA or SEA-based prediction model (i.e. EN 12354-5) with an empirical correction to convert the estimated sound pressure level from $\max\{L_{\mathrm{eq,125ms}}\}$ to L_{Fmax}. This empirical correction and the use of 125ms has been assessed in a previous investigation by the authors (8) using idealised time-varying signals which ramp up and down. This showed that the empirical correction has some dependence on the ramp duration as well as the ramp levels; for ramp levels of 10dB and all ramp durations the empirical correction was 5dB, for ramp levels of 20/30/40dB and a ramp duration of 125ms the empirical correction was 7.5dB and for ramp levels of 20/30/40dB with ramp durations ≥500ms the empirical correction was 6dB.

The current paper builds on the work in (8) to use the reception plate with power injected by a shaker with idealised time-varying signals to determine the highest $L_{\mathrm{eq,125ms}}$ and then predict the maximum Fast time-weighted sound pressure level in a heavyweight building-like situation using an SEA model with the empirical correction. The initial comparison is made using one-third octave bands but practical assessments of machinery noise often require an A-weighted maximum Fast time-weighted sound pressure level; hence an energetic summation is used to assess whether an A-weighted value could also be estimated from the frequency band data.

2. EXPERIMENTAL SET-UP

Twenty wav files of idealised time-varying signals were created in Matlab. These had different rising and falling ramp durations of 125ms, 500ms, 1s, 2s and 5s with increasing and decreasing ramp levels of 10/20/30/40dB as indicated by the examples in Figure 1. The signals are played into an electrodynamic shaker on a reception plate and a floor in a building-like situation in the laboratory at Stuttgart (8).

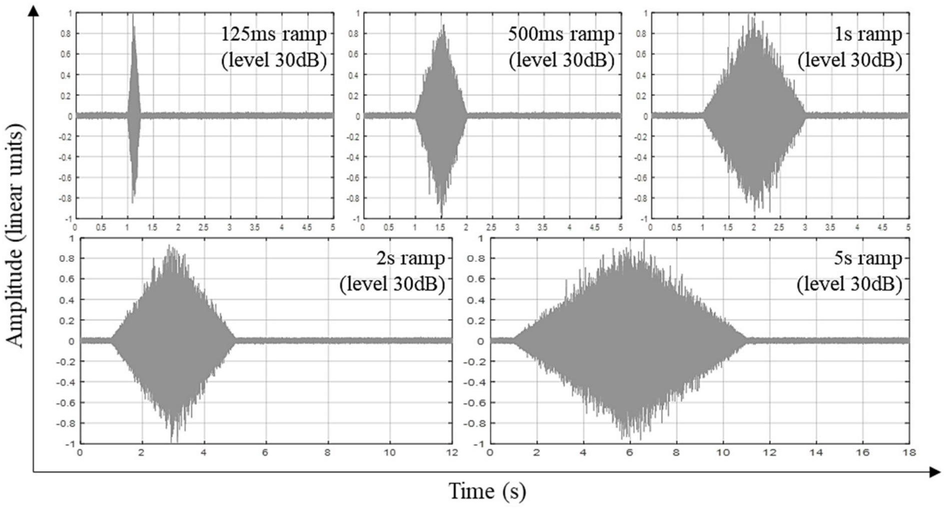

Figure 1 – Example of idealised time-varying signals for all ramp durations with a ramp level of 30dB.

2.1 Reception Plate for Structure-borne Sound Characterisation

The reception plate test rig at Stuttgart consists of three decoupled plates due to resilient supports around the edges (1,9). In this paper, only the horizontal 100mm concrete (low-mobility) plate with an area of 5.6m² is used. Three excitation positions are taken for a shaker to quantify the injected structure-borne sound power in terms of $\max\{L_{\mathrm{eq,125ms}}\}$ in each one-third octave band using the proposed weighting factor in (10,11) that combines velocity measurements of all four corners and central zone positions (≥ 0.5m away from edges).

2.2 Building-like Situation for Structure-borne Sound Transmission

A floor test facility is used to represent a building-like situation in which there is suppressed flanking transmission (using independent wall linings) such that only direct sound transmission from the floor is dominant. The concrete test floor is 140mm thick with an area of 19.4m². The receiving room has a volume of 51.1m³.

Three positions on the concrete floor are excited by the electrodynamic shaker to determine the vibration field on the floor and the sound field in the receiving room. The spatial-average velocity level is determined in terms of max$\{L_{\text{eq,125ms}}\}$ and L_{Fmax} on the separating floor using seven accelerometer positions (two corner/edge positions and five central zone positions that are ≥0.5m away from floor edges). The spatial-average sound pressure level is obtained in terms of max$\{L_{\text{eq,125ms}}\}$and L_{Fmax} using four microphone positions in the central volume of the room (>0.5m away from room boundaries).

3. SEA PREDICTION MODEL FOR A COUPLED ROOM-PLATE SYSTEM

To describe the steady-state sound transmission in the building-like situation, an SEA model of a coupled room-plate system is used by considering a homogenous plate (subsystem 1) coupled to a receiving room (subsystem 2) – see Figure 2.

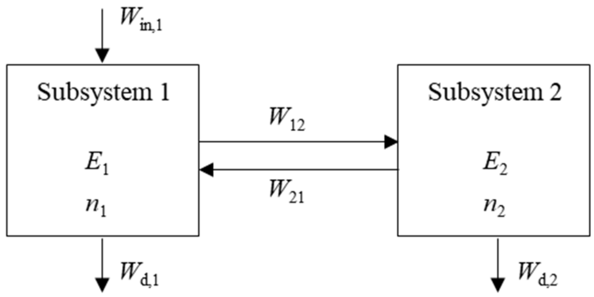

Figure 2 – Two-subsystem SEA model for a coupled room-plate system.

The energy balance of this coupled room-plate system is determined from knowledge of the vibrational power input into the plate, the coupling between the subsystems and the power dissipated through internal and coupling losses to other subsystems (12,13).

The power balance equations for a coupled room-plate SEA model are:

$$W_{\text{in,1}} = \omega\eta_{11}E_1 + \omega\eta_{12}E_1 - \omega\eta_{21}E_2 \tag{1}$$

$$\omega\eta_{12}E_1 = \omega\eta_{22}E_2 + \omega\eta_{21}E_1 \tag{2}$$

where $W_{\text{in,1}}$ is the power injected into the plate (1), η_{11} represents the losses of the plate (internal losses and the sum of coupling losses from the plate to connected walls and floors), η_{22} represents the losses of the receiving room (determined from the reverberation time), η_{12} and η_{21} are the coupling loss factors from the plate (1) to the room (2) and from the room (2) to the plate (1), respectively, and E represents the subsystem energies.

The experimentally-determined input data are the vibrational power of the source, the loss factors of the plate and in the receiving room as well as the plate radiation efficiency. The radiation efficiency is determined using shaker excitation with white noise from measurements of the sound pressure and the plate velocity based on the following equation:

$$\sigma = A\left\langle p^2 \right\rangle \Big/ \left(4S\rho_0^2 c_0^2 \left\langle v^2 \right\rangle\right) \tag{2}$$

where A is the absorption area of the room, S is the area of the plate, ρ_0 is the air density, c_0 is the speed of sound, $\langle p^2 \rangle$ is the spatial-average mean-square pressure and $\langle v^2 \rangle$ is the spatial-average mean-square velocity.

4. RESULTS

4.1 One-third Octave Bands

To assess the results it is assumed that an acceptable difference between the two-subsystem SEA prediction and the measurement is ±5dB for the low-frequency range up to 200Hz and ±3dB for the mid- and high-frequency range from 250Hz to 3.15kHz. The allowable error is larger in the low-frequency range where uncertainties are larger in reverberation time measurements and in the spatial variation of the sound pressure and the plate velocity (13).

Figure 3 shows the difference between predicted and measured velocities in terms of L_{Fmax} on the concrete floor in the building-like situation. This shows that the SEA model is able to predict the measured vibrational response of the concrete floor within the acceptable error limits for all ramp durations with only a few exceptions (e.g. 125ms ramp at 50Hz) where the error is up to 1.4dB higher than the acceptable error limits. In general, there is no significant offset, although for the 125ms ramp the prediction appears to slightly overestimate between 50Hz and 100Hz and for the 1s, 2s and 5s ramps the prediction appears to slightly overestimate between 630Hz and 3.15kHz.

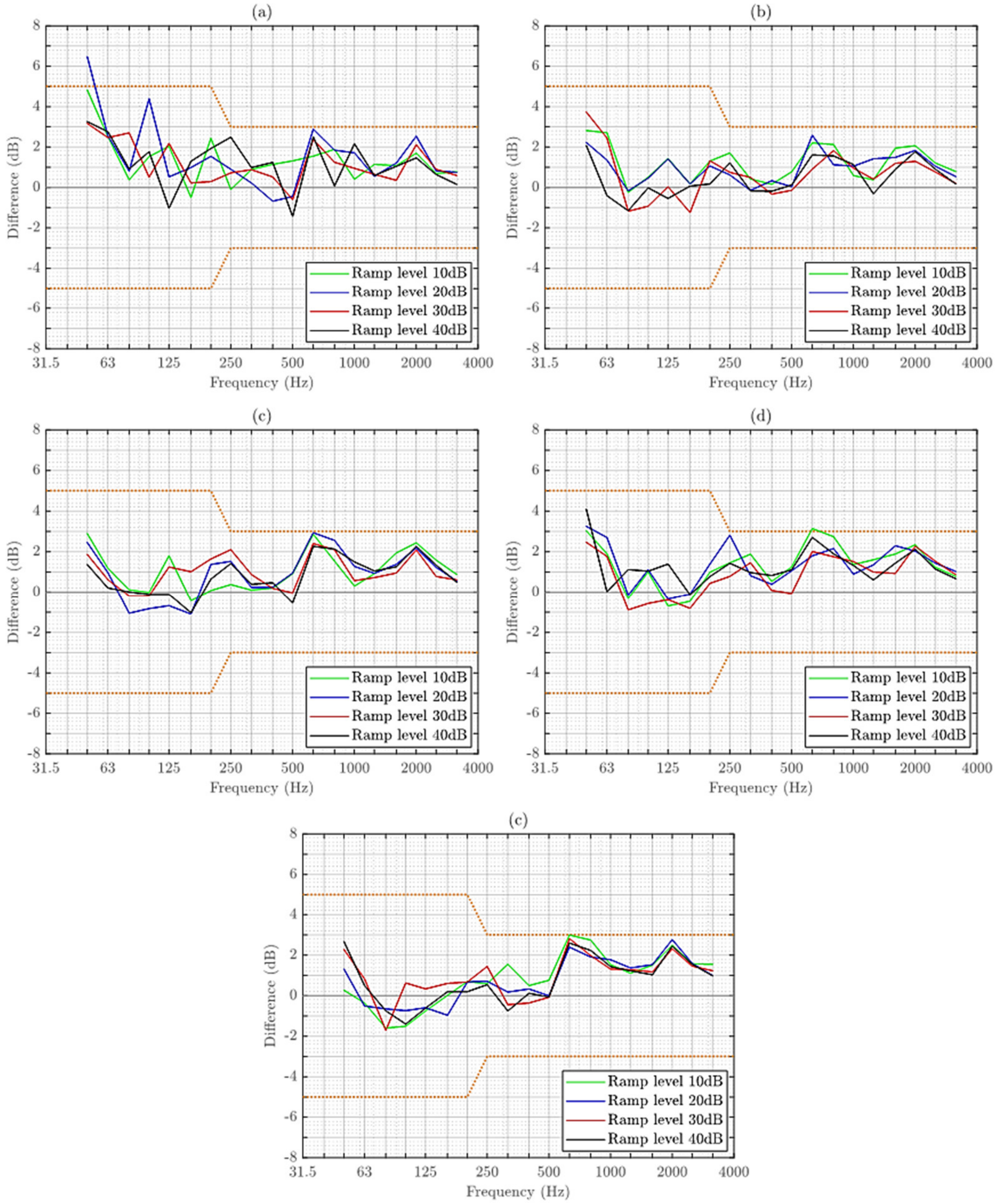

Figure 3 – Difference between predicted and measured velocity levels in terms of L_{Fmax} (predicted – measured). (a) 125ms ramp, (b) 500ms ramp, (c) 1s ramp, (d) 2s ramp and (e) 5s ramp.

Figure 4 shows the difference between predicted and measured sound pressure levels in terms of L_{Fmax}. These differences are similar to those observed for the plate velocity with the prediction model having only a slightly higher overestimation than with velocity. For a 125ms ramp there are five exceedances of the acceptable error by up to 1.3dB whereas for ramp durations ≥500ms all ramp levels are within the acceptable error. However, such differences are similar to SEA predictions of airborne or impact sound insulation (steady-state sources) with only direct sound transmission (13).

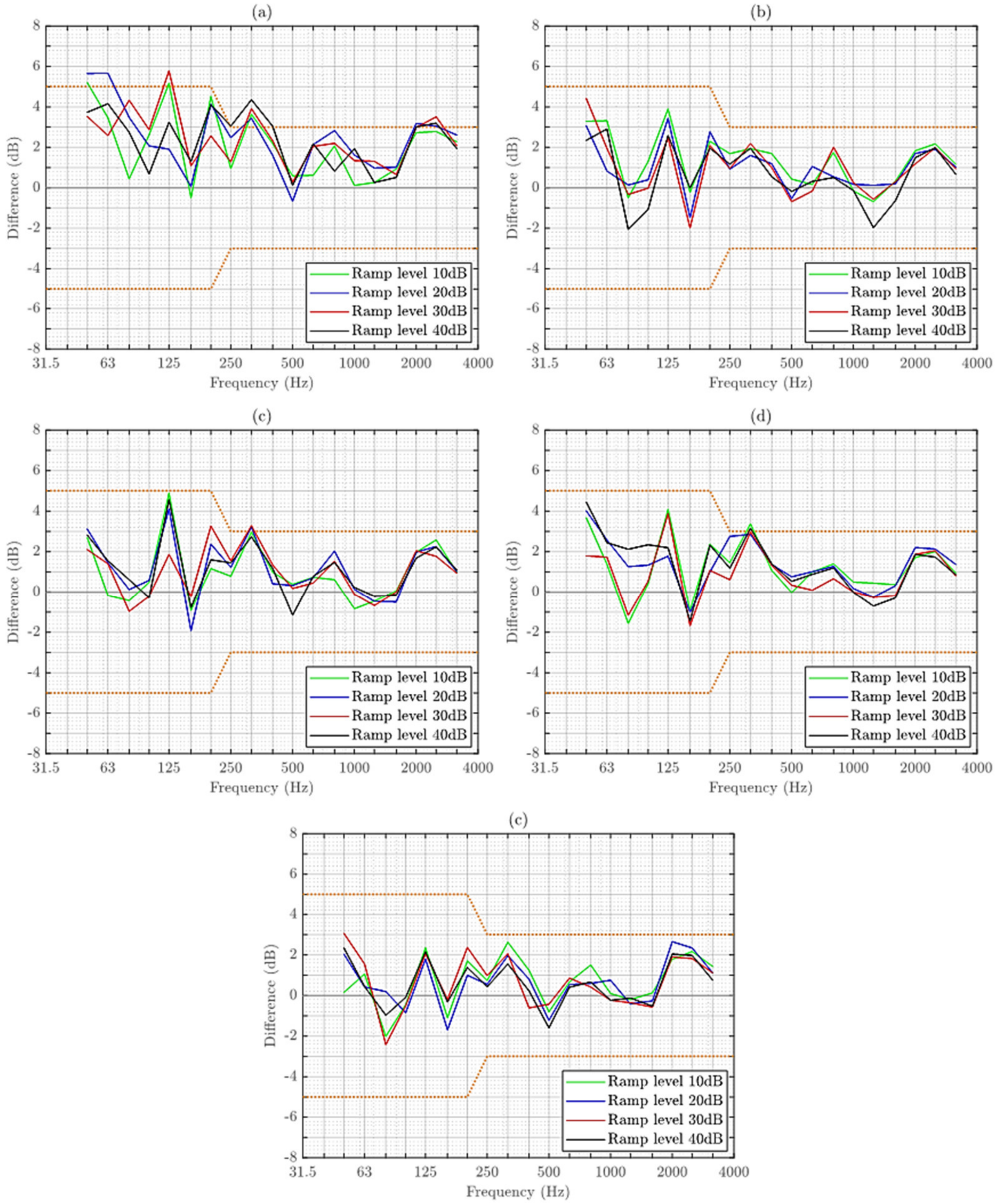

Figure 4 – Difference between predicted and measured velocity levels in terms of L_{Fmax} (predicted – measured). (a) 125ms ramp, (b) 500ms ramp, (c) 1s ramp, (d) 2s ramp and (e) 5s ramp.

The above results provide evidence that by using the specific empirical correction for a known ramp level and a known ramp duration it is feasible to estimate L_{Fmax} within ±3dB. However, on the basis that the ramp level and the ramp duration is not known for the majority of building equipment, it would be convenient to adopt a single empirical correction that could be used with simplified forms of SEA such as in EN 12354-5. The empirical corrections from reference (11) range from 5dB to 7.5dB; hence it is reasonable to consider 6dB as a candidate for a single empirical correction as this is approximately in the middle of this range. The implications of choosing this value are that for ramp levels of 10dB it will overestimate L_{Fmax} by ≈1dB, but it will exactly correspond to the empirical correction for 20/30/40dB with ramp durations ≥500ms. The results using a single empirical correction are shown in Figure 5. These show that for ramp levels of 20/30/40dB and all ramp durations the error is within the acceptable limits. With a ramp level of 10dB, the prediction tends to overestimate and occasionally this error is outside the acceptable error by ≈1.2dB; however, this simplification still seems justifiable for an SEA-based approach like EN 12354-5.

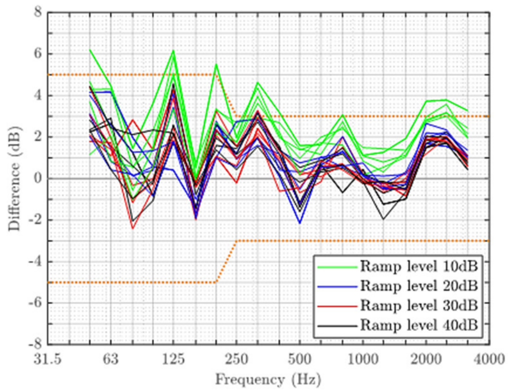

Figure 5 – Difference of predicted and measured sound pressure levels, L_{Fmax} using a single empirical correction of 6dB.

Note that this paper only considers direct transmission whereas structure-borne sound transmission in the field between horizontally, vertically or diagonally adjacent rooms in heavyweight buildings will involve flanking transmission. However, in these situations the propagation times for bending waves across heavyweight walls and floors are sufficiently short that the use of $L_{eq,125ms}$ should be reasonable.

4.2 A-weighted Levels

This stage assesses whether it is feasible to estimate L_{AFmax} from L_{Fmax} values in one-third octave or octave bands by subtracting the A-weighting and energetically summing them. The L_{AFmax} measurements are carried out with a high-pass filter above 20Hz and a low-pass filter below 6.3kHz. For the prediction of L_{Fmax} an A-weighting from 20Hz to 5kHz is applied. The frequency-dependent L_{AFmax} can be converted into a single value using an energy summation. Table 1 shows the differences between the predicted and measured L_{AFmax}. The differences are below 2.5dB which would be suitable for most building acoustics applications.

Table 1 – Predicted L_{AFmax} minus measured L_{AFmax}

Ramp level		10dB	20dB	30dB	40dB
ΔL_{AFmax} (dB)	125ms ramp	1.9	2.4	1.5	1.6
	500ms ramp	0.4	0.7	0.0	-0.1
	1s ramp	1.1	1.1	0.3	0.6
	2s ramp	1.1	0.8	0.5	0.5
	5s ramp	0.5	0.8	0.8	0.4

5. CONCLUSIONS

Validated procedures have been developed to predict maximum Fast time-weighted sound pressure levels in a receiving room due to time-varying vibrational power injected into a heavyweight floor. Comparison between SEA predictions and the measured L_{Fmax} in one-third octave bands shows that the difference is within ±3dB. To simplify the approach, a single empirical correction has been assessed that could be used for simplified SEA-based models such as described in EN 12354-5. In addition, it has been shown to be feasible to estimate L_{AFmax} from predicted one-third octave band L_{Fmax} values with close agreement.

The approach described in this paper has the potential to be incorporated into EN 15657 and EN 12354-5 so that estimates of the maximum Fast time-weighted sound pressure level can be carried out before machinery with a time-varying structure-borne sound power is installed in a heavyweight building.

REFERENCES

1. EN 15657:2017 Acoustic properties of building elements and of buildings – Laboratory measurement of structure-borne sound from building service equipment for all installation conditions.
2. EN 12354-5:2009 Building acoustics – Estimation of acoustic performance of building from the performance of elements – Part 5: Sound levels due to service equipment.
3. VDI 4100:2012 Sound insulation between rooms in buildings – Dwellings – Assessment and proposals for enhanced sound insulation between rooms.
4. Robinson, M. and Hopkins, C. (2014). Prediction of maximum time-weighted sound and vibration levels using transient statistical energy analysis – Part 1: Theory and numerical implementation. Acta Acustica united with Acustica, 100(1), 46-56.
5. Robinson, M. and Hopkins, C. (2014). Prediction of maximum time-weighted sound and vibration levels using transient statistical energy analysis – Part 2: Experimental validation. Acta Acustica united with Acustica, 100(1), 57-66.
6. Robinson, M. and Hopkins, C. (2015). Prediction of maximum fast time-weighted sound pressure levels due to transient excitation from the rubber ball and human footsteps. Building and Environment, 94, 810-820.
7. Hirakawa, S. and Hopkins, C. (2018). Experimental determination of transient structure-borne sound power from heavy impact sources on heavyweight floors with floating floors using an inverse form of transient statistical energy analysis. Applied Acoustics, 140, 74-82.
8. Reinhold, S., Hopkins, C. and Seiffert, G. (2018). Estimating maximum Fast time-weighted vibration levels from short equivalent continuous vibration level measurements of structure-borne sound sources on heavyweight plates. Proceedings of the 11th European and Exposition on Noise Control Engineering (Euronoise), Heraklion, Crete, 1609-1616.
9. Späh, M. M. and Gibbs, B. M. (2009). Reception plate method for characterisation of structure-borne sound sources in buildings: Assumptions and application. Applied Acoustics, 70, 361-368.
10. Reinhold, S., Hopkins, C. and Zeitler, B. (2017). Numerical simulation of a laboratory reception plate using finite elements. Proceedings of the 43rd Annual Conference on Acoustics (DAGA), Kiel, Germany, 525-528.
11. Reinhold, S., Hopkins, C. and Zeitler, B. (2017). Low-frequency structure-borne sound power measurements using heavyweight reception plates. Proceedings of the 24th Congress on Sound and Vibration (ICSV24), London, UK, 1-8.
12. Lyon, R. H. (1975). Statistical energy analysis of dynamical systems: Theory and applications. Cambridge: MIT Press, ISBN 0-262-12071-2.
13. Hopkins, C. (2007). Sound Insulation. Butterworth-Heinemann, ISBN 978-0-7506-6526-1.