AN INVERSE FORM OF TRANSIENT STATISTICAL ENERGY ANALYSIS TO DETERMINE THE TRANSIENT POWER INPUT WITH FLOATING FLOOR SYSTEMS

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Transient Statistical Energy Analysis (TSEA) can be used to predict Fast time-weighted maximum sound pressure levels in rooms due to soft/heavy impacts on heavyweight floors. This requires knowledge of the transient power input into the floor. For excitation with the ISO rubber ball the blocked force can be measured using a force plate in order to calculate the power input. However, this is not possible when there is a floating floor on top of the base floor. For this reason there is a need for a new approach to measure the transient power input into a base floor when the impact is applied to the floating floor. In this paper the approach considered is an inverse form of TSEA (ITSEA) on a concrete base floor. Locally-reacting mass-spring systems were used as idealizations of a floating floor that were sufficiently compact to be measured on a force plate. This allowed comparisons of the transient power input from the force plate and ITSEA. Without a mass-spring system, the average difference between the normalised transient power input from ITSEA and the force plate was 1.3dB. In general, the errors with and without a locally reacting mass-spring system will tend to cancel out below 160Hz when calculating the change in transient power input due to a floating floor.

Keywords: TSEA, impact sound insulation, rubber ball

1. Introduction

The assessment of impact sound insulation due to heavy impacts (e.g. ISO rubber ball) on floors in buildings is described in International, Japanese and Korean standards [1,2,3,4]. These require measurement of the Fast time-weighted maximum sound pressure level, $L_{p,Fmax}$ in the room underneath the excited floor. To allow prediction of $L_{p,Fmax}$ from transient excitation in heavyweight buildings, Robinson and Hopkins have shown that Transient Statistical Energy Analysis (TSEA) can be used to predict the combination of direct and flanking transmission [5,6]. More recent work shows that TSEA can be used to predict $L_{p,Fmax}$ in a room due to excitation of a concrete floor by the rubber ball and human footsteps [7]. TSEA models require a transient power input from the excitation source. For the rubber ball and human footsteps, this power input can be calculated from the measured blocked force and the driving-point mobility of the receiver structure.

To extend the application of TSEA to real heavyweight buildings it is necessary to include the effect of floating floors. Hirakawa *et al* recently carried out experimental work with excitation from a rubber ball to investigate idealised floating floors formed from a steel plate on different resilient materials to represent a locally reacting mass-spring system [8]. With and without a mass-spring system, $L_{v,Fmax}$ (velocity) measurements on a concrete base floor and $L_{p,Fmax}$ measurements in a receiving room indicated that the change in transient power determined from force plate measurements and the change in $L_{v,Fmax}$ or $L_{p,Fmax}$ were only similar when the resilient material in the mass-spring system was dynamically stiff.

For practical purposes it will be necessary to predict sound insulation with TSEA for a wide range of floating floors, most of which are unlikely to be locally reacting, and complex to model. For this reason it would be beneficial to be able to use laboratory experiments to quantify the transient power input into a full-size concrete base floor when the impact from the rubber ball is applied to the base floor, and to the base floor with a full-size floating floor. The difference between these values would give a correction factor for a specific floating floor that could be applied to the predicted transient power input for the base floor in the field situation. As the use of TSEA has already been validated for heavyweight structures this paper proposes use of experimental data as input into an inverse form of TSEA (ITSEA). The feasibility of using ITSEA is assessed for the rubber ball dropped onto the concrete base floor and the locally reacting mass-spring systems.

2. Theory: Transient forms of SEA

2.1 TSEA

TSEA predicts a time-varying, spatial average mean-square energy in each frequency band using a defined power input and loss factors. The theory to solve the power balance equations in the time domain is described by Powell and Quartararo [9] and Lyon and Dejong [10].

The time-dependent power balance is given in Eq. (1) where the first bracketed term on the right-hand side is the power gain term, and the second is the power loss term,

$$\frac{\mathrm{d}E_i(t)}{\mathrm{d}t} = \left(W'_{\mathrm{in},i}(t) + \sum_{j(j\neq i)} \omega\eta_{ji}E_j(t) \right) - \left(\omega\eta_{ii}E_i(t) + \sum_{i(i\neq j)} \omega\eta_{ij}E_i(t) \right) \tag{1}$$

where η_{ij} is the coupling loss factor from subsystem i to subsystem j, η_{ii} is the internal loss factor of subsystem i, E_i is the energy in subsystem i, and $W'_{\mathrm{in,i}}$ is the transient power input into subsystem i.

The accuracy of the solution depends on the size of Δt for which the lower and upper limits for the time interval give the preferred range as [5,10]

$$\frac{1}{b\omega\eta_i} \leq \Delta t \geq \frac{d_{\mathrm{mfp}}}{2c_{\mathrm{g}}} \tag{2}$$

where b is an integer constant for which Hopkins and Robinson have shown that for the prediction of maximum time-weighted levels, the optimum value will typically fall in the range $3\leq b \leq 43$.

Power input from the transient excitation is injected to the source subsystem over one or more time steps such that the injection time period approximately equals the actual duration of the transient.

For numerical implementation, Eq. (1) can be rewritten to calculate the energy in time step $t_{\mathrm{n+1}}$ from the energy in time step t_{n} using

$$E(t_{n+1}) = E(t_n) + \Delta t \left[\left(W'_{\mathrm{in}}(t_n) + \sum_{j(j\neq i)} \omega\eta_{ji}E_j(t_n) \right) - \left(\omega\eta_{ii}E_i(t) + \sum_{i(i\neq j)} \omega\eta_{ij}E_i(t_n) \right) \right] \tag{3}$$

The power loss term in Eq. (3) can be simplified by making it a function of the total loss factor, η_i, for subsystem i as

$$E_{\mathrm{i}}(t_{n+1}) = E_i(t_n) + \Delta t \left(W'_{\mathrm{in}}(t_n) + \sum_{j(j\neq i)} \omega\eta_{ji}E_j(t_n) - \omega\eta_i E_i(t_n) \right) \tag{4}$$

A force plate can be used to measure the rms force, F_{rms}, from a rubber ball impact from which the normalised transient power input can be calculated using the real part of the driving-point mobility of the source subsystem, $\mathrm{Re}\{Y_{\mathrm{dp}}\}$, where

$$W'_{\mathrm{in,Force\ Plate}} = W'_{\mathrm{in}} = \frac{t_{\mathrm{w}}}{t_{\mathrm{F}}} F^2_{\mathrm{rms}} \mathrm{Re}\{Y_{\mathrm{dp}}\} \tag{5}$$

where t_{w} is the FFT window length and t_{F} is the duration of the transient force [5].

2.2 Inverse form of TSEA (ITSEA)

The aim with ITSEA is to estimate the transient power input from the time-varying, mean-square energy in each frequency band on a source subsystem that is excited by a transient source (i.e. rubber ball).

Numerical experiments are initially used to assess whether ITSEA is feasible. Input data is taken from a TSEA model of a 140mm concrete floor, firstly in isolation such that there is a one-subsystem TSEA model and secondly when this floor is connected to walls on all four sides to give a 14-subsystem TSEA model [6,7]. The time-varying, mean-square energy in the 50Hz, 250Hz and 500Hz one-third octave bands for these two TSEA models is shown in Fig. 1 where the transient excitation corresponds to an 18.8ms pulse applied by a rubber ball drop [7,8]. During the exponential growth in energy the two TSEA models are nominally identical (i.e. values within 2.3% which corresponds to a 0.1dB difference) up to 18.8ms for 50Hz (exactly the same as the transient power duration), up to 8.3ms for 250Hz and up to 6.1ms for 500Hz. The peak occurs at 18.8ms for both TSEA models which corresponds to the transient power duration. The peak value is higher with the 14-subsystem model than the single subsystem model by a factor of 1.025 at 50Hz (corresponding to a 0.1dB difference), a factor of 1.11 (corresponding to a 0.5dB difference) at 250Hz and a factor of 1.18 (corresponding to a 0.7dB difference) at 500Hz. This is because energy returns to the source subsystem from the other 13 subsystems that make up the 14-subsystem model. The subsequent decays from the two TSEA models also differ because energy returns to the source subsystem with the 14-subsystem model.

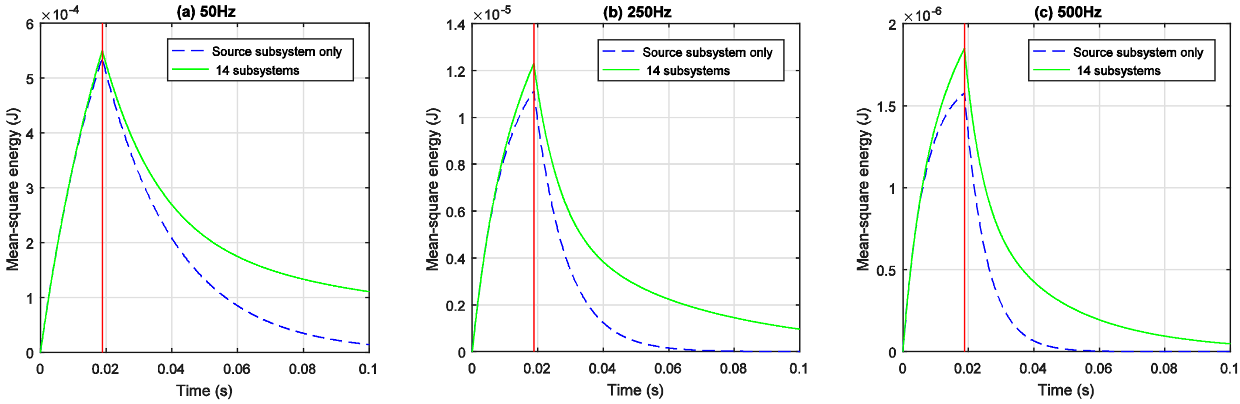

Figure 1. TSEA prediction of the time-varying, mean-square energy in the (a) 50Hz, (b) 250Hz and (c) 500Hz one-third octave bands for a one-subsystem model and a 14-subsystem model.

The above assessment leads to the conclusion that if it is possible to identify the time, t_{peak}, at which the peak occurs in the time-varying, mean-square energy, then it should be feasible to sum the mean-square energy between 0ms and t_{peak} to estimate the transient power. However, when the base concrete floor is coupled to other walls and floors there will be (relatively small) errors in the peak value. Note that the effect of energy returning from the room(s) to the excited floor can affect the decays in structural reverberation time measurements but the peak tends to be unaffected [11].

Following from Eq. (4) for TSEA the transient power input into source subsystem i can be estimated with ITSEA using

$$W_{\text{in},i} = \frac{1}{N}\sum_{n=1}^{N}\frac{\left(E_i(t_{n+1}) - E_i(t_n)\right)}{\Delta t} - \left(\sum_{j\neq i}\omega\eta_{ji}E_j(t_n) - \omega\eta_i E_i(t_n)\right) \quad (6)$$

where N is the integer number of time steps between 0ms and t_{peak}.

To quantify the transient power input to be injected into a TSEA model during the period of applied force, the transient power input obtained from Eq. (6) needs to be normalised using

$$W'_{\text{in,ITSEA}} = \frac{t_{\text{peak}}}{t_{\text{input\_duration}}} W_{in,i} \quad (7)$$

where $t_{\text{input\_duration}}$ is the actual duration of the force pulse (for a heavyweight floor this can be determined from force plate measurements, but this will only be approximate when the rubber ball excites the rigid walking surface of a lightweight floating floor).

Use of Eq. (6) requires (a) the time-varying, mean-square energy on the source subsystem and all subsystems directly connected to the source subsystem, (b) all the CLFs that directly transfer energy from other subsystems to the source subsystem, and (c) the TLF of the source subsystem. In practice, it is possible to measure the CLFs and the TLF [12] but their inclusion in Eq. (6) is likely to increase the uncertainty. In addition, it is experimentally demanding to measure time-varying, mean-square energy on the source subsystem and all the subsystems that are directly connected to it. Therefore, for practical purposes it is simpler if ITSEA only considers the source subsystem, this would allow Eq. (6) to be simplified to

$$W_{\text{in},i} \approx \frac{1}{N}\sum_{n=1}^{N}\left[\frac{\left(E_i(t_{n+1}) - E_i(t_n)\right)}{\Delta t} + \omega\eta_i E_i(t_n)\right] \quad (8)$$

To assess the errors involved in using Eq. (8) the two TSEA models considered earlier in this section are used to determine the difference between the actual transient power input used in TSEA and the transient power input determined using ITSEA with Eq. (8); see Fig. 2. This shows that the error is 0dB for a one-subsystem model and <0.7dB for the 14-subsystem model. Hence if it was possible to have a laboratory with a suspended concrete floor base, or one that rested upon resilient materials that isolated it from the rest of the structure, then that would effectively represent the one subsystem case where errors should be negligible. In practice, concrete floors are likely to be rigidly connected to walls in order to provide structural stability and to provide TLFs that are representative of the field situation. Fortunately, below 500Hz the 14-subsystem model indicates that the error is <0.5dB which is negligible.

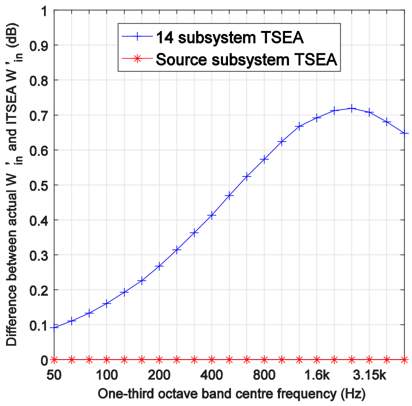

Figure 2. Difference between the transient power used in TSEA and the values calculated using ITSEA using TSEA as input data.

2.3 Experimental implementation

As with SEA and TSEA, ITSEA considers the spatial-average response of each subsystem and therefore $W'_{\text{in, ITSEA}}$ can be determined with Eq. (8) from the time-varying, mean-square energy derived from a single accelerometer, and then values from multiple accelerometer positions can then be averaged to give the final estimate of $W'_{\text{in, ITSEA}}$. Experimental implementation of ITSEA also requires that the one-third octave or octave band filters used to measure the time-varying mean-square energy do not significantly affect the exponential growth and the peak value. This will be assessed with the experimental work in the remainder of the paper.

The measured instantaneous acceleration is integrated to give instantaneous velocity using a 1st order Butterworth high-pass filter which is equivalent to an analogue integrator found in a charge amplifier [13]. This is squared and then divided by two to convert to instantaneous mean-square velocity. This signal is then passed though one-third octave band filters.

Unlike the smooth TSEA curve of energy vs time that was shown in Fig. 1, the resulting instantaneous mean-square velocity from measurements has many fluctuations with zero-value points; see example in Fig. 3a. This is problematic with Eq. (8) because the energy gradient with time needs to be positive. For this reason, the local maxima of the instantaneous mean-square velocity are selected and linear interpolation is carried out between them to give an envelope curve as shown in Fig. 3b. This approach is reasonable because the measurement comes from a real floor with a spatially-varying vibration field for which the response is specific to the floor geometry, excitation position and accelerometer position, but the aim is to determine the spatial-average response of a plate subsystem with arbitrary geometry and arbitrary excitation position. Fig. 3a indicates that the zero values in the instantaneous mean-square velocity differ for the two accelerometer positions. Therefore, if the boundaries of the floor were altered (but the floor area remained the same) then the peaks and troughs shift in time. Hence it is reasonable to use the envelope so that the results are more applicable to a subsystem of arbitrary geometry but similar area and perimeter.

The instantaneous mean-square velocity is converted to mean-square energy by multiplying by the mass of the concrete slab.

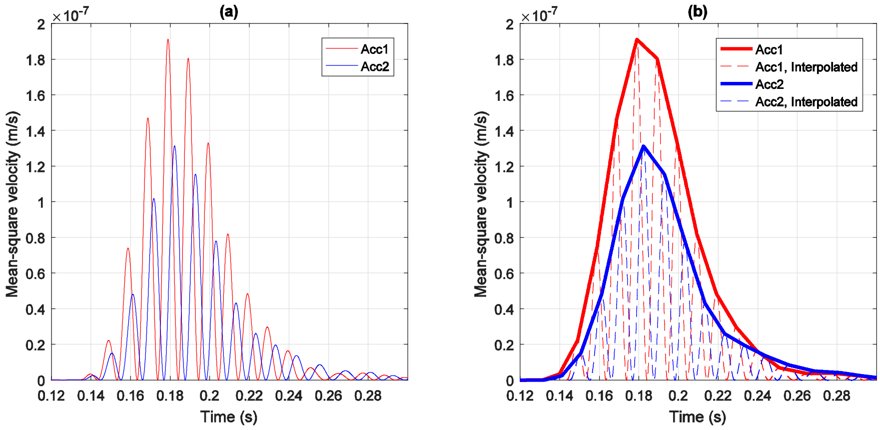

Figure 3. (a) Instantaneous mean-square velocity from measurements using two accelerometers at different points on a concrete floor, (b) Same signals as (a) but with linear interpolation to give the envelope curves.

3. Experimental validation

3.1 Transmission suite measurements

Measurements used to assess ITSEA were carried out in a vertical transmission suite with a concrete floor at BRE (Watford, UK) that was used for previous validations of TSEA [5,6,7]. The floor was a 140mm concrete slab which was excited by the rubber ball with and without five different locally reacting mass-spring systems. Five different excitation positions were used on the concrete floor slab with two accelerometers (B&K Type 4371) fixed to the floor at random positions for each excitation position. Time recordings were carried out using a B&K Time Data Recorder.

3.2 Force plate measurements

The force plate is constructed from a base plate of 35mm thick circular steel with a 175mm radius (26.4kg) and an upper plate of 15.2mm thick circular aluminium with a 110mm radius (1.5kg) as indicated in Fig 3. The force is measured by summing the output from three Kistler 9041A force transducers that are bolted between the plates. The force-time spectrum was measured using the B&K PULSE Labshop system with a time resolution of 61.04μs and a frequency resolution of 1Hz.

The force plate was used to measure the mean-square force with (a) a rubber ball impact from a drop height of 1m and (b) the same rubber ball impact on top of the mass-spring system (see Fig. 3).

The transient power input was calculated using Eq. (6) for each excitation position using the measured driving-point mobility of the concrete floor at that position. The transient power inputs from all excitation positions were then averaged to give a spatial-average value for comparison with ITSEA.

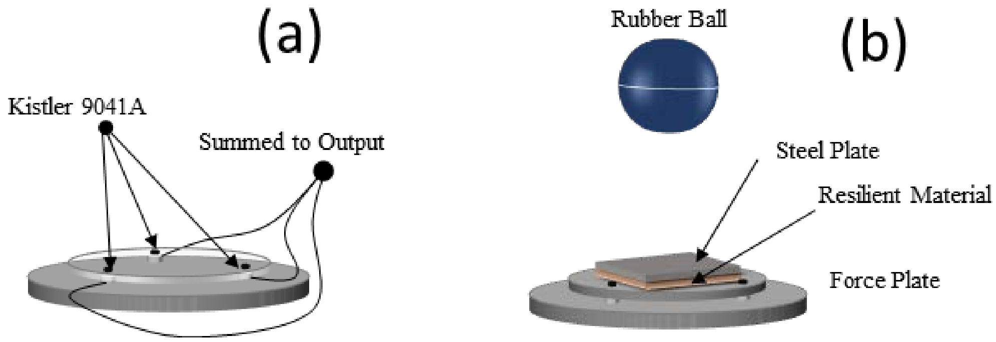

Figure 4. Force plate showing (a) force washers and (b) supporting the locally-reacting mass-spring system.

3.3 Locally-reacting mass-spring systems

Five locally reacting mass-spring systems are formed from a 20mm thick steel plate (200mm x 200mm) on five different resilient materials. The dynamic stiffness of these resilient materials is determined using the general approach described in ISO 29052-1 [14] but using a force hammer to apply a peak force of 1500N±50N that is similar to the peak force applied by the rubber ball [8]. The internal loss factor of the resilient material is determined from the 3dB down points of the magnitude of the driving-point mobility measured to determine the dynamic stiffness. The properties of the resilient materials are given in Table 1.

Table 1: List of the resilient materials used in the experiment

Sample (Resilient Material)	Sample thickness (mm)	Dynamic stiffness per unit area (MN/m^3)	Internal Loss Factor (-)	Mass-spring resonance frequency (Hz)
A (Recycled Foam)	15	5.5	0.27	30
B (Yellow Sylomer)	15	25.1	0.47	64
C (Green Sylomer)	15	32.6	0.32	73
D (EVA*)	20	41.2	0.61	82
E (EVA*)	25	89.6	0.55	121
*EVA is Ethylene-Vinyl Acetate				

4. Results

4.1 Rubber ball excitation of concrete slab

Results for the rubber ball directly on the concrete floor are shown on Figure 5. Measurements were possible up to 500Hz because above this frequency they were affected by background noise. The average difference is 0.4dB with the largest absolute difference being 3dB. Numerical experiments in Section 2.2 using TSEA models indicated that for a concrete slab connected to heavyweight walls ITSEA could overestimate the transient power input due to energy returning from these walls. The results here indicate that, on average, the error is acceptable.

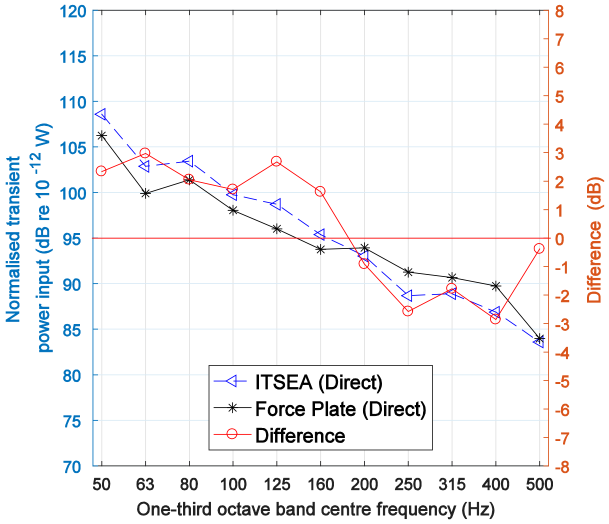

Figure 5. Comparison of the transient power input for the ISO rubber ball exciting a 140mm concrete base floor determined from ITSEA and the force plate.

4.2 Rubber ball excitation of mass-spring systems on the concrete slab

With the locally-reacting mass-spring systems, the maximum measurable frequency depends on to the effectiveness of each mass-spring system. Figure 6 allows comparison of the transient power inputs from ITSEA and the force plate. For all five mass-spring systems, $W'_{\mathrm{in,ITSEA}}$ gives slightly higher estimates than $W'_{\mathrm{in,Force\ Plate}}$. The average differences between the transient power input from ITSEA and the force plate are -0.8, 1.9, 3.6, 2.9 and 2.7dB for mass-spring systems A, B, C, D, and E respectively. In general, the error for the mass-spring system is positive between 50 and 160Hz which is similar to the positive error for the rubber ball directly on the base floor (Fig. 5); therefore by calculating the difference between the transient power inputs with and without a mass-spring system the errors will tend to cancel below 160Hz.

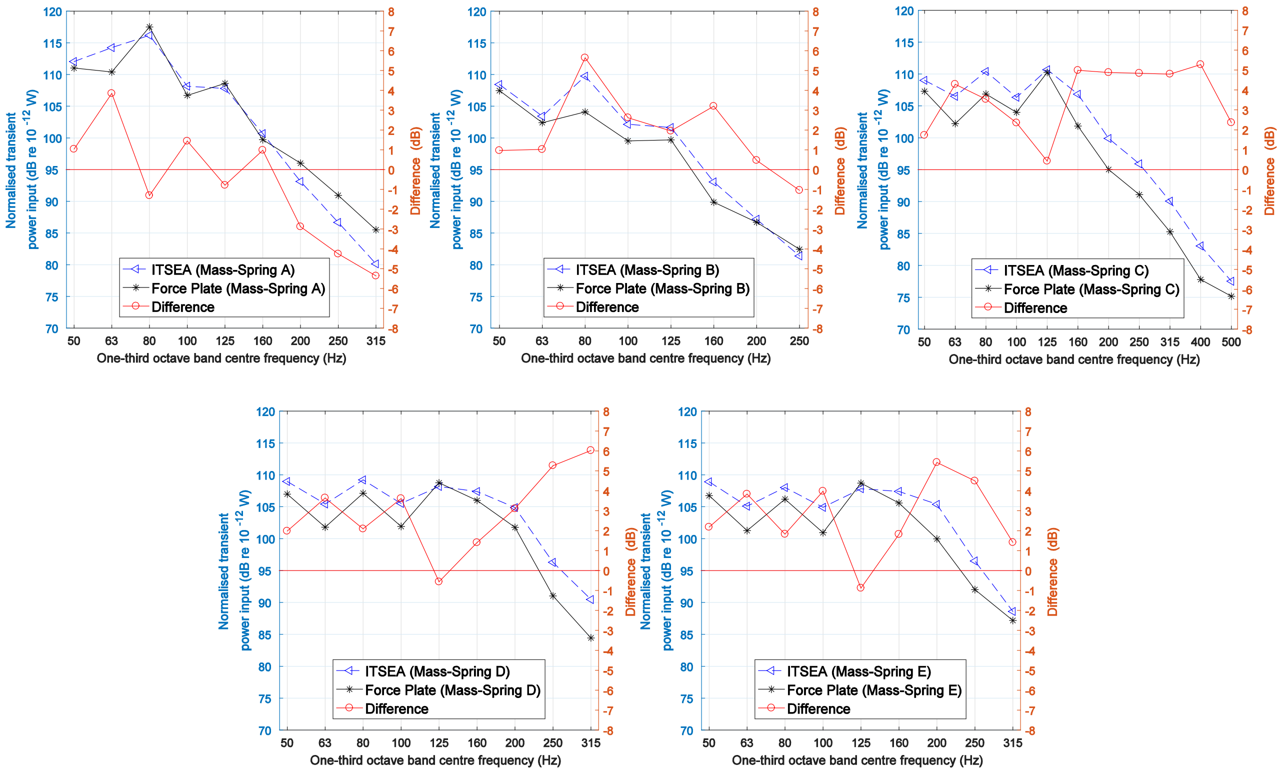

Figure 6. ISO rubber ball exciting locally reacting mass-spring system A (top left), B (top centre) and C (top right), D (bottom left), E (bottom right).

5. Conclusions

This paper compares the prediction of the normalised transient power input using ITSEA with measurements using a force plate to provide input data for TSEA models. The aim was to assess whether it might be possible to calculate the change in the transient power injected by the ISO rubber ball into a heavyweight floor due to the addition of a floating floor. Full-scale measurements were carried out on a concrete floor with and without five different locally reacting mass-spring systems. Without a mass-spring system, the average difference between the normalised transient power input from ITSEA and the force plate was 1.3dB. Below 160Hz, the errors with and without a locally reacting mass-spring system will tend to cancel out when calculating the change in transient power input due to a floating floor.

The next stage is to use ITSEA to quantify the transient power input with full-size floating floors on a concrete base floor, and use this as input data in a TSEA model to predict the Fast time-weighted maximum sound pressure levels in the receiving room.

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