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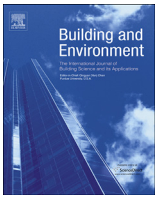

Prediction of maximum fast time-weighted sound pressure levels due to transient excitation from the rubber ball and human footsteps

M. Robinson, C. Hopkins*

Acoustics Research Unit, School of Architecture, University of Liverpool, Liverpool, L69 7ZN, UK

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ABSTRACT

This paper primarily concerns the use of Transient Statistical Energy Analysis (TSEA) to predict impact sounds in heavyweight buildings in terms of the maximum Fast time-weighted sound pressure level using transient sources of mechanical excitation that have complex force time-histories. The sources considered were the rubber ball that is used to measure heavy/soft impacts in buildings, and human footsteps with three different kinds of footwear. A force plate was used to measure the blocked force from these sources in order to calculate a hybrid transient power for input into the TSEA model. TSEA predictions were validated against measurements in a heavyweight building where each of the sources in turn were used to excite a 140 mm concrete floor. Close agreement was observed between measurements and TSEA predictions of maximum Fast time-weighted velocity levels on the concrete floor and a connected masonry flanking wall, as well as the maximum Fast time-weighted sound pressure level in the room below the floor. This confirmed the following: (a) correct implementation of transient power from the measured force time-history in the TSEA model, (b) correct modelling of structure-borne sound transmission between the concrete floor and the masonry wall which confirms that the TSEA model has the potential to include flanking transmission and (c) correct radiation coupling between the concrete floor and the room.

1. Introduction

At the design stage for a building it is important to be able to predict sound transmission from transient sources such as footsteps on floors in order to be able to assess human response in terms of annoyance and the potential for sleep disturbance. Previous work by the authors [1,2] introduced a general framework using Transient Statistical Energy Analysis (TSEA) to determine time-weighted sound and vibration levels in built-up structures due to mechanical excitation by transients. The validations in this work used a single impact from a force hammer which produced a relatively simple force time-history [2]. This paper develops an approach using TSEA to predict sound transmission in heavyweight buildings with realistic transient sources that are of practical importance, but which are significantly more complex in terms of their force time-history. These sources are the rubber ball [3] which is used in National and International test standards to measure the impact sound insulation from heavy impacts, and human footsteps which are the most commonly reported type of structure-borne sound that are heard by complainants in studies about the poor sound insulation of floors [4].

The rubber ball is a heavy/soft impact source for floors that provides repeatable excitation and applies a large force similar to that applied by a child jumping or from footsteps in bare feet [5]. It is incorporated in the Japanese standard JIS A 1418-2 [6], Korean standard KS F 2810-2 [7] and the International standard ISO 10140-3 [8] for the measurement of impact sound insulation. All three standards require measurement of Fast time-weighted maximum sound pressure levels in one-third octave or octave bands. It has been shown that people in heavyweight buildings judge real impact sources to be similar to the rubber ball and that the measured data in frequency bands can be combined into a single-number quantity that shows good correlation with subjective evaluation of impact sound [9,10].

To gain insight into the dynamics of the rubber ball, Park et al. [11] examined its deformation upon impact and measured its modal response which allowed prediction of the main features in the impact force spectrum. Schoenwald et al. [12] used a simplified analytical model to calculate the force that was applied by the

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* Corresponding author.
E-mail address: carl.hopkins@liverpool.ac.uk (C. Hopkins).

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rubber ball when impacting a rigid surface. Comparison with measurements indicated that the rubber ball was a significantly more complex source than the analytical model of a hollow spherical shell. There was a lack of agreement in the predicted force spectrum above the 63 Hz octave band which could be attributed to the fact that the analytical model takes no account of the modal response of the ball. Fortunately, for the purpose of the prediction model in this paper, the force applied by the rubber ball can be measured. This means that there is no need to rely on a model to calculate the applied force for heavyweight floor structures because the force effectively represents a blocked force.

To predict maximum Fast time-weighted sound pressure levels in octave bands from heavy impacts using the bang machine on a concrete floor, Kimura and Inoue [13] developed an impedance model. This approach considers the blocked force that is applied to the concrete floor, the impedance of the floor itself, and direct sound radiation from the floor into the room; hence flanking transmission is not considered. In addition, it uses empirical correction factors to estimate Fast time-weighted maximum levels from the steady-state levels predicted by the model. Koga et al. [14] noted that this impedance model was not validated with large-span concrete slabs and proposed that the terms relating to the effective radiating area of the floor and the absorption area in the room were not needed. Koga [15] proposed two further developments to the model which were validated against measurements with the rubber ball as well as the bang machine. The first development was to specifically include the decay constants of the floor vibration, sound field and the Fast time-weighting. The second development was to increase the flexibility of the model to deal with irregular-shaped floors by incorporating impedance values predicted from finite element models. Okano and Koyanagi [16] noted that when using the impedance model for the bang machine on a concrete floor there were often errors of 5–10 dB in the 63 Hz octave band. The accuracy of the prediction was improved by accounting for the rapid change in the force spectrum between the lower and upper band edge frequencies of the 63 Hz band, and by using transfer impedances for the floor that were determined using finite element methods.

The authors are unaware of any other prediction models that have been developed and validated for the entire building acoustics frequency range (50 Hz to 5 kHz) for heavyweight buildings that can (a) calculate maximum Fast time-weighted sound pressure levels from mean-square time signals, (b) include the combination of both direct and flanking transmission, and (c) incorporate excitation from the rubber ball and human footsteps; all these aspects are addressed in this paper by using TSEA.

2. TSEA prediction using measured force inputs

TSEA predicts a time-varying, spatial-average mean-square energy in a given frequency band for a set of SEA subsystems using a defined power input and loss factors. The power balance equations in the time domain are given by Powell and Quartararo [17] and Lyon and DeJong [18].

$$E_i(t_{n+1}) = E_i(t_n) + \Delta t \left[W_{\mathrm{in},i}(t_n) + \omega \left[\sum_{j(j \neq i)} \eta_{ji} E_j(t_n) - \eta_i E_i(t_n) \right] \right] \tag{1}$$

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, $W_{\mathrm{in},i}(t_n)$ is the time-varying power input into subsystem i, Δt is the time interval, η_{ij} is the coupling loss factor from subsystem i to subsystem j and η_i is the total loss factor of subsystem i.

Equation (1) is used to calculate a set of time-varying subsystem energies in a given frequency band through an iterative calculation of energy in each successive time step. After calculating the energy at each time step over a chosen duration for all subsystems and a desired frequency range, energy can be converted into mean-square pressure for spaces, or mean-square velocity for structures [1]. The result is a time-varying level in each frequency band, from which the maximum level is determined.

An alternative to the forward Euler finite difference approach described by Equation (1) has recently been proposed by Guasch and García [19] that uses a local time-stepping algorithm. Taking an example where a transient is applied to a wall in a heavyweight building, Guasch and García show that whilst the peak in the energy is correctly predicted with the finite difference approach, instabilities sometimes occur at high frequencies and that this can be avoided by using a local time-stepping algorithm. However, with the model and frequency range used in this paper such instabilities do not occur; hence all calculations use the forward Euler finite difference approach.

The choice of time interval, Δt, is based upon two factors [1]. The first factor is the rate at which energy decays in a single subsystem. As the time interval increases, the response will be ‘smeared’ in the time domain. As a result the energy in subsequent time steps will become increasingly inaccurate. Limiting the maximum value of the time interval ensures that large changes in the energy response will not occur between successive time steps. The second factor uses path statistics to consider the time for energy transfer from the point of excitation to a boundary of the physical subsystem. This gives a lower limit for the time interval because subsystems cannot be considered coupled in a statistical sense that is relevant to SEA if energy from the excitation has not yet reached the boundary along which the two subsystems are coupled. By adhering to this lower limit, the use of steady-state SEA coupling loss factors is appropriate. A time interval can then be identified that satisfies the upper and lower limits.

2.1. Evaluation of maximum velocity levels on highly damped source plates

When validating the TSEA model, the first step is to compare the measured and predicted maximum velocity level on the source plate. However, on a highly-damped structural subsystem which is undergoing excitation, the measured maximum velocity level can be due to the direct field component rather than the reverberant field component. An issue arises because it is only the latter that is being predicted by the TSEA model. For this reason, evaluation of the maximum level should only begin once sufficient time has elapsed to allow the bending wave to travel from the excitation position to a plate boundary and back into the central area of the plate where the reverberant vibration field is sampled in the measurement. For rectangular walls and floors, Robinson and Hopkins [1,2] have shown that the source-to-boundary-to-receiver distance is adequately described by the analytical solution for the mean free path. Hence the bending wave group speed can be used to calculate the time taken to travel the mean free path. Another issue is the inherent time delay in the response of constant-percentage bandwidth filters [20]. Therefore the start point for evaluation of the time-weighted level detector output needs to be shifted to account for the time it takes for a wave to travel the average source-to-boundary-to-receiver path distance plus the filter time delay. For typical heavyweight walls and floors using measurements with one-third octave band filters, the filter delay tends to be the more significant time delay below 1 kHz. This modification to the measurement signal ensures that the maximum velocity level is compatible with that predicted by TSEA. This is