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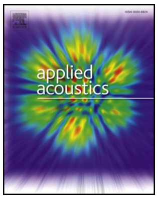

Experimental determination of transient structure-borne sound power from heavy impact sources on heavyweight floors with floating floors using an inverse form of transient statistical energy analysis

Susumu Hirakawa, Carl Hopkins*

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

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ABSTRACT

For heavy impacts on floors in heavyweight buildings, prediction models are needed at the design stage to estimate the spatial-average Fast time-weighted maximum sound pressure level in the receiving room. This paper extends previous work using Transient Statistical Energy Analysis (TSEA) in heavyweight buildings by introducing an inverse form of TSEA (ITSEA) to determine the transient structure-borne sound power input from heavy impact sources into a heavyweight base floor with a floating floor. The difference in the power input with and without a floating floor gives a correction factor that can be used to modify the power input into the base floor. This allows the effect of the floating floor to be incorporated in a TSEA model of a heavyweight building. ITSEA is initially validated with heavy impacts from a rubber ball directly onto a concrete base floor and with small, locally reacting, mass-spring systems. Laboratory experiments are then used to quantify the transient structure-borne sound power input into a full-size concrete base floor when a heavy impact is applied to the base floor, and to the base floor with a full-size Ondol floating floor. The resulting TSEA model shows close agreement with the predicted change in the Fast time-weighted maximum sound pressure level due to the floating floor.

1. Introduction

The measurement of impact sound insulation in buildings due to heavy impacts on floors is described in International, Japanese and Korean standards [1–4] which use standardized excitation sources such as a rubber ball or bang machine. These standards require measurement of the Fast time-weighted maximum sound pressure level, $L_{\mathrm{p,Fmax}}$ in the room underneath the floor that is excited by the heavy impact.

Experimental work (e.g. see [5,6]) has previously quantified the time-dependent force from the rubber ball and/or bang machine. However, there are very few models available to predict Fast time-weighted maximum sound pressure levels due to these heavy impact sources. Kimura and Inoue [7] developed an approach to predict the impact sound insulation in heavyweight buildings due to excitation with the bang machine. This used an impedance model to predict direct sound radiation from the floor to the receiving room by using an empirical correction factor to estimate the Fast time-weighted maximum level from the predicted steady-state level. Koga et al. [8] subsequently proposed that the terms relating to the effective radiating area of the floor and the absorption area in the room were not needed, although later work has quantified the effect of the reverberation time in the receiving room on the impact sound pressure level that is measured with heavy impact sources [9]. Koga [10] further developed the model to include decay constants of the floor vibration, sound field and the Fast time-weighting. Koga also incorporated impedance values that were predicted from finite element models to model different floor shapes and boundary conditions. Okano and Koyanagi [11] noted that when using the impedance model for the bang machine on a concrete floor there were often errors of 5 to 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. However, the impedance model does not account for flanking transmission and is limited to direct transmission. To allow prediction of $L_{\mathrm{p,Fmax}}$ from any form of transient excitation in heavyweight buildings, Robinson and Hopkins [12,13] showed that Transient Statistical Energy Analysis (TSEA) can be used to predict this parameter from the combination of direct and flanking paths. They subsequently showed that TSEA can be used to predict $L_{\mathrm{p,Fmax}}$ due to excitation of a concrete base floor that is directly excited by the rubber ball or human footsteps [14]. However, there will usually be a floating floor on top of this base floor to provide

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

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insulation against light impacts such as footsteps from walkers in shoes, as well as heavy impacts such as from children running or jumping. For this reason it is necessary to identify and experimentally validate a new approach to incorporate floating floors in TSEA models of heavyweight buildings, and this is the focus of this paper.

TSEA models require a transient power input from the excitation source. This can be calculated by using a force plate to measure the blocked force from the rubber ball, bang machine or human footsteps along with knowledge of the driving-point mobility of the receiver structure (e.g. base floor) [7]. However, the size of the force plate means that this experimental approach is not feasible for a large floating floor with a rigid walking surface that is undergoing wave motion due to the excitation. Assuming the surface of the floating floor has a low mobility relative to the mobility of the heavy impact source, one possibility could be to predict the dynamic behaviour of the floating floor to predict the improvement in impact sound insulation. While models exist for a floating floor comprising a rigid walking surface and resilient layer, they do not accurately predict the decrease in the impact sound insulation near the mass-spring resonance frequency of the floating floor and would not account for any non-linear response caused by heavy impacts [15]. Modern buildings incorporate floating floors with multiple rigid or resilient layers (as well as heating pipe systems) and the walking surface often has a similar or higher mobility than the impact source; hence, it is not feasible to rely on current prediction models for the range of floating floors that are built in practice. To facilitate the inclusion of floating floors in TSEA models, this paper proposes an inverse form of TSEA (ITSEA) to experimentally determine the transient power input for the combination of the heavy impact source and floor, and the combination of the heavy impact source, floating floor and floor.

In this paper, the validation of ITSEA is initially carried out with heavy impacts from a rubber ball onto small, locally reacting, mass-spring systems on a full-size concrete base floor. These represent highly idealised versions of floating floor systems which are sufficiently small that they fit on top of a force plate in order to measure the blocked force. Laboratory experiments are then used to quantify the transient structure-borne sound power input into a full-size concrete base floor when a heavy impact is applied to the base floor, and to the same base floor with a full-size floating floor. The difference between these values gives a correction factor for a specific floating floor that can be applied to the predicted transient power input for the base floor when using TSEA to predict the impact sound insulation; this approach is also validated with a full-size floating floor on a base floor.

2. Theory

2.1. Transient statistical energy analysis

Transient Statistical Energy Analysis can be used to predict time-varying, spatial average, mean-square energy in frequency bands from a given power input and loss factors. The approach is essentially a time domain version of Statistical Energy Analysis (SEA) which solves the power balance equations in short time intervals as described by Powell and Quartararo [16] and Lyon and DeJong [17]. The forward difference approach is used to determine energy at a specific time step by using the energy calculated at the previous time step. For any subsystem i, the time-dependent power balance is given in Eq. (1) by the difference between the power lost and the power gained,

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

where η_{ij} is the coupling loss factor (CLF) from subsystem i to subsystem j, η_{ii} is the internal loss factor (ILF) of subsystem i, E_i is the energy in subsystem i, and $W'_{\mathrm{in},i}$ is the normalised transient power input into subsystem i which is applied over the duration of the transient input force [5].

Power input from the transient excitation is injected to the source subsystem over one or more time intervals such that the time period over which the injection occurs is approximately equal to 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

$$E_i(t_{n+1})=E_i(t_n)+\Delta t\left[\left(W'_{\mathrm{in},i}(t_n)+\sum_{j(j\neq i)}\omega\eta_{ji}E_j(t_n)\right)-\left(\omega\eta_{ii}E_i(t)+\sum_{i(i\neq j)}\omega\eta_{ij}E_i(t_n)\right)\right]\tag{2}$$

where Δt is the time interval.

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

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

where η_i is the total loss factor of subsystem i.

The accuracy of the solution depends on the size of Δt for which the lower and upper limits can be estimated using the subsystem properties in the TSEA model as given by [5,10]

$$\frac{d_{\mathrm{mfp}}}{2c_{\mathrm{g}}}\leqslant\Delta t\leqslant\frac{1}{b\omega\eta}\tag{4}$$

where b is an integer constant for which the optimum value for the prediction of maximum time-weighted levels will typically fall in the range $3\leq b\leq 43$ [5], η is the total loss factor, d_{mfp} is the mean free path and c_{g} is the group velocity of bending waves into which the power is injected.

2.1.1. Proposal to incorporate floating floors in TSEA

Laboratory measurements with ITSEA are used to experimentally determine the normalised transient power input into the base floor for the heavy impact source on the base floor ($W'_{\mathrm{in,ITSEA,Base}}$) and on the combination of the floating floor and base floor ($W'_{\mathrm{in,ITSEA,Base\_with\_floating\_floor}}$) indicated in Fig. 1. The applicability of these laboratory measurements to the field requires that the

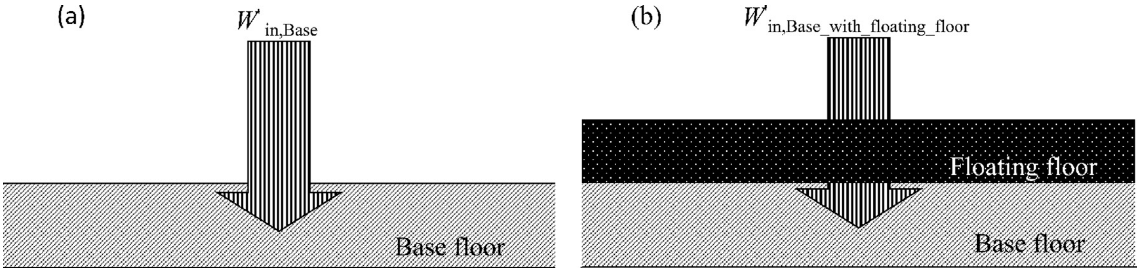

Fig. 1. Power injection into (a) the base floor and (b) the base floor when there is a floating floor.