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Fast mean and variance computation of the diffuse sound transmission through finite-sized thick and layered wall and floor systems

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A B S T R A C T

A method is developed for computing the mean and variance of the diffuse field sound transmission loss of finite-sized layered wall and floor systems that consist of solid, fluid and/or poroelastic layers. This is achieved by coupling a transfer matrix model of the wall or floor to statistical energy analysis subsystem models of the adjacent room volumes. The modal behavior of the wall is approximately accounted for by projecting the wall displacement onto a set of sinusoidal lateral basis functions. This hybrid modal transfer matrix-statistical energy analysis method is validated on multiple wall systems: a thin steel plate, a polymethyl methacrylate panel, a thick brick wall, a sandwich panel, a double-leaf wall with poro-elastic material in the cavity, and a double glazing. The predictions are compared with experimental data and with results obtained using alternative prediction methods such as the transfer matrix method with spatial windowing, the hybrid wave based-transfer matrix method, and the hybrid finite element-statistical energy analysis method. These comparisons confirm the prediction accuracy of the proposed method and the computational efficiency against the conventional hybrid finite element-statistical energy analysis method.

1. Introduction

Layered wall and floor systems are frequently applied in order to achieve a high thermal insulation and/or a high sound insulation with a relatively low weight. Examples are double walls with decoupled wall leafs, sandwich panels, floors with floating screeds, double and triple glazing, etc. At high frequencies, the airborne or impact sound transmission through such layered systems can be computed with high accuracy using the transfer matrix method (TMM) [1–3]. It is then assumed that the wall or floor is of infinite lateral extent and that the adjacent sound fields can be modeled statistically, as diffuse fields. This enables computing the ensemble mean of the diffuse sound transmission through each solid, fluid and/or poro-elastic layer analytically in the frequency-wavenumber domain.

However, the conventional TMM has two disadvantages. Firstly, the assumption of an infinite wall may lead to important prediction errors at low and medium frequencies. The influence of edge diffraction, which is important below the critical frequency, may be accounted for by spatial windowing [4,5], but then the numerical integration of the plane-wave transmission over all possible angles of incidence for obtaining the mean sound transmission loss results in a large computation time when implemented in a straightforward way. Different analytic revisions of the finite size correction attempt to reduce the computation time [6,7]. The assumption of similar lateral dimensions speeds up the calculations very significantly [8]. However, with spatial

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windowing the modal behavior of the wall is still neglected. An alternative has therefore been developed [9,10], in which the wall displacement is projected onto a set of sinusoidal lateral basis functions, such that the wall impedance at a given frequency and for a given lateral basis function (hence lateral wavenumber) can be computed using the TMM. This approach accounts approximately for modal wall behavior when the boundary conditions are simply supported: if the radiation impedance of the sound field to the chosen basis functions can be computed with high accuracy, then the results are accurate for thin plates as the mode shapes of the plate correspond to the imposed basis functions. For most thick and layered systems, sinusoidal lateral basis functions also result in accurate transmission loss predictions. The predictions will be less accurate if the damping is low and the stiffness's of the different layers differ strongly from each other, as in the case of double glazing or double walls without absorbent material in the cavity [9,10]. The approximate modal version of the TMM will be referred to as mTMM in the remainder of this article. As shown later in the present paper, the accuracy of the ensemble mean transmission loss predictions obtained with mTMM depends critically on the chosen method for approximating the modal sound radiation impedances.

A second disadvantage of conventional TMM concerns the diffuse field assumption in both the sending and receiving room. A diffuse sound model is a statistical model representing an ensemble of rooms that are identical except for wave scattering at the room boundaries or by objects within the room: this wave scattering is modeled statistically in a maximum entropy sense, i.e., the uncertainty induced by the wave scattering is maximized [11,12]. Only the ensemble mean of the sound transmission loss can be computed by the different variations of the TMM. Other statistics that are inherent to the diffuse sound field assumption, such as the variance of the sound transmission loss, can not be obtained.

There exists an alternative vibro-acoustic modeling approach for which this variance can be computed: the hybrid finite element-statistical energy analysis (FE-SEA) approach [13–15]. Using the diffuse field reciprocity [12,16], the hybrid framework enables modeling the rooms of the overall room-wall-room system to carry a diffuse field (as in statistical energy analysis, SEA), while the wall is modeled deterministically, with finite element analysis. Since both the mean and the variance of the transmission loss can be computed [14], the uncertainty on the transmission loss predictions that is inherent to the assumption of diffuse sound fields in the rooms can be assessed [15]. However, at high frequencies a conventional FE-SEA model can be computationally demanding as a very fine mesh is required for modeling the wall with finite elements.

In the present paper, the aforementioned limitations of the FE-SEA method and the mTMM method are overcome by developing a hybrid mTMM-SEA method. This method can be viewed as a fast alternative for the hybrid FE-SEA method. The computational efficiency is achieved by replacing the finite element model of a thick or layered wall in the hybrid FE-SEA model by a semi-analytical modal transfer matrix model. This still enables to account for the diffraction effects at the wall boundaries and (approximately) the modal behavior of the wall, while reducing the computational effort substantially. However, such replacement is only possible when the wall satisfies the following assumptions: it is baffled, rectangular and consists of homogeneous layers. From an mTMM point of view, casting the mTMM within the hybrid framework enables to make it more general and robust. The detailed contributions of the hybrid mTMM-SEA framework that is presented in this paper are (1) with respect to the TMM and related approaches (1a) that the variance, which is inherent to the diffuse field models of the sound fields can be computed at low computational cost, (1b) that cross-modal coupling is accounted for, while keeping a similar computation cost as in the conventional mTMM and (1c) that numerical difficulties in evaluating the plane-wave transmission, related to grazing incidence, are avoided; and (2) with respect to the hybrid FE-SEA approach: a substantial increase in computational efficiency when the system is simple enough to be modeled with mTMM.

The remainder of this article is organized as follows. The theory is summarized in Section 2. Section 2.1 introduces the hybrid deterministic-SEA approach to sound transmission modeling in general. Sections 2.2 and 2.3 elaborate the computation of the dynamic stiffness matrices of respectively the deterministic part (wall) and the stochastic parts (rooms). In the former the connection is made with the transfer matrix method. In the latter, the approach for computing the modal sound radiation impedance in the hybrid method is compared with the conventional approaches employed in mTMM. Subsequently, the performance of the hybrid mTMM-SEA approach is investigated in detail for six walls with increasing complexity, by comparing the predicted sound insulation values with results of other hybrid approaches and with measured values. The considered wall types are a steel plate (Section 3.1), a polymethyl methacrylate panel (Section 3.2), a brick wall (Section 3.3), a sandwich panel (Section 3.4), a double-leaf wall with poro-elastic material in the cavity (Section 3.5), and finally a double glazing (Section 3.6). The conclusions are presented in Section 4.

2. A hybrid modal transfer matrix - statistical energy analysis framework

2.1. Modeling strategy

Throughout this article, a room-wall-room system is considered, where the rooms carry a diffuse wave field and the wall a deterministic wave field (cfr. Fig. 1). The out-of-plane displacement u_z of the partition wall is approximated using a finite set of N_m global basis functions ϕ (e.g. the in-vacuo modes) and corresponding generalized coordinates q. When the wall is thin, the transverse displacement of the wall in position $\mathbf{x} = (x, y)$ at frequency ω is independent of the z-coordinate:

$$u_\mathrm{z}(\mathbf{x}, \omega) \approx \sum_{p=1}^{N_\mathrm{m}} \phi_p(\mathbf{x}) q_p(\omega) \tag{1}$$