



Predicting the sound insulation of finite double-leaf walls with a flexible frame

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ABSTRACT

With double-leaf wall systems such as plasterboard walls, a high sound insulation can potentially be achieved with a relatively low weight. The accurate sound transmission analysis of this type of wall is challenging since the leaves are usually coupled to a common frame, and since the finite dimensions play a role at lower frequencies. Existing analytical models for sound insulation prediction account for the deformation of the wall in an approximate way, while detailed numerical models are computationally very demanding. In this work, a sound insulation prediction model that achieves a high prediction accuracy at a low computational cost is developed. The wall components that display low geometrical complexity, such as the wall leaves and the cavity, are modelled in an analytical way. Sound absorbents in the cavity are modelled as equivalent fluids. The metal studs, which have a highly deformable cross section, are modelled in full detail with finite elements. The sound fields in the sending and receiving rooms are modelled as diffuse; they are rigorously coupled to the deterministic wall-room model by employing a hybrid deterministic-statistical energy analysis framework. With the resulting room-wall-room model, the airborne sound insulation is predicted for a range of double-leaf plasterboard walls with single, double and triple plating and with different cavity depths. The obtained transmission losses are validated against the results of an extensive set of experimental tests. A very good agreement between predicted and measured transmission loss values is observed. The single number ratings for the airborne sound insulation for nearly all walls differ from the experimental values by 0–2 dB, which is close to the average experimental reproducibility. At the same time, the computational cost is more than three orders of magnitude lower than for recently proposed models of similar accuracy.

1. Introduction

Double-leaf wall systems are often used in the construction, aerospace, railway, and other industries because of their light weight and potentially high sound insulation. Even when the walls are not load bearing, the leaves are usually coupled to a common frame for reasons of cost and lateral stability. A typical example is a double-leaf plasterboard wall where the leaves are screwed into a common metal stud frame. Walls of this type are very often employed in the construction industry for partitioning large open spaces into smaller rooms. However, the common frame introduces a structural transmission path between both leaves in addition to the airborne path through the cavity. The sound insulation of this type of wall is therefore lower than for a wall with structurally decoupled leaves, at least above the mass-spring-mass resonance frequency of the decoupled system, where the leaves vibrate as rigid masses, compressing the cavity fluid. The prediction of the airborne sound insulation of double stud walls is challenging

since it is characterized by many parameters and physical phenomena. Experimental parametric studies by Hongisto et al. [1], Vermeir and Gerretsen [2], and Mechel and Royar [3] have shown that the airborne sound insulation of a decoupled double wall depends mainly on the individual plate thicknesses, the number of plates, the combination of different thicknesses and plate materials, the cavity depth, and the wall dimensions. The stud geometry, the number of studs and the number of screws per stud are additional parameters influencing the sound insulation when the leaves are coupled. The mass-spring-mass resonance is both defined by the total weight of the leaves and the cavity depth. The coincidence frequency, at which the wavelength of the incident wave and the bending wavelength of a leaf are equal, depends on the material parameters of the leaf and its thickness. All these different phenomena and input parameters make it hard to accurately predict the airborne sound insulation using a simplified model.

Many models for the prediction of the airborne sound insulation of double-leaf walls exist. A concise review of these models is given in

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Chapter 2. They can be subdivided into analytical models and numerical models. Analytical models are often used to gain insight into the main physical phenomena, e.g. the mass-spring-mass resonance and coincidence. A low computational cost is achieved by assuming diffuse conditions in the transmission rooms and by using simplified models for the vibrational behavior of the leafs and the cavity. The prediction of the airborne sound insulation is often inaccurate due to this simplified representation of the wall components and since some physical phenomena are omitted, e.g. the dynamic behavior of the studs. An overview of these models is given in Section 2.1.

Numerical models, e.g. finite element models, manage to capture the vibratory behavior of both the wall and the transmission rooms in full detail, making it possible to accurately predict the single number rating. However, these models are not practical due to the large number of boundary and/or finite elements needed at high frequencies. An overview of these models is given in Section 2.2.

The goal of this work is to close the gap between these two types of models. A prediction model for the airborne sound insulation of double walls is developed with both a high prediction accuracy and a low computational cost. Due to this low computational cost and high prediction accuracy, the model can be used as a design tool for the sound insulation of double walls.

The wall is modelled deterministically to accurately capture its vibratory behavior while the sound fields in the transmission rooms are modelled as diffuse. The wall components that display low geometrical complexity, such as the wall leafs and the cavity, are modelled in an analytical way to reduce the computational cost. When a single leaf consists of multiple plates, an expression of the equivalent bending stiffness of the composite leaf is used. For a wall with soft sound absorbents in the cavity, an equivalent fluid model for the acoustic wave propagation inside the cavity is employed. The metal studs, which have a highly deformable cross section, are modelled in full detail with finite elements. The hybrid Deterministic-Statistical Energy Analysis (DET-SEA) framework [4,5] is adopted to rigorously couple the deterministic wall model to the diffuse room models by employing the diffuse field reciprocity relationship [6]. The prediction model presented in this work is validated against the results of an extensive set of experimental tests of double plasterboard walls with a common flexible stud frame [2].

The remainder of this article is structured as follows. A review of existing prediction models is given in Section 2. They are divided in analytical models and numerical models. The deterministic model of the double wall and the coupling to the sound fields in the adjacent transmission rooms is elaborated in Section 3. In Section 4, the experimental setup and test results for the measurements of the sound insulation of studded double plasterboard walls are presented. The results of the model are extensively compared with experimental results for double plasterboard walls with a single stud frame. Conclusions and final remarks are listed in Section 5.

2. Review of existing models

A concise review of existing models for the prediction of the airborne sound insulation of double-leaf walls is provided here. They are subdivided into two categories. The analytical models are based on simplified representations of the leafs, the cavity and the transmission rooms. The numerical models mainly use finite elements and/or boundary elements to predict the sound insulation.

2.1. Analytical models

Early analytical models for the airborne sound insulation of double-leaf walls concentrated on the airborne transmission path through walls with very large planar dimensions. Structural connections between the wall leafs were not considered, and the leafs themselves were modelled as being of infinite extent. The first models such as the one of Beranek

and Work [7] considered only normally incident sound waves and therefore included only the mass of the leafs and the width of the cavity. They allowed for a qualitative study of physical effects such as the mass-spring-mass resonance of the leafs onto the compressive air cavity, and standing waves in the cavity. In 1950, London introduced a model for the sound transmission under obliquely incident sound waves, in which also the stiffness and dissipation of the leafs plays a role [8]. This model therefore includes additional physical effects such as coincidence. The diffuse transmission loss in the model of London is obtained from the Paris equation, i.e., as a weighted summation of the plane-wave oblique transmission loss over all angles of incidence.

Mulholland and coworkers extended the model of Beranek and Work to include oblique incidence [9] and later on extended their model by including multiple reflections of sound in the cavity [10,11]. This so-called multiple reflection model can be used to examine the effects of absorption in the cavity. The absorption is taken into account using a damping ratio on the reflected waves either on the plate-cavity interface or on the cavity edges. Heckl went back to the original model of Beranek and Work to include sound absorbing materials based on the stiffness per unit area, s' , of the material inside the cavity [12]. He modelled the sound insulation of double walls consisting of two thin plates with a resilient material in between. This model showed good results for highly absorbing cavities but underestimated the sound insulation for empty cavities. Fahy [13,14] introduced cavity absorbents in the model of Beranek and Work for pure normal incidence using an equivalent fluid model for the wavenumber and the density of the air in the cavity. Au and Byrne [15,16] introduced expressions for the impedances of porous layers, impervious barriers, and air spaces. Kang et al. [17] compared results of the previous models with experimental data and found that the angles close to grazing incidence were attenuated better than angles close to normal incidence. By introducing a Gaussian weighting on the Paris equation, they were able to predict the sound insulation better for empty cavities. For absorbing cavities the angles close to grazing incidence were already more attenuated so the Gaussian weighting was not needed. At low frequencies, the previously discussed models deviate from the experimental results due to the modal behavior of the wall. Donato [18] suggested a correction for the finite size of the wall using a wavenumber approach for the models of Beranek and Work, and London. This correction can be applied to all previous models that assume infinite panel size. He also simplified the integrals obtained in the Paris equation both in the works of Beranek and Work, and London so that they could be evaluated analytically.

In the previous models, structural connections through the studs are not taken into account. Rigid connections between the wall leafs, so-called ‘sound bridges’, were included by Sharp [19,20] and later by Cremer and Heckl [21]. These models divide the transmission of the sound through the wall in a structure-borne and an airborne path with the assumption that both paths do not influence each other. Sharp adopted the model of London for the calculation of the transmission through the airborne path. Above the so-called bridge frequency, i.e. the frequency where the transmission trough the stud and through the cavity are equal, a correction for the transmission through the rigid stud is introduced. Lin and Garrelick [22] derived an analytical solution for the sound insulation of double walls of infinite extent with periodically spaced rigid studs. The connections between the plates and the rigid studs are modelled as springs. The interaction between the studs and the pressure field inside the cavity was not included. The approach was later adapted by Brunskog [23]. In his model, the interactions between the rigid studs and the pressure field in the cavity were taken into account. Several authors, including Gu and Wang [24], Wang et al. [25], Poblet-Puig et al. [26], Davy [27–29], Vigran [30] and Guigou-Carter et al. [31], have extended analytical models to include flexible studs. The studs are then modelled either as a series of decoupled point springs [31], as line springs [24,26,29,30], or as a smeared elastic layer [25]. Some authors include only a translational spring stiffness [24,29–31], others also include a rotational stiffness [25,26]. This type

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