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Development of a 3D finite element acoustic model to predict the sound reduction index of stud based double-leaf walls

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ABSTRACT

Building standards incorporating quantitative acoustical criteria to ensure adequate sound insulation are now being implemented. Engineers are making great efforts to design acoustically efficient double-wall structures. Accordingly, efficient simulation models to predict the acoustic insulation of double-leaf wall structures are needed. This paper presents the development of a numerical tool that can predict the frequency dependent sound reduction index R of stud based double-leaf walls at one-third-octave band frequency range. A fully vibro-acoustic 3D model consisting of two rooms partitioned using a double-leaf wall, considering the structure and acoustic fluid coupling incorporating the existing fluid and structural solvers are presented. The validity of the finite element (FE) model is assessed by comparison with experimental test results carried out in a certified laboratory. Accurate representation of the structural damping matrix to effectively predict the R values are studied. The possibilities of minimising the simulation time using a frequency dependent mesh model was also investigated. The FEA model presented in this work is capable of predicting the weighted sound reduction index R_w along with A-weighted pink noise C and A-weighted urban noise C_{tr} within an error of 1 dB. The model developed can also be used to analyse the acoustically induced frequency dependent geometrical behaviour of the double-leaf wall components to optimise them for best acoustic performance. The FE modelling procedure reported in this paper can be extended to other building components undergoing fluid–structure interaction (FSI) to evaluate their acoustic insulation.

1. Introduction

Double-leaf walls consisting of roll-formed structural sections and gypsum plasterboards are widely used in building construction. As multi-family housing becomes more common, engineers are increasingly faced with the requirement to provide adequate acoustic insulation [1]. Additionally, thorough understanding and accurate prediction of the acoustic behaviour of buildings components are at the forefront of sustainable building design [2]. This has stimulated considerable interest in the acoustic behaviour of stud based double-leaf walls.

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Double-leaf walls are composed of a structural frame made of steel studs, supporting gypsum plasterboards on either side. The plasterboards are connected to the stud frame by a row of screw fixings. Frame members are usually spaced between 300 mm and 600 mm centres depending upon the wall's design requirements [3]. Compared to traditional masonry construction, double-leaf walls are lighter, cost effective and quick to assemble; they also leave a cleaner building site and need less time to erect [2].

Researchers have been working for many years on the development of various theoretical and analytical models to study the acoustic behaviour of lightweight double and single wall structures [4–10]. Fahy [11] commented that the prediction of acoustic insulation of double-leaf walls is a highly challenging problem because of the dynamic vibration of each panel, coupled with the acoustic pressure response within the air-gap.

For the theoretical prediction of sound transmission through a plane homogeneous structure, a number of established mathematical models can be identified. However, predicting the air borne sound transmission through multilayer structures with air-gaps and structural links, under the influence of fluid–structure interaction (FSI) is a rather difficult task due to the complex dynamic system involved [12].

Several simplified models dealing with the acoustic insulation of double-leaf walls were developed by researchers [11–16]. The prediction of the sound transmission through finite plates at low frequencies using a modified mass law was proposed by Novikov [17]. However, it was found that the modified mass law could not predict the variation in the acoustic response due to the dynamic behaviour of the two leaves.

The case of acoustic insulation through double-leaf walls for identical leaves was studied by London [18]. However, the effects of structural connection between the walls were not considered. Studies conducted by Poblet-Puig et al. [19] suggest that the effect of vibration of structural links is critical for the effective prediction of sound transmission through double-leaf walls. This is due to direct vibration transmission that exists through the studs linking the two leaves.

Mathematical models to represent the complex phenomenon involved in acoustic insulation are extremely intricate due to the large number of variables involved [4]. The simplified models for predicting the sound transmission that were previously developed have improved the understanding of the acoustic phenomena, but they cannot be used as a solution for predicting the acoustic insulation for various engineering and building applications.

Various numerical methods were used to analyse the sound transmission of single and double-leaf walls. Steel et al. [20] used the statistical energy analysis (SEA) along with the finite element method (FEM) to evaluate the sound transmission between two solid plates. From the results, it was revealed that FEM could be used for the possible determination of the acoustic coupling between the plates. Numerical models, developed by Craik et al. [21,22] to predict the sound transmission through double-leaf partitions, assumed the structural links as infinitely rigid connections. Accordingly, these models cannot be used to predict the acoustic insulation of double-leaf walls with lightweight structural links.

In a comparative study of existing acoustic prediction models by Hongisto [16], it was pointed out that only five of the seventeen acoustic models considered the existence of structural connections, and only two of them allowed the rigidity of the studs to be taken into consideration.

A 2D finite element approximation model for double-leaf walls with studs was introduced [23]. However, this model only considered the vibration and fluid–structure interaction along a 2D plane, making it impossible to analyse the three dimensional behaviour of the double-leaf wall and its effect on the sound transmission.

The lack of literature on FEM to predict the acoustic insulation of building components such as double-leaf walls has been reported in various publications [4,23–25]. The reason for this is the complexity of the dynamic behaviour along with a vast number of variable parameters. Some of these parameters are difficult to evaluate, and have a considerable influence on the refinement of simulation models. In particular, it is difficult to include the effect of mechanical connections between leaves, non-uniformly distributed mechanical damping mechanisms, and structure–acoustic coupling [24,25]. However, various contributions can be found where FEM is used at least in part of the domain, where the problem is limited to low frequencies or studied in structural domain alone [26–30].

In this work, a 3D harmonic acoustic finite element model to predict the sound reduction index of double-leaf walls with light weight structural connections (studs) at one-third-octave band frequencies (100–3150 Hz) is developed. The model includes the effect of mechanical connection between leaves, and non-uniformly distributed mechanical damping. Specific boundary admittance and fluid–structure interaction are also included in the model to simulate a realistic scenario. The possibilities of using a frequency dependent mesh model to improve the solution time are assessed. The 3D geometrical behaviour of the double-leaf along with the spatial distribution of fluid pressure within the source and receiving room at selected frequencies are also demonstrated in this work. An experimental test complying with ISO 10140 [31] to obtain the air borne sound reduction index of stud based double-leaf wall was also carried out. The suitability of the FE model to predict the sound reduction index R along with A-weighted pink noise C and urban noise C_{tr} is also evaluated and compared with experimental test data.

2. Methods

2.1. Acoustic analysis

Acoustic interference in a fluid medium creates fluctuations in the density and pressure of the fluid as a function of time and position. The difference between the instantaneous pressure and the static pressure can be then called sound pressure.