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Finite element acoustic analysis of a steel stud based double-leaf wall

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ABSTRACT

Optimum acoustic performance of building components is a fundamental factor towards sustainable building design. Accordingly, it is essential that designers have the capability to effectively predict the acoustic performance to achieve sustainable designs. This paper introduces a 2-D Harmonic Acoustic Finite Element Analysis to predict the sound insulation of stud based double-leaf walls. This research was motivated by the necessity to develop acoustically efficient light weight building structures, which are both affordable and sustainable. Prediction of the Sound Reduction Index (R) of plasterboard partitions with structural links is a challenging problem due to the fluid-structure interaction (FSI) between the structural and fluid systems. Several finite element models to predict the sound reduction index of double-leaf walls were developed in compliance with BSENISO 717 and 140. The validity of the finite element predictions were assessed by comparison with experimental test results carried out in a certified laboratory. The effect of using different mesh sizes, fixing mechanisms and sound source locations on the predicted sound reduction index were looked into. The effects of air humidity and temperature on the experimental measurements of R values were 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}) to within an accuracy of ± 1 dB. Furthermore, the finite element modelling procedure reported can be extended to efficiently predict the acoustic behaviour of other building components undergoing FSI.

1. Introduction

Accurate prediction of sound transmission in building components is a challenging problem [1]. The European Union's Green Paper on Future Noise policy [2] estimates 80 million people suffering from unacceptable noise levels that cause sleep disturbance and an additional 170 million having annoyance during the daytime due to inadequate acoustic insulation. The recent standard for buildings includes a requirement for increased acoustic resistance of walls assemblies including metal framed double-leaf walls [3].

The physics of sound transmission and its interaction with structures have been extensively studied over the past years. Different measurement methods to quantify the acoustical properties of building materials and construction have been standardised and used to generate data that are now available for building design. However, these measurement techniques are often time consuming and need highly specialised equipment. They also require differentiated setup along with expert technicians and can only be carried out in a specialist test laboratory.

The sound transmission characteristics of walls are currently recognized as one aspect of the total design criteria [3]. In the UK, building standards are now being implemented incorporating quantitative acoustical criteria to ensure adequate sound insulation. Also, as multi-family housing becomes more common, designers are increasingly faced with the requirement of providing adequate sound insulation [4]. Therefore, accurate and effective prediction of acoustic performance of buildings components is at the forefront of efficient building design.

Light weight partitions have been the subject of intense investigations for many years [5–11]. This was due to the popularity of light weight double-leaf walls to be used as an alternative to traditional masonry partitions. It was found that double panels with structural links can reduce the sound insulation efficiency due to the way in which the studs are modelled [12]. Light weight double-leaf walls are usually composed of a structural frame made

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of metal studs, supporting gypsum plaster boards on either side. The plasterboards are connected to the stud frame by a row of screw fixings. The frame members are usually spaced from 300 mm to 600 mm centres depending upon the design requirements [13].

According to researchers [14,15], the major factors affecting the acoustic behaviour of stud based double-leaf walls are screw fixing, screw spacing (the fixing methods used to fix the gypsum boards to the studs), stud spacing, stud geometry and the air-gap between the studs. Structure borne sound transmission between point connected structures has been studied extensively by other researchers [16–18]. For a theoretical prediction of sound transmission through a single plane homogeneous structure, a number of established mathematical models can be identified [19]. 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.

This is due to the numerous variables that contribute to the air borne sound transmission through a structural section. These include: frequency range, angle of incidence of the sound wave, the existence of weak points in plaster board, structural rigidity, mass damping and in the case of multiple elements, the number of panels, their individual characteristics and separation. The transmission of sound between two rooms depends not only on the separation elements, but also on the connections between the surrounding elements, and on the way in which sound travels inside the emitting and receiving rooms. Therefore, the mathematical description of the phenomena involved in acoustic insulation is complex. However, by employing the Finite Element Method (FEM), it is now possible to include most of the variables and boundary conditions including FSI for a realistic prediction of the acoustic behaviour [20].

In this work, a finite element model to predict the sound reduction index (R) at one-third-octave band frequencies (100 Hz–3150 Hz) for a double-leaf wall with structural links was developed. The fluid-structure interaction along the fluid and structural interfaces were considered to predict a realistic acoustic behaviour. An experimental test complying with BSEN ISO 140-3 [21], to obtain the air borne sound reduction index of stud based double-leaf wall, was also carried out. The effects of air humidity and temperature on the experimental measurement of *R* values were also studied. The finite element predictions and the experimental test results were compared to validate the suitability of the model developed.

2. Methods

2.1. Acoustic analysis and governing equations

The vibration of a wall produces pressure disturbances to the fluid with which it is in contact. Whatever the frequency of vibration, the resulting fluid pressure is governed by the acoustic wave equation [22]. As the physical systems interact (structure and fluid), a solution cannot be reached without considering the coupled system. Consequently, the fluid and the structural systems cannot be solved separately without considering the fluid-structure interaction (FSI) [23]. For the current analysis, the fluid-structure interaction constitutes a sound field, which is influenced at a particular frequency by the following factors.

(i) The properties of the fluid (air).
(ii) The geometry of the vibrating wall surfaces (gypsum board and stud).
(iii) Type of fixing mechanism connecting the vibration surfaces.
(iv) The material and damping properties at the interface surfaces including boundary admittance.
(v) The spatial distribution of the component of vibrational acceleration normal to the surface of the vibrating structures [22,23].

The vibration source operates directly on the structure (on one of the wall surfaces of the source room); the FSI couples the structural and fluid components to form an integral vibrating system.

For the current acoustic fluid-structure interaction problem, the structural dynamics equation needs to be considered along with Navier–Stokes equations and the flow continuity equation [24]. The Navier–Stokes and continuity equations were simplified to get the acoustic wave equation using four principal assumptions. Based on the assumptions listed below, the acoustic wave equation can be written as shown in Equation (1).

(i) The fluid is compressible.
(ii) The fluid is inviscid.
(iii) There is no mean flow of the fluid (constant flow rate).
(iv) The mean density and pressure are uniform throughout the fluid.

$$\frac{1}{c^2}\frac{\partial^2 P}{\partial t^2} - \nabla^2 P = 0 \tag{1}$$

$$c = \sqrt{k/\rho_0} \tag{2}$$

Where, c is the sonic velocity as shown in Equation (2), P is the acoustic pressure, t is the time, k is the bulk modulus, and ρ_0 is the mean fluid density.

Since the viscous dissipation has been neglected, Equation (1) can be considered as the lossless wave equation for propagation of sound in fluids. Accordingly, the harmonically varying pressure can be defined using Equation (3), where $\overline{P}$ is the pressure amplitude.

$$P = \overline{P}e^{j\omega t} \tag{3}$$

Introducing the gradient and divergence matrix operators, the element matrices can be obtained by discretising the wave equation using the Galerkin procedure [25] using a virtual change in pressure and integrating over the volume of the domain Ref. [26]. Nevertheless, material damping plays an important role in determining acoustic behaviour for building elements [27]. Therefore, damping should be introduced to the discretised wave equation.

In order to completely describe the fluid-structure interaction, the fluid pressure load acting at the interface should also be taken into account. Using the resulting dynamic elemental equation [27] based on discretised acoustic wave equation most of the variables considered in this study can be represented. However, for the current analysis additional terms and equations must be included to reflect particular solutions and boundary conditions.

Sound transmission between two rooms through a double-leaf partition wall is shown in Fig. 1, where I_{in} is the incident sound intensity, I_r is the reflected sound intensity, I_a is the absorbed sound intensity and I_{tr} is the transmitted sound intensity. It is impossible to hear the sound intensity directly, as the hearing experience is based on the perceived sound pressure in the sound wave. Accordingly, the relationship between the sound intensity and sound pressure can be expressed as shown in Equation (4).

$$I = P^2/n\rho c \tag{4}$$