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Noise control of a rectangular cavity using macro perforated poro-elastic materials

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ABSTRACT

The effectiveness of macro perforated porous materials to control noise levels inside a cavity is investigated. This is done using a finite element formulation based on the Biot–Allard theory that accounts for sound propagation in a poro-elastic medium. Earlier investigations have shown that macro-holes in a porous material can enhance low frequency sound absorption. However, this has been demonstrated in free field or waveguide environments. When such an approach is used in a cavity, it is seen that only certain patterns of macro-holes, dictated by cavity mode shapes, enhance noise reduction in the higher frequency ranges. This phenomenon is shown to be independent of porous material properties by considering two different materials. A correlation between the mode shapes and material removal is also established. A detailed convergence study for both cavity and poro-elastic finite element models, establishes the suitability of using higher order interpolation functions for coupled cavity-poro-elastic acoustic analysis.

1. Introduction

In automotive and aircraft applications sound absorbing materials are commonly used to reduce interior noise levels. Sound absorbing materials, such as foam and mineral wool have shown the ability to dissipate acoustic waves propagating in their medium. Acoustical behaviour of porous materials can be modeled as either rigid framed or elastic framed porous materials.

In rigid porous materials the solid part is assumed rigid, while the porous part is considered to be an equivalent fluid with an equivalent density [1] and bulk modulus [2]. Attenborough [3] developed a theoretical model to predict the acoustical characteristics of rigid fibrous absorbents and granular materials. Brennan and To [4] have derived non-dimensional expressions for the acoustic wave number and characteristic impedance for wave propagation in a rigid-frame porous material using the concept of acoustic mass, stiffness and damping. Craggs [5] presented an absorption finite element model for rigid porous material, based on the variational principle given by Morse and Ingard [6]. Later Craggs [7] developed a procedure for coupled acoustic and absorption finite element model. This model leads to only one compressional wave propagating through the rigid porous material. But most of the sound absorptive materials have a non-rigid frame, namely elastic porous materials.

Elastic porous materials such as foams differ from other porous materials by the number of wave types that propagate in the porous media. Elasticity of the skeleton is taken into account while modeling of elastic porous materials. The fundamental theory for acoustic wave propagation in elastic framed materials was developed by Zwikker and Kosten [8]. However, in their formulation the effect of shear was neglected leading to two simultaneous longitudinal wave types in the elastic frame porous material. Biot [9] established the theory of wave propagation in fluid saturated porous media which leads to two compressional and one shear wave. By using Biot's [9] theory, Allard [1] characterized the acoustic wave propagation in poro-elastic materials. In poro-elastic materials, analytical solutions are difficult to obtain because of the complexity due to multiple wave speeds. To solve such problems, numerical models of wave propagation in poro-elastic materials can be used to predict the acoustic behaviour. Three different types of formulation, displacement, relative displacement and mixed displacement-pressure can be used to model the poro-elastic materials.

A coupled two-dimensional acoustic poro-elastic finite element model was developed by Kang and Bolton [10], based on displacement formulation. It was used to predict the acoustical behaviour of poro-elastic materials having finite dimensions and this may not be valid for considerable spread of materials. Panneton and Atalla [11] solved the three-dimensional poro-elasticity problem based on Biot–Allard [1] theory and modeled porous materials in terms of the classical Biot's solid ($\underline{u}$) and pore fluid ($\underline{U}$) displacements. In their model frequency dependent coefficients were taken out from damping and stiffness matrices to reduce computational time at each frequency step. However, this model requires porous material required six degrees-of-freedom (DOF) per node, leading to a large finite element model. Atalla et al. [12] developed a mixed

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displacement-pressure $(\underline{u}, p)$ formulation theory for poro-elastic materials saturated by air. In this model pore fluid displacement $(\underline{U})$ is expressed in terms of the pressure p and solid $(\underline{u})$ displacement. It leads to four DOF per node instead of six DOF per node for the displacement formulation.

The main advantage of the $(\underline{u}, p)$ formulation is that it handles coupling conditions with acoustic and other poro-elastic media quite naturally [13]. Even though using of mixed displacement formulation, the computational cost for convergence of poro-elastic material is so high. Dauchez et al. [14] examined the convergence problem with linear monophasic elements according to each type of Biot wave. In order to get convergence with these elements six elements per wavelength are required for one dimensional poro-elastic model. More importantly the authors [14] reported that obtaining convergence of three-dimensional poro-elastic material is difficult with trilinear elements. Convergence of poro-elastic elements are slower than the convergence of either equivalent solid or fluid elements [14], because of two phase phenomena. With the use of hierarchical elements, the convergence issues of biphasic poro-elastic models are addressed by Rigobert et al. [15]. However, hierarchical elements have physical and generalized amplitudes related to solid and fluid phases, which require extra shape functions to classify edge modes, face modes and internal modes. These generalized amplitudes do not have physical meaning but add to the total DOF.

In general porous materials work well in middle and high frequencies as seen from Delany and Bazley's [16] empirical equation while it provides poor performance at low frequencies. Bécot and Sgard [17] have examined five different numerical formulations for poro-elastic materials. This was applied to the problem of a parallelepiped cavity with one flexible wall. The sound radiation from the flexible wall when excited by a mechanical/acoustic excitation was investigated. The changes in sound radiation were examined [17] by applying the porous material on one wall at a time (including the flexible wall) or two walls simultaneously. While significant attention has been paid to numerical modeling of porous materials, efforts to increase the absorption characteristics of a porous material have been few. The acoustic efficiencies of porous materials are influenced by their physical properties. To increase the absorption performance at low frequencies without any change in physical properties, Atalla et al. [18] investigated macro perforated porous materials. Here, the porous material was removed completely over pre-determined areas and modeled as an equivalent fluid with equivalent density and bulk modulus. They found that the absorption performance of such macro perforated porous materials increased in a semi-infinite rectangular waveguide and obtained low frequency absorption by using non-homogeneous patch-works. Sgard et al. [19] presented design rules to optimize noise control solution for macro perforated porous materials. Normal incidence absorption coefficient of macro perforated porous material was examined. All numerical examples in the paper are related to the case of a macro perforated material placed in a infinite waveguide; the method is based on the Atalla $(\underline{u}, p)$ poro-elastic formulation. In particular, the removal of materials was based on random distributions.

While the macro perforated foam was shown to improve low frequency absorption in an infinite waveguide, its performance in a cavity has not been explored. Also if it does enhance absorption, what pattern will improve absorption is to be examined. This paper examines how the macro perforated patterns in a porous material affects the sound pressure levels inside a cavity. A three-dimensional rectangular cavity is chosen for this purpose. It is shown that the cavity mode shapes influence the material removal patterns for significant noise reduction. Guidelines for locating the macro-perforations based on the mode shapes are also developed.

2. Problem description

The structure under investigation is a three-dimensional rectangular rigid cavity lined with porous material as shown in Fig. 1. The porous material is well bonded to one side of the rigid cavity having dimensions of $0.6 \times 0.4 \times 0.4$ m corresponding to the X, Y and Z directions respectively. It is assumed that the sound field in the cavity is excited by an acoustic point source. Harmonic time dependance in the form of $(e^{j\omega t})$ is assumed for the analysis which is based on the $\underline{u}$ and p model of Atalla et al. [12]. The poro-elastic material is considered to be homogeneous and isotropic, saturated by air. The frame motion is also included unlike Atalla et al. [18] where it has been neglected.

The acoustic cavity is modeled using FEM with pressure as a field variable. The poro-elastic material is modeled with solid phase displacement and pore pressure as field variables. The physical properties of the glass wool porous material from Atalla et al. [12] is considered first analysing the problem and is given in Table 1. The theory for mechanical behaviour of fluid saturated media has been formulated by Biot [9]. This model can be used to predict the sound absorption characteristic of porous materials, when the solid part is elastic. Application of Biot's theory to acoustics was made by Allard [1]. The finite element modelling of the porous material/cavity and their coupling are discussed in the next few sub-sections.

2.1. Poro-elastic modeling

The mixed displacement-pressure formulation [12] is used to model the poro-elastic material. Displacement $(\underline{u}, \underline{U})$ formulation of Biot–Allard [1] model for sound propagation in poro-elastic material, was the basis of the mixed formulation:

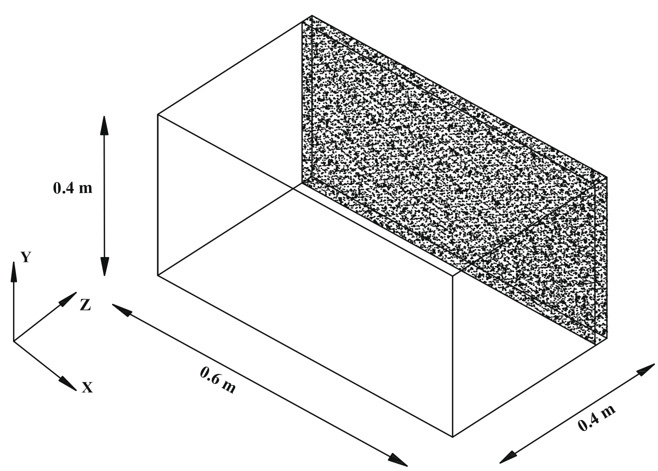

Fig. 1. Geometry of the rigid cavity coupled with poro-elastic materials.

Table 1
Physical properties of the materials used for analysis.

Property	Glass wool	Foam
Tortuosity, α_∞	1.06	1.4
Porosity, h	0.94	0.98
Flow resistivity, σ (Nm^{-4} s)	40,000	15,000
Viscous characteristic length, λ (m)	0.56×10^{-4}	0.4×10^{-4}
Thermal characteristic length, λ' (m)	1.10×10^{-4}	1.2×10^{-4}
Shear modulus, N (KPa)	2.2×10^3	18
Frame structural damping, η	0.1	0.05
Mass density of frame, ρ_1 (kg/m^3)	130	15