Applied Acoustics 90 (2015) 1–8

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

A finite element model of perforated panel absorbers including viscothermal effects

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ARTICLE INFO

Article history:
Received 10 June 2014
Received in revised form 23 September 2014
Accepted 23 October 2014
Available online 10 November 2014

Keywords:
Perforated panels
Sound absorption
Navier-Stokes equations
FEM

ABSTRACT

Most of the analytical models devoted to determine the acoustic properties of a rigid perforated panel consider the acoustic impedance of a single hole and then use the porosity to determine the impedance for the whole panel. However, in the case of not homogeneous hole distribution or more complex configurations this approach is no longer valid. This work explores some of these limitations and proposes a finite element methodology that implements the linearized Navier Stokes equations in the frequency domain to analyse the acoustic performance under normal incidence of perforated panel absorbers. Some preliminary results for a homogenous perforated panel show that the sound absorption coefficient derived from the Maa analytical model does not match those from the simulations. These differences are mainly attributed to the finite geometry effect and to the spatial distribution of the perforations for the numerical case. In order to confirm these statements, the acoustic field in the vicinities of the perforations is analysed for a more complex configuration of perforated panel. Additionally, experimental studies are carried out in an impedance tube for the same configuration and then compared to previous methods. The proposed methodology is shown to be in better agreement with the laboratorial measurements than the analytical approach.

1. Introduction

Perforated panels backed by an air cavity and a rigid wall are sound absorbers commonly used in noise control applications. The sound absorption is produced by viscous losses in their pores so that, when reduced in size, they provide high acoustic resistance and low mass reactance necessary for a wide-band sound absorber. These systems have become an environmentally friendly alternative to fibres and foams, providing higher durability and enhancing sound absorption at low frequencies.

Numerous works have been dedicated to modelling the acoustic impedance of such devices [1–3], based on the model of sound propagation in narrow tubes studied by Crandall [4] and Rayleigh [5]. Most of these models determine the acoustic performance of this type of resonators from their orifice diameter, perforation rate, panel thickness and depth of the air gap. Although typically studied configurations consist of a flat rigid surface with periodically arranged circular holes or slits, some authors have proposed ways to model different perforation shapes or non-traditional designs of the perforated panel [6,7]. Atalla and Sgard [8] have shown that a perforated plate or screen can be modelled as an equivalent fluid following the Johnson–Champoux–Allard approach [9–11] with an equivalent tortuosity and that those classical models can be reobtained by using this simple approach. Even though most of these models have been experimentally validated through the years, some uncertainties related to more complex configurations arise.

Some of the above analytical approaches are based on the assumption of no interaction effect between the perforations (widely separated holes). According to Rschevkin [12], Fok's function can be used to correct the reactive effect for the case of interacting perforations. Nevertheless, in some cases this effect is linked to the porosity effect and is difficult to estimate its contribution isolated. For example, Miasa et al. [13] investigated experimentally the use of multiple sizes of holes in perforated panels. They observed that the sound absorption characteristics were enhanced and attributed this fact to the interaction effect, but did not compare the results with any theoretical model. In a recent work by Tayong [14], the effects of hole interaction along with heterogeneity

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http://dx.doi.org/10.1016/j.apacoust.2014.10.013
0003-682X/

distribution are investigated. In doing so, an inverse method is used to obtain the geometrical tortuosity that accounts for both effects and which is integrated in the characteristic impedance expression following Atalla and Sgard model. Cobo and Montero de Espinosa [15] proposed a slight modification of the Maa and equivalent fluid models to deal with perforated panel manufactured by infiltration. Unfortunately, the main drawback of these latter studies is the requirement of some type of fitting procedure for the characterization of samples. To overcome these and other limitations in the characterization process, complementary modelling techniques must be developed.

Modelling the propagation of acoustic waves through narrow geometries such as orifices of perforated panels cannot neglect dissipative effects of viscous shear and heat conduction of the medium (air). Linearized Navier Stokes formulation, unlike isentropic/lossless acoustics governed by the Helmholtz equation, takes these viscothermal effects into account. The modelling of the behaviour of air in these situations requires the use of prediction methods that can handle this formulation. In this context, and given the progressive increase in the calculation speed of computers, the use of simulation techniques such as the Boundary Element Method (BEM) or the Finite Element Method (FEM) to approach these types of problems becomes feasible and can be very useful.

Craggs and Hildebrandt [16] presented a simplified finite element model to solve Navier-Stokes equations for one-directional sound propagation in tubes of various shapes. Afterwards, Christensen et al. [17] compared different analytical and numerical models using as references two test cases with circular geometry, obtaining similar results for all models. Later on, Kierkegaard et al. [18] developed a methodology with a linearized Navier-Stokes equations solver in the frequency domain to efficiently simulate two-dimensional acoustic wave propagation in duct systems. The simulated results were compared to experimental data using a frequency scaling and showed an excellent agreement. More recently, Herdtle et al. [19] performed CFD (Computational Fluid Dynamics) estimations of the acoustic impedance of microperforated panels for different hole designs using an axisymmetric model generated parametrically, but did not compare the results with any experimental work.

The main disadvantage of the finite element discretization of the full viscothermal acoustic formulation is its high computational cost, since a large number of elements is needed to properly model thermal and viscous boundary layers. Notwithstanding this problem, and although other more efficient models as the Low Reduced Frequency (LRF) model have been used to describe viscothermal propagation in simple tube or layer geometries [20], the full model offers a wide applicability since no geometric restrictions are imposed for the calculations. So as to increase the computational efficiency compared to the full model, Kampinga et al. [21] presented an approximate model that can also be used for arbitrary geometries. Moreover, as the analytical models of perforated panel absorbers represent the extreme situation in which the resonant system is infinitesimal, through the use of a finite element procedure the effect of the finite geometry on the absorption performance can be captured. Therefore, the finite element modelling of perforated panels with viscothermal acoustics represents an interesting alternative for those complex configurations in which no estimation models are available.

The main aim of this work is to estimate the absorption performance of different perforated panel systems using a frequency domain finite element methodology for viscothermal acoustics. The study is focused on thin rigid panels with circular shaped holes and does not consider mean flow or any motion of the plate. In order to validate the proposed characterization methodology, the sound absorption coefficient under normal incidence is determined for the analysed configurations. The results are then compared to a well-established analytical model and to experimental measurements performed by means of an impedance tube. The experiments are performed in the range of sound pressure level where the linear impedance model is valid, showing a good agreement when compared to the model simulations.

The structure of the paper is as follows; in Section 2, the Maa impedance model for the case of perforated panels backed by an air cavity is reviewed; in Section 3, the set of linearized Navier-Stokes equations in the frequency domain for viscothermal acoustics and their finite element implementation are briefly introduced, and in Section 4 the numerical setup implemented for the simulations is described; then, in Section 5, the proposed methodology is compared with the analytical model for a test case and validated through measurements in an impedance tube for different perforated panel configurations; finally, Section 6 describes the main conclusions of this paper.

2. Acoustic impedance of a perforated panel absorber

Fig. 1 shows a schematic representation of a rigid perforated panel excited by a plane wave and immersed in a fluid medium. The panel is assumed to be of infinite extent and composed by a periodic distribution of identical cylindrical perforations of circular cross-section.

The classical approaches to analyse such systems consist in evaluating the acoustic impedance of a single perforation and then use the porosity to determine the impedance for the whole panel. This complex impedance will depend mainly on the perforation rate ϕ, perforation diameter d and panel thickness t. Its resistive part is induced by the viscous boundary layers within the perforations and at the panel surface, and by the flow distortion effects generated at the edges of each hole, while the reactive part accounts for the inertia effects from the motion of air cylinders in the holes of the panel. The previously described phenomena are included in both real and imaginary parts of impedance as additive terms or multiplicative factors, depending on the analytical model. One common particularity of most of these models is that they consider small thickness and shape of the perforations so that thermal energy loss can be considered to be negligible compared to viscous loss. Moreover, they are based on the underlying assumption that no interaction exists between neighbouring holes. Such assumption may not be appropriate if the holes are fairly close, and so a modification of the impedance expression using

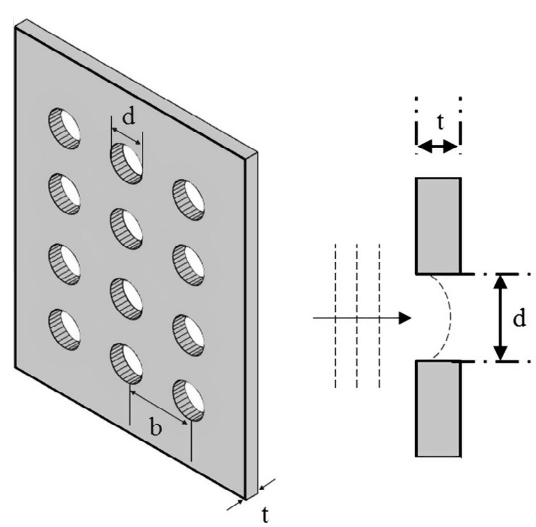

Fig. 1. Schematic diagram of a perforated panel excited by a plane wave and immersed in a fluid medium.