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Technical note

Assessment of methods to study the acoustic properties of heterogeneous perforated panel absorbers

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ABSTRACT

Heterogeneous perforated panels are of great interest as sound absorbers, while achieving a smart high-end decoration in meeting rooms, showrooms, conference halls, etc. However, their uneven nature may pose a difficulty when trying to predict their acoustic performance using traditional impedance models. This work explores the use of four different methodologies: Admittance Sum Method, Parallel Transfer Matrix Method, Equivalent Circuit Method and Finite Element Method, together with the Johnson-Champoux-Allard (JCA) model, to estimate the acoustic properties of heterogeneous perforated panels. The proposed approaches were compared in terms of the computed sound absorption curves for different absorber arrangements. Even though the above methodologies exhibit a good agreement on the predictions, it was found that special attention must be paid to the type of backing cavity configuration (isolated or non-isolated) to yield correct results. Additionally, equivalent circuits for configurations with multiple cavity depths were proposed and their sound absorption also analyzed. In general, preliminary results show that these methodologies may be useful in the design stage of such devices.

1. Introduction

Heterogeneous perforated panels may be considered heterogeneous structures with surface regions of different perforation rates or whose perforations differ in size. Because of their positive visual impact, these materials are preferably chosen for indoor spaces in which a smart high-end decoration is pursued (e.g. in meeting rooms, showrooms, conference halls, etc. In this context, perforated panels backed by an air cavity and a rigid wall work as resonant sound absorbers [1,2], the sound attenuation being produced by viscothermal losses in their holes. Miasa et al. [3] investigated experimentally the performance of perforated panels with holes of multiple sizes compared to uniform size configurations. Their results showed that a multi-size perforated panel absorber may enhance and widen the effective absorption frequency band of the resonator. Therefore, the development of predictive models to study the acoustic properties of these systems is of great interest.

Generally, flat rigid perforated panels containing periodically arranged circular perforations are modeled using a simple theoretical approach (e.g. Zwikker and Kosten [4], Maa [5], etc.). For perforations with other cross-sectional shapes, the models by Stinson [6] or Atalla and Sgard [7] can be used instead. In brief, once the geometrical characteristics of the panel are known, the acoustic properties of the absorber under normal plane wave incidence can be easily predicted using any of these approaches. Nevertheless, these models are limited to homogeneous perforated panels, and do not account for the uneven nature of the heterogeneous panels, which may result in notable differences when predicting their absorption performance. As a matter of fact, these discrepancies may become even more significant for the case of multi-size perforated panels if there is a high contrast between the diameters of the holes. For this reason, the need for alternative methodologies that overcome these limitations and serve as accurate predictive tools is justified.

One of the most general and widespread methods used to determine the acoustic behaviour of heterogeneous perforated panel absorbers is the Finite Element Method (FEM). Wang and Huang [8] studied several configurations consisting on a waveguide coupled to the panel-cavity system to be analyzed, the panel being described following the Maa model [5]. In doing so, their sound absorption performance when impinged by a normal incidence plane wave was estimated. A more simplified approach for this same analysis is the Admittance Sum Method (ASM), which obtains the global surface admittance of the resonator and thus its sound absorption from the sum of the surface admittances

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of the different perforated regions in the panel. Sakagami et al. [9,10] used this method to analyze the excess attenuation of two perforated panel absorbers with different perforation ratios arranged periodically and alternately in parallel. In these latter works, the specific model for perforated panels proposed by Maa [5] was used. Another methodology is the Parallel Transfer Matrix Method (PTMM), which relies on the fundamentals of transfer matrix analysis [11]. This transfer matrix analysis uses a matrix representation to model the plane wave propagation in a serial arrangement of any number of layers of porous materials and to predict the absorption performance of the whole system. Each of these layers is typically modeled following the classical Johnson-Champoux-Allard (JCA) model for rigid porous media [12,13]. By the PTMM, Verdière et al. [14] extended this analysis to deal with heterogeneous sound absorbing materials such as patchworks, acoustic mosaics, and other acoustic elements assembled in parallel. Given that these materials resemble in some way the case of a panel with differentiated perforated regions (i.e. heterogeneous perforated panel), this method may be interesting to the study of its acoustic properties. In fact, according to [14], the PTMM can be applied to predict the absorption properties of any parallel assembly of finite size materials. More recently, Pieren and Heutschi [15] showed that the same universality is offered by the Equivalent Circuit Method (ECM). Moreover, they demonstrated that a large variety of backing termination conditions can be handled using this method.

This work explores the use of the above introduced methods to predict the acoustic properties of heterogeneous perforated panel absorbers. For this purpose, a macroscopic description of the heterogeneous medium is first derived, and then the four sets of prediction methods tested: the Admittance Sum Method (ASM), the PTMM (Parallel Transfer Matrix Method), the Equivalent Circuit Method (ECM) and the Finite Element Method (FEM). All of these methods make use of an equivalent fluid description based on the well-known JCA approach to model the different perforated regions of the panel. Calculations in terms of sound absorption were performed for different representative heterogeneous perforated panel absorber configurations, and served to assess the adequacy of these methods depending on the type of absorber configuration. Additionally, equivalent circuits and absorption performance results for configurations having different cavity depths were also studied.

This paper is organized as follows: in Section 2, a macroscopic description of the heterogeneous perforated panel, and the JCA model [12,13] used to describe the fluid in the perforated regions, are presented. Section 3 is devoted to review the different methods used to predict the acoustic properties of the resonator system. In Section 4, the applicability of these methods is assessed by comparing the predictions for the sound absorption coefficient for different absorber configurations. Besides, equivalent circuits developed for configurations having different cavity depths are also presented, and their corresponding sound absorption performance analyzed. A discussion on the above results and on the limits of the methods is conducted as well. The main conclusions are summarized in Section 5.

2. Materials

2.1. Heterogeneous perforated panels

A heterogeneous perforated panel consists of a series of perforated regions whose perforation rates and/or hole sizes differ from one region to others. One of the main advantages of these panels when compared to homogeneous is that, when being part of a panel-cavity resonator system, they allow broadening its absorption frequency range without necessarily increasing the cavity depth [3,9,10]. This potential feature is of great interest in the context of building acoustics, where the space constraints are especially demanding. Furthermore, the combination of different hole sizes or perforations rates not only paves the way for a large variety of aesthetic designs, but also to explore extra capabilities.

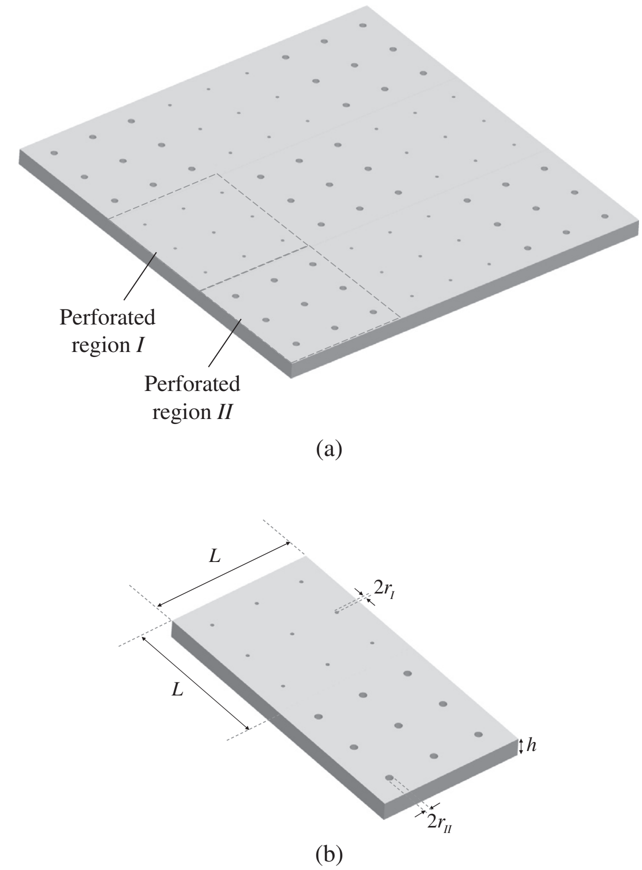

Fig. 1. Schematic representation of the heterogeneous perforated panel: (a) general view, and (b) elementary cell.

2.2. Macroscopic description

Let us consider the rigid heterogeneous perforated panel of infinite lateral extent shown in Fig. 1a. For the sake of simplicity, the panel herein described comprises only two equally sized but different periodic perforated regions of dimension $L \times L \times h$ (as shown in Fig. 1b), denoted as *I* and *II*, even though this description could be extended for more regions if these are properly arranged.

As a rule, a macroscopic acoustic description of a heterogeneous periodic structure can be derived if its periodicity is much smaller that the sound wavelength of interest. Under this assumption, a fluid equivalent to the panel can be defined for normal incidence plane wave propagation by appropriately accounting for each region. The contribution of either region can be described separately from their acoustic properties, namely characteristic impedance, Z_i, and wave number, k_i.

$$Z_i = \sqrt{\rho_{eq,i} K_{eq,i}} \quad (1)$$

$$k_i = \omega \sqrt{\rho_{eq,i}/K_{eq,i}} \quad (2)$$

where $\rho_{eq,i}$ and $K_{eq,i}$ are the complex density and bulk modulus of the equivalent fluid in the *i*th region, respectively, and ω is the angular frequency. The two first parameters account for the viscothermal dissipative mechanisms in the perforated regions, and can be determined by using a classical impedance model as the one to be described in Section 2.3.

After the relevant acoustic properties are obtained, the normal incidence sound absorption coefficient, α, of the heterogeneous perforated panel absorber can be calculated from