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MODELING OF PERFORATED PANELS WITH SLIT-LIKE DEAD-END PORES

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Abstract
The acoustic behaviour of common porous media is highly dependent on their open porosity, this consisting of an interconnected network of pores including kinematic and dead-end porosities. A properly chosen dead-end porosity can help enhance the sound absorption properties of such materials because of the thermal exchanges between the fluids filling each of these pores. This paper presents a model to deal with previous situations for the specific case of rigid panels with periodically arranged circular holes containing slit-like dead-end pores. Analytical solutions describing acoustic wave propagation in pores of circular cross-section and slits are used together to this end. The effect of width, height and length of the slits in the absorption performance of the perforated panel is studied. Preliminary results show the improved absorption capability of these systems, making them a promise alternative to traditional perforated panel solutions. Additionally, the model is proven to be a useful tool to estimate their acoustic properties in a simple manner that can also be extended to other geometry cases.

Keywords: Perforated panels, dead-end porosity, slit, acoustic properties.

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1 Introduction

Perforated panels are used nowadays in many noise control systems such as duct mufflers [1], noise barriers [2] and resonant absorbers [3]. Typically studied configurations consist on a flat rigid surface with periodically arranged circular holes or slits, the sound being attenuated mainly due to viscous friction in their pores. When backed by an air cavity and a rigid wall, perforated panels form a resonant absorber, being commonly used to address architectural acoustics issues in terms of sound absorption [4, 5]. In this context, a positive visual impact is of great importance, so not only creating an acoustically effective system but also an aesthetical product is encouraged. This can be accomplished by using a grooved acoustic panel design, which comprises a substrate with a slotted front surface and a back surface with perforated circular holes. These devices achieve an excellent absorption performance while creating a smart high-end decoration for its use in workspaces, gymnasiums, auditoriums, etc. Even though some previous works have investigated other complex perforated panel configurations [6-10], to the authors' knowledge, there is a lack of work concerning the acoustic modeling of grooved acoustic panels. Consequently, given that the development of this type of absorbent solutions is usually based on trial and error tests, the use of predictive models is of great interest to reduce costs in their design stage. In addition, it may be helpful for understanding the acoustic wave propagation in such systems and to choose an optimal configuration adapted in each case to the design constraints.

Several models exist in the literature [11-14] to predict the acoustic behaviour in the linear regime of traditional perforated panel systems, which may be determined from their orifice diameter, perforation ratio (or porosity), panel thickness and cavity depth. It is well known that the cross-sectional shape of the perforations may also have a substantial influence on the absorber performance. Thereby, one shall look for the theoretical solutions for the sound propagation in uniform tubes of the shapes to be studied. While most of these latter approaches are based on the approximate solution suggested by Zwikker and Kosten [15], which assumes circular-shaped perforations, some authors [16, 17] have developed models to handle other simple geometries. In a recent work [18], a model based on the expressions for the complex density and compressibility for uniform pores of rectangular cross-section given by Stinson and Champoux [17] is used to calculate the acoustical properties of slotted panels. Nevertheless, these analytical models are limited to specific geometries and are not directly applicable to grooved acoustic panels. To overcome this problem, the transfer matrix method (TMM) can be used to describe the acoustic field in these systems.

This paper presents a simple model to predict the acoustic properties of grooved acoustic panel absorbers. For this purpose, the expressions for the complex density and compressibility of pores of circular cross-section and slits and are used together to represent the air inside the panel. The models used to describe the acoustic wave propagation in these pore geometries are those worked out by Zwikker and Kosten [15] and Stinson [17], respectively. The transfer matrix method is then employed to analyze the propagation of plane waves through the entire absorber. The sound absorption coefficient under normal incidence is used to assess the absorption performance of such device. A finite element procedure was used to verify the utility of the model and discuss its limits. In general, comparison between theoretical and numerical results for the sound absorption coefficient show that this simple approach provides good predictions. Even though further research and a comprehensive experimental study are needed, preliminary results are promising and encourage the use of this model for practical design of grooved acoustic panels.

This paper is organized as follows: In Section 2, the model at the macroscopic scale of the grooved acoustic panel, and the analytical solutions used to describe the sound propagation through its circular tubes and slits, are presented. The transfer matrix method theory is then recalled and developed to predict the absorption performance descriptors of the absorber. In Section 3, the proposed model is validated by comparing its predictions for the sound absorption coefficient with finite element simulations. The limits of the model are also discussed. The main conclusions are summarized in Section 4.

2 Model for grooved acoustic panels

2.1 Model at the macroscopic scale

First, a general description on the macroscopic scale of an air-saturated grooved acoustic panel is derived. Figure 1 shows a schematic representation of this system. It consists of a substrate medium with rigid walls constituted by two series regions of pores of different shape: slotted in the front surface and circular in the back surface. Hence, the acoustic behaviour of the grooved acoustic panel is given by the contribution of both types of pores. Hereinafter, the subscripts S and C refer to the slits and the circular tubes of the panel, respectively.

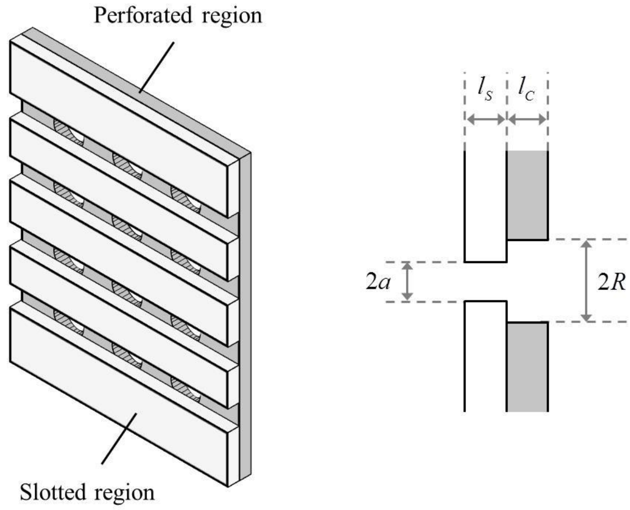

Figure 1 - Schematic representation of a grooved acoustic panel. (Left) General view. (Right) Detailed view.

Let each region of the panel be characterized by its porosity or volume proportion of open pores (ϕ_S for the slotted pores region, and ϕ_C for the circular pores region) and their characteristic size (half-height a in the case of slits, and radius R in the case of circular tubes). The panel may be considered as a periodic lattice structure of cells consisting of a slit aligned with one single perforation. Thus, a representative elementary volume can be defined and a homogenization method used to derive an equivalent fluid description of the whole panel. This method is valid only if the wavelength of the sound wave of interest is much larger than the dimensions of the volume of homogenization. Since the homogenization process implies that identical waves propagate in each cell, the acoustic properties of each region of the whole panel, namely characteristic impedance, Z, and wave number, k, may be evaluated as [19]

$$Z = \sqrt{\rho K} \tag{1}$$

$$k = \omega\sqrt{\rho/K} \tag{2}$$

where ρ and K are the complex density and bulk modulus of the fluid in each region, and ω is the angular frequency. These two acoustic properties, ρ and K, represent the viscous friction and thermal loss mechanisms at the pore walls of these regions, respectively, and can be written as

$$\rho = \frac{\rho_0}{\phi F(\omega)} \tag{3}$$

$$K = \frac{1}{\phi}\frac{\gamma P_0}{\gamma-(\gamma-1)F(N_P\omega)} \tag{4}$$

where ρ_0 is the air density, γ the ratio of specific heats, P_0 the atmospheric pressure, N_P the Prandtl number and F is obtained from the models described next.

2.2 Sound propagation in circular tubes

The wave propagation in cylindrical pores having a circular cross-section can be described using the simplified model suggested by Zwikker and Kosten [15]. In this model, a uniform circular tube of radius R is considered. In order to calculate the complex density and bulk modulus expressions of the circular perforated region of the grooved acoustic panel, the following expression for F is used

$$F_C(\omega) = 1 - \frac{2J_1\left(s\sqrt{-j}\right)}{s\sqrt{-j}\,J_0\left(s\sqrt{-j}\right)} \tag{5}$$

where $s = \left(\omega\rho_0 R^2/\eta\right)^{1/2}$, being η the dynamic viscosity of air.

2.3 Sound propagation in slits

The approach used in the present work to model the acoustic properties of the slits is based on studies on the sound propagation in uniform tubes of arbitrary cross-section shape worked out by Stinson [17]. It is assumed that the slits in the grooved acoustic panel are infinitely long. The validity of this approach will be discussed in the limits part of the present study. For the case of a single slit, F is obtained from

$$F_S(\omega) = 1 - \frac{\tanh\left(s'\sqrt{j}\right)}{s'\sqrt{j}} \tag{6}$$

with $s' = \left(\omega\rho_0 a^2/\eta\right)^{1/2}$, where a stands for the half-height of the slit.

From this equation, the expressions for the complex density and the bulk modulus, the inverse of the compressibility, of the slotted region of the grooved acoustic panel may be evaluated. Although the slits have a slightly lower acoustical resistance than the circular holes, they play an aesthetic role on the grooved acoustic panel and can still work for practical purposes while reducing the overall manufacturing cost.

2.4 Transfer matrix method

To extend the above models to the specific case of a grooved acoustic panel absorber, the transfer matrix method can be employed. This method is widely used in acoustics to analyze the propagation of plane waves through layered porous media assumed laterally infinite [20], as is the case under study. By means of this general technique, the acoustic performance of the absorber system can be estimated.

Consider the periodic unit cell of a grooved acoustic panel shown in Figure 2. This cell can be divided into two series porous elements, the first one corresponding to the slotted region and the second to the perforated one. It follows that the sound pressure and particle velocity at the upstream and downstream of each region are related by the generic transfer matrix

$$[T]_i = \begin{bmatrix} \cos\left(k_i l_i\right) & jZ_i \sin\left(k_i l_i\right) \\ \dfrac{j}{Z_i}\sin\left(k_i l_i\right) & \cos\left(k_i l_i\right) \end{bmatrix} \tag{7}$$

where l_i is the length of each region i, whose acoustic properties are obtained from Eqs. (1) to (6), depending on the region itself.

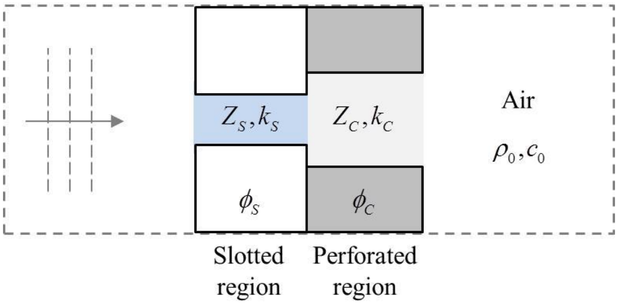

Figure 2 - Cell geometry of a grooved acoustic panel.

If the panel is backed by an air cavity and a rigid wall, a resonator system is achieved. By multiplying transfer matrices for both perforated panel regions and the airspace, the overall transfer matrix of the absorbent system can be derived

$$[T] = \begin{bmatrix} t_{11} & t_{12} \\ t_{21} & t_{22} \end{bmatrix} = [T]_S [T]_C [T]_A \tag{8}$$

where $[T]_S$, $[T]_C$, and $[T]_A$ correspond to the transfer matrices of the slotted region, the perforated region and the air cavity, respectively, the acoustic properties for the backing cavity being those for air at ambient conditions.

The normal incidence sound absorption coefficient of the absorber is thus given by

$$\alpha = 1 - \left| \frac{Z_I - \rho_0 c_0}{Z_I + \rho_0 c_0} \right|^2 \tag{9}$$

where $Z_I = t_{11}/t_{21}$ is the surface impedance and c_0 is the sound propagation velocity in air.

Moreover, the influence of filling the backing cavity of the perforated panel absorber with other porous materials (e.g. fibers, foams, etc.) can be assessed by using complementary predictive impedance models.

3 Results

3.1 Model validation

The proposed approach is validated against a finite element model implemented using the commercial software COMSOL Multiphysics®. For this purpose, the sound absorption characteristics of two grooved acoustic panel absorbers are numerically determined and compared with those predicted by the analytical approach. The absorber systems consist of panels whose geometrical characteristics are summarized in Table 1. These geometrical parameters were chosen arbitrarily, but served to verify the correctness of the proposed model.

Table 1 – Geometrical parameters of the two grooved acoustic panel configurations.

	a (mm)	l_A (mm)	$l_{C,S}$ (mm)	ϕ_C (%)	ϕ_S (%)	R (mm)
GAP1	1	50	10	4.9	5	5
GAP2	1.5	20	10	3.1	7.5	4

The numerical procedure reproduces the standardized impedance tube method [21] to determine the acoustic properties of one unit cell of this absorber. It is based on a simple configuration, which consists of a duct (i.e. the impedance tube) connected to the unit cell, and this in turn to an air cavity. Figure 3 shows the resulting numerical model.

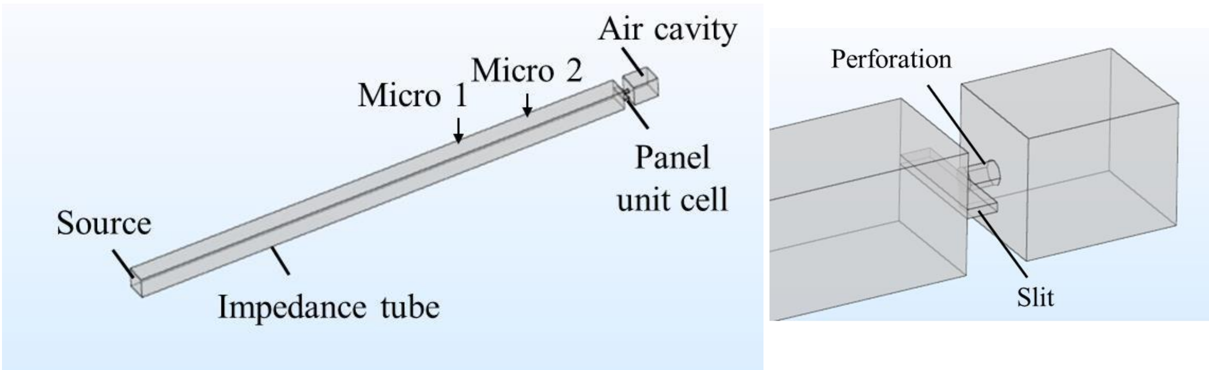

Figure 3 - Numerical model of the impedance tube setup. (Left) General view. (Right) Detailed view.

The impedance tube and air cavity domains were modeled as air, and the different fluid regions in the panel unit cell as porous media using complex density and bulk modulus given by the above approaches. The discretization of the problem domain was performed with tetrahedral elements having a maximum size of 34 mm, corresponding to a maximum frequency of 1 kHz with a 10 elements per wavelength criterion. A harmonic plane wave pressure field was applied at the left end of the impedance tube and the normal incidence sound absorption coefficient calculated at each frequency of interest. In Figure 4, the predictions of the numerical model are compared to those obtained with the proposed approach for both system configurations.

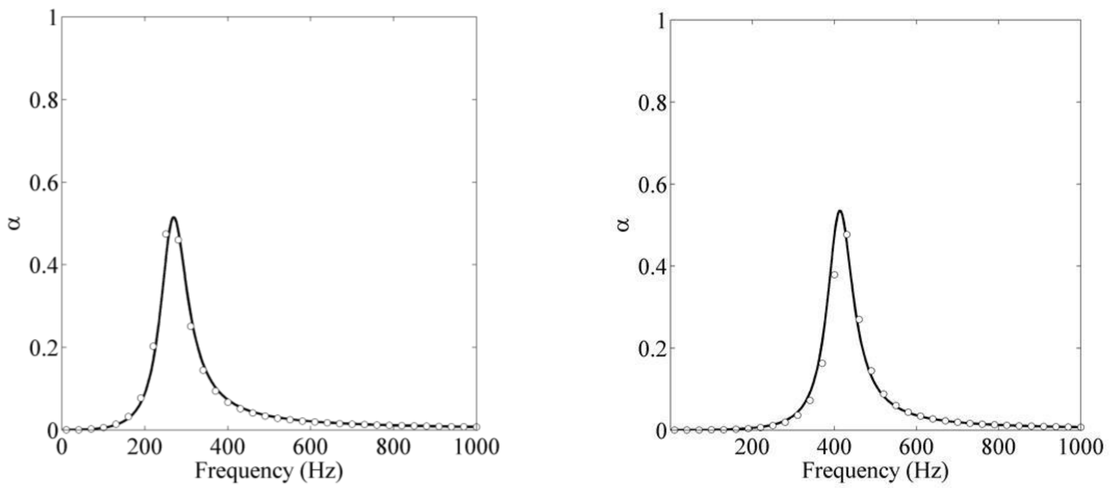

Figure 4 - Normal incidence sound absorption coefficient for the configurations (Left) GAP1 and (Right) GAP2. Solid line, TMM model; circles, FEM model.

It can be seen that there is a good agreement between the predictions associated with both approaches for GAPs 1 and 2 for the normal incidence sound absorption coefficient throughout the considered frequency range. At first sight, it is shown that a larger slit height and smaller perforation lead to slightly higher absorption values. In fact, the absorption value is primarily influenced by the viscothermal loss mechanisms through the panel, which depend on the shape and size of the perforations (i.e. height of the slit and radius of the hole). The peak resonance shift towards higher frequencies is usually associated to the air cavity depth. Nevertheless, in this case this effect might be also linked to the higher porosities ratio, and therefore is difficult to estimate its contribution alone. It should be noted that the proposed model accounts for the viscous dissipation and inertia effects occurring around the panel edges by using an additional end correction tern in the surface impedance expression. In general, the finite element simulations are in good agreement with the proposed model for the studied grooved acoustic panel absorbers.

3.2 Limits of the model

The model proposed in the present paper can be valid only under a series of conditions. It is thus of great importance to tackle some of the limitations of this approach. The macroscopic description derived in Section 2.1 states that the acoustic field in each hole is independent of the field in the neighboring holes. This assumption implies that the interaction effect between pores is neglected (i.e. low porosity cases). However, one has to be aware that this way of modeling is not able to account for the position of the pores in the panel with respect to each other [9, 10]. Regarding the analytical solution used to describe the acoustic wave propagation in slits, it assumes the opening to have an infinite length. This approximation is a valid only when the length of the slit is large compared to its height, the exact solution for a slot of rectangular shape being necessary otherwise [18]. In this regard, note that the back end of the slotted pores region is only partially connected to the circular pores region in the path connecting the front and rear surface of the panel. Hence, to extend the model to higher porosities ratio further investigation is recommended. On the other hand, care must also be taken regarding the effects of finite dimensions of the panels for practical applications. Since the transfer matrix method assumes a panel of infinite extent, additional corrections must be carried out to account for geometrical finite size effect [19]. Nonetheless, the model is able to capture most of the underlying physics related to the sound propagation through these types of absorbers in a simple and straightforward manner without the need of additional fitting procedures or modified formulations.

4 Conclusions

A simple approach has been proposed to analyze the acoustic properties of grooved acoustic panel absorbers. Classical approaches are not able to properly describe the acoustic properties of such devices because of the nontrivial geometry thereof. The presented model accounts for the different pore shapes through the thickness of the panel from analytical solutions for sound propagation in circular tubes and slits, and uses the transfer matrix method to successfully describe the acoustic behaviour of the absorber. As expected, it was found that its absorption performance is largely influenced by the geometrical characteristics of the panel as well as its perforation rate. Additionally, a finite element procedure is used to verify the validity of the model. The agreement between both approaches show that the acoustic properties of these absorbers can be predicted using the proposed model. The advantages and limits of the model have also been discussed. Moreover, other geometry cases can be analyzed using this simple approach without significant changes in the modeling procedure. Even though a comprehensive experimental study must be conducted after the analytical and numerical investigation, this research motivates the use of this simple approach to design grooved acoustic panel absorbers for practical applications.

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