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MICROPERFORATED PANEL ABSORBERS WITH POROUS PARTITIONS: A PRELIMINARY STUDY

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ABSTRACT
Some of the most extended approaches to widen the sound absorption bandwidth of microperforated panel absorbers are the use of different cavity depths or multi-layer arrangements. Unfortunately, these solutions are seldom adopted in practice because of the technical installation difficulties or their excessive cost. An effective alternative to these systems is the use of multi-size microperforated panels with a partitioned backing cavity. This work explores the use of porous partitions to further broaden the working frequency range of such devices and hence improve their sound absorption performance. A simple model for the prediction of the acoustic properties of such resonators is also proposed, the results showing a good agreement when compared to finite element simulations, thus easing their design and analysis.

RESUMEN
Algunas de las propuestas más extendidas para aumentar el ancho de banda de absorción acústica de los paneles microperforados absorbentes son el uso de diferentes espesores de cavidad trasera o las configurationes multipanel. Desafortunadamente, estas soluciones rara vez se adoptan en la práctica debido a las dificultades técnicas de instalación o su excesivo coste. Una efectiva alternativa a estos sistemas es el uso de paneles perforados multi tamaño con cavidades traseras particionadas. Este trabajo explora el uso de particiones porosas para ampliar aún más el rango de frecuencia de trabajo de tales dispositivos y, por lo tanto, mejorar su rendimiento de absorción acústica. También se propone un modelo simple para la predicción de las propiedades acústicas de dichos resonadores, mostrando los resultados una buena correlación al compararlos con simulaciones de elementos finitos, lo que facilita el diseño y análisis de los mismos.

1. INTRODUCTION

Over the last decades, perforated panel absorbers have been widely used as passive noise control systems to reduce noise in urban environments [1] and buildings [2]. These absorbers consist of a perforated flat surface backed by an air cavity to form an acoustic resonator which attenuates sound due to viscous friction in its holes. When their holes are reduced in size, these devices are referred as Micro-Perforated Panel (MPP) absorbers, resulting in a wide-band sound absorber [3]. Despite their good sound absorption performance, a lot of research has been carried out in recent years to further improve and widen their sound absorption bandwidth by using different partitioned cavity depths [4], optimized multi-layer arrangements [5] or ultra-micro perforations [6]. Unfortunately, these solutions are rarely adopted in practice mainly due to the technical installation difficulties or because being considered too costly. Besides, the use of panels with uniform size perforations may pose a limitation to broaden the absorption bandwidth of the resonator system.

Miasa et al. [7] investigated experimentally the sound absorption performance of partitioned MPP absorbers whose holes have multiple sizes. Their results showed that a multi-size MPP absorber may enhance and widen the absorption effective frequency band when compared to those of uniform size. Yairi et al. [8] also analyzed the sound absorption of a combination of different MPP absorbers, an equivalent circuit model being validated against impedance tube measurements. These compound MPP absorbers were further analyzed by Wang and Huang [9], a finite element procedure being proposed to simulate its acoustic behaviour under normal incidence. More recently, Li et al. [10] studied the use of parallel-arranged perforated panels with extended tubes. In doing so, several configurations that achieved a widened low frequency absorption were proposed, an equivalent circuit based modeling procedure being also performed. In an effort to further improve the performance of multi-size absorbers, Kim and Yoon [11] devised the use of a porous partition instead of a rigid partition to separate the backing air cavities. In their work, finite element simulations together with a numerical optimization technique were used to analyze the influence of such partitions and derive an optimized design of these absorbers. While the above works rely on well-established impedance models [3, 12, 13] and methods to predict the acoustic behaviour of these resonators, to the author's knowledge, no previous research has been devoted to analytically model these latter multi-size MPP absorbers with porous partitions.

In this work, a simple model to predict the acoustic properties of multi-size MPP absorbers with porous partitions is proposed. For this purpose, electro-acoustic equivalent circuit theory together with the Maa model [3] and Johnson-Champoux-Allard (JCA) model for rigid porous media [14, 15] were used to describe the microperforated panel and the porous partition, respectively. Equivalent circuits have been successfully used in the literature to study the acoustic properties of MPP absorbers [3, 4, 6, 8, 12], the major novelty of the herein proposed approach being the use of the Kennelly theorem (i.e. Y-Δ transform) [16] to tackle the inclusion of the porous partition in the equivalent circuit of the absorber. In order to verify the applicability of the developed model, several examples were analyzed and compared to finite element simulations in terms of sound absorption performance, showing a good agreement. It was also demonstrated that a target absorption frequency band can be achieved by appropriately choosing the hole multi-sizes of the panel and the porous partition characteristics.

2. BACKGROUND THEORY

2.1. Multi-size MPP absorber with porous partitions

A schematic representation of a multi-size MPP absorber with porous partitions is depicted in Fig. 1. For simplicity, a microperforated panel composed of two different microperforated regions, denoted as *I* and *II*, whose respective backing air cavities (not plotted in the figure) are separated with a porous partition was chosen, although the subsequent description can be extended for more regions.

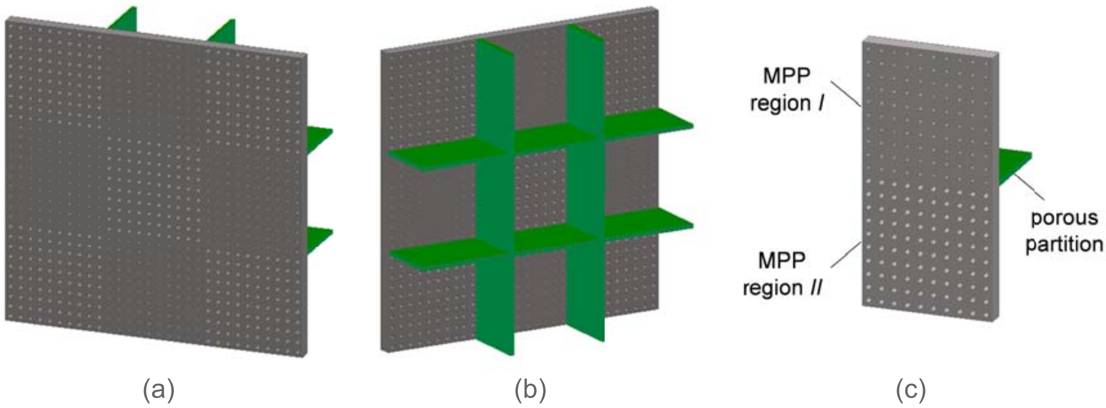

Fig. 1. Schematic representation of a multi-size MPP absorber with porous partitions: (a) frontal view, (b) rear view, and (c) elementary cell.

When the dimensions of these regions are much smaller than the wavelength of interset, the electro-acoustic analogy can be adopted to derive an equivalent circuit of the absorber and thus predict its sound absorption performance under plane wave normal incidence. To this end, and given the periodicity of the resonator system, the elementary cell of the resonator system shown in Fig. 1c was considered. To undergo the analysis of the resulting equivalent circuit, acoustic transfer impedances of the elements involved must be known beforehand. Specifically, the Maa model [3] for MPPs and the JCA model for rigid porous media [14, 15] were chosen to define the impedances of the microperforated regions and porous partition, respectively. These impedance models are described next, whereas the implementation of the equivalent circuit of the absorber will be described in Section 3.1.

2.2. Maa model for MPPs

Maa proposed an expression for the transfer impedance of a flat rigid microperforated panel whose circular perforations are periodically distributed along its surface, which reads as follows [3]

$$Z_{MPP} = \frac{1}{\phi}\left(j\omega\rho_0 t \left(1 - \frac{2J_1\left(s\sqrt{-j}\right)}{s\sqrt{-j}J_0\left(s\sqrt{-j}\right)} \right)^{-1} + \sqrt{2\eta\rho_0\omega} + j\frac{\omega\rho_0 1.7R}{\psi(\xi)} \right) \qquad (1)$$

where $s = R(\omega\rho_0/\eta)^{1/2}$, R being the radius of the perforations, ρ_0 the density of air, ω the angular frequency, and η the dynamic viscosity of air; ϕ is the perforation rate, t the panel thickness, J_n is the Bessel function of the first kind for order n, and $\psi(\xi)$is the Fok function, which accounts for the holes interaction effect [17], and is given by

$$\psi(\xi) = \left(1 - 1.40925\xi + 0.33818\xi^3 + 0.06793\xi^5 - 0.02287\xi^6 + 0.03015\xi^7 - 0.01641\xi^8 + ...\right)^{-1} \quad (2)$$

with $\xi = 0.88(2R)/b$, being b the distance between perforations.

Therefore, by knowing the geometrical characteristics of each microperforated region of the panel, their respective acoustic transfer impedances can be derived.

2.3. Johnson-Champoux-Allard (JCA) model for rigid porous media

The porous partitions of the multi-size MPP absorber can be replaced on a macroscopic scale by an equivalent fluid described by a complex characteristic impedance, Z_C, and wave number, k

$$Z_C = \sqrt{\rho K} \quad (3)$$

$$k = \omega\sqrt{\frac{\rho}{K}} \quad (4)$$

where ρ and K represent the complex dynamic density and bulk modulus of this equivalent fluid, which can be modeled following the Johnson-Champoux-Allard (JCA) model for rigid porous media [14, 15]. This approach relies on prior knowledge of four intrinsic physical parameters of this porous media, viz., open porosity, static air flow resistivity, high frequency limit of the tortuosity, and viscous and thermal characteristic lengths; whose values must be obtained over a representative elementary volume thereof. The expressions for the above effective properties are written as follows [18]

$$\rho = \frac{\alpha_\infty \rho_0}{\phi}\left(1 + \frac{\sigma\phi}{j\omega\rho_0\alpha_\infty}\sqrt{1 + \frac{4j\omega\alpha_\infty^2\eta\rho_0}{\sigma^2\Lambda^2\phi^2}}\right) \quad (5)$$

$$K = \frac{\gamma P_0}{\phi}\left(\gamma - (\gamma - 1)\left(1 + \frac{8\eta}{j\omega\Lambda'^2 N_{\mathrm{Pr}}\rho_0}\sqrt{1 + \frac{j\omega\Lambda'^2 N_{\mathrm{Pr}}\rho_0}{16\eta}}\right)^{-1}\right)^{-1} \quad (6)$$

where α_∞ is the high frequency limit of the tortuosity, ϕ the open porosity, σ the static air flow resistivity, Λ and Λ' are the viscous and thermal characteristic lenghts, respectively, γ is the ratio of specific heats, P_0 is the atmospheric pressure, and N_P is the Prandtl number.

By using the Impedance Transfer Method (ITM) [19], it is then straighforward to obtain the acoustic transfer impedance of the porous partition as if it was anechoically backed by using the expression

$$Z_{PP} = Z_C \frac{-jZ_0 \cot(kd) + Z_C}{Z_0 - jZ_C \cot(kd)} \quad (7)$$

where Z_0 is the characteristic impedance in air and d is the thickness of the porous partition.

3. METHODS

3.1. Equivalent Circuit Method (ECM)

Once the acoustic elements conforming the multi-size MPP absorber were identified and their respective acoustic transfer impedances defined, the modeling procedure using the Equivalent Circuit Method (ECM) is described. The electro-acoustic equivalent circuit theory is frequently used to solve an acoustical problem by representing the system under study with a schematic diagram. In particular, it turns out to be a very useful tool to predict the sound absorption performance of MPP absorbers [3, 4, 6, 8, 12]. The resulting model will let us obtain the surface impedance of the resonator system and thus predict its sound absorption performance by following an impedance analysis. Fig. 2 shows a schematic diagram of an elementary cell of a multi-size MPP absorber with porous partitions and its corresponding equivalent acoustic circuit.

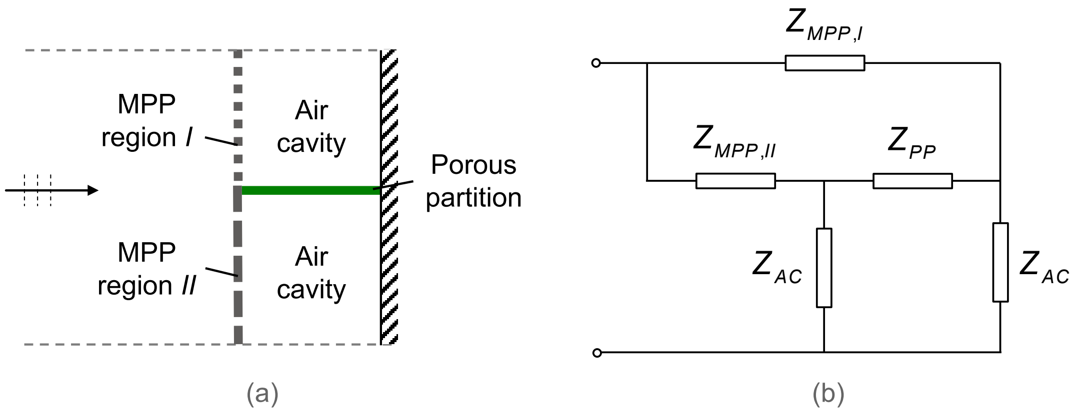

Fig. 2. Multi-size MPP absorber with porous partitions: (a) Schematic diagram of an elementary cell, and (b) equivalent acoustic circuit.

In that circuit, the acoustic transfer impedance Z_{PP} corresponds to the porous partition, $Z_{MPP,I}$ and $Z_{MPP,II}$ to the microperforated regions, and Z_{AC} = $-jZ_0\cot(k_0D)$ to the air cavities of thickness D, k_0 being the wave number in air. In case the partitions were rigid (the branch of Z_{PP} being removed), the whole absorber could be described from the parallel combination of the impedances of each microperforated region, Z_I and Z_{II}, coupled to the impedance of their respective air cavities, Z_{AC}. The point is that, in the case under study, these cavities are in turn coupled by a porous partition (Z_{PP}). This slight difficulty can be overcome by means of the Kennelly theorem or Y-Δ transform [18], which establishes equivalence for networks with three terminals as those depicted in Fig. 3.

Given that the impedance between any pair of terminals must be the same for both networks, the following relations between impedance elements must be fulfilled

$$Z_A = \frac{Z_1 Z_3}{Z_1 + Z_2 + Z_3} \tag{8}$$

$$Z_B = \frac{Z_1 Z_2}{Z_1 + Z_2 + Z_3} \tag{9}$$

$$Z_C = \frac{Z_2 Z_3}{Z_1 + Z_2 + Z_3} \tag{10}$$

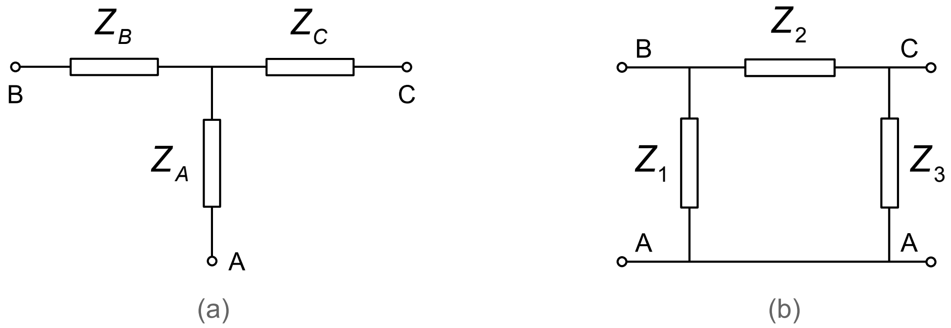

Fig. 3. Equivalence for networks with three terminals according to the Kennelly theorem or Y-Δ transform: (a) star (or Y) network, and (b) delta (or Δ) network.

Thereby, by substituting Z_1, Z_2, and Z_3 by Z_{AC}, Z_{PP} and Z_{AC}, respectively, the Kennelly theorem can be used in the equivalent circuit of Fig. 2. It should noted that every acoustic impedance in this circuit must be previously divided by the surface ratio $r_i = S_i/S$, where S_i and S are the cross-sectional surface areas of the corresponding acoustic element i and the elementary cell, respectively (S_i = 0.5S in the case of the porous partition). Once these transformations are applied, basic circuit analysis theory can be used to derive the surface impedance of the whole absorber from

$$Z_S = \left(Z_{MPP,I} + Z_B\right) \parallel \left(Z_{MPP,II} + Z_C\right) + Z_A = \frac{\left(Z_{MPP,I} + Z_B\right)\left(Z_{MPP,II} + Z_C\right)}{Z_{MPP,I} + Z_{MPP,II} + Z_B + Z_C} + Z_A \qquad (11)$$

It is straightforward then to derive the normal incidence sound absorption coefficient as

$$\alpha = 1 - \left|\frac{Z_S - Z_0}{Z_S + Z_0}\right|^2 \qquad (12)$$

Thereupon Eq. (11) is generic and may serve to analyze both cases (i.e. rigid and porous partition) in a simple manner without the need of additional corrections.

3.2. Finite Element Method (FEM)

For the purpose of verification of the proposed approach, a numerical model of an impedance tube setup was implemented using the finite element method. Following the procedure described in the standard ISO 10534-2 [20], the sound absorption coefficient under normal incidence for a multi-size MPP absorber with porous partitions was obtained. Fig. 4 shows the implemented numerical scheme.

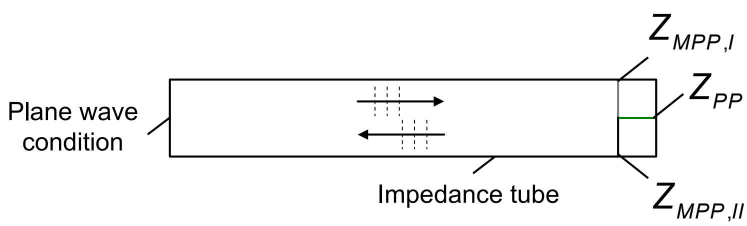

Fig. 4. Numerical scheme of a multi-size MPP absorber in an impedance tube.

In the numerical model, both the impedance tube and the air cavities domains were modeled as air. The MPP regions were modeled as acoustic transfer impedances using the Maa model, whereas the porous partition was modeled using the JCA model. The problem domains were discretized using quadratic tetrahedral elements, the maximum element size being set to 0.02 m (small enough relative to the acoustic wavelengths of interest). A plane wave incidence pressure was imposed at the opposite side of the resonant absorber and the sound absorption coefficient obtained from the pressure field data computed for each frequency in the numerical simulations.

4. RESULTS AND DISCUSSION

Results for the sound absorption coefficient of a multi-size MPP absorber with rigid and porous partitions are shown in Fig. 5. The predictions were obtained both with the ECM and the FEM, the geometrical characteristics of the microperforated regions, the porous partition and the air cavities being listed in Table 1.

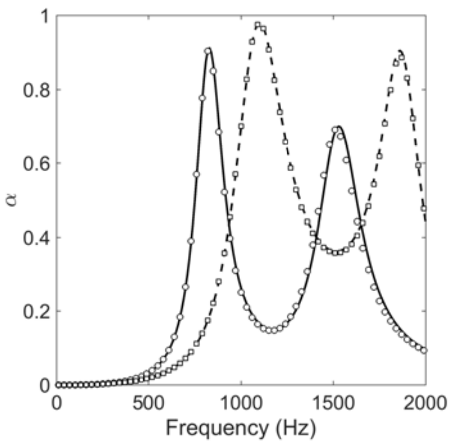

Fig. 5. Sound absorption coefficient of the multi-size MMP absorber with rigid (ECM: continuos line, FEM: ○) and porous (ECM: discontinuos line, FEM: □) partitions whose geometrical characteristics are listed in Table 1.

Table 1. Geometrical characteristics of the multi-size MPP absorber.

Microperforated regions				ϕ	R (mm)	t (mm)
MPP I				0.01	0.5	3
MPP II				0.04	1	3
Porous partitions	d (mm)	α_∞	ϕ	σ (Ns/m^4)	Λ (mm)	Λ' (mm)
PP	3	1	0.01	57600	0.5	0.5

The agreement between the proposed model and the finite element simulations is shown to be satisfactory in both cases. Regarding the absorption performance, it can be seen that the use of porous partitions shifts to higher frequencies the absorption peaks but notably enhances and broadens the sound absorption bandwith. It is worth mentioning that the geometrical characteristics of the porous partition were chosen similar to those of the microperforated regions but with smaller perforations. This choice lets conceive an absorber whose porous partitions are in turn rigid, thus extending its applicability for such cases in which a minimum structural strength is required while yielding an improved sound absorption performance.

5. CONCLUSIONS

This paper presents some preliminary work on the modeling of microperforated panel absorbers with porous partitions. For this purpose, the ECM together with the Maa and JCA approaches for microperforated panels and porous media, respectively, are used to predict the sound absorption coefficient of such devices. The proposed model was validated through numerical simulations using the FEM for both rigid and porous partitions configurations. Results show that the use of porous partitions instead of usual rigid ones may improve the sound absorption features of conventional MPP resonators. Preliminary results encourage to conduct a parametric study that lets look into the influence of the geometrical parameters on the acoustic behaviour of the absorber and show the utility of such model as a design tool.

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