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Technical note

Multi-layer perforated panel absorbers with oblique perforations

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ABSTRACT

Many different solutions exist to improve the low-frequency sound absorption performance of acoustic resonators, extending or coiling up space into the resonator being some of the most widespread. In this context, modern additive manufacturing processes pose a new scenario in which these devices can be engineered to yield outstanding acoustic properties. In a recent work by the authors, a solution consisting of a perforated panel with oblique perforations was analyzed, results showing an enhanced sound absorption performance when compared to traditional perforated panel absorbers. This technical note aims to show the potential of these panels when used in multi-layer arrangements both to widen their effective sound absorption bandwidth and to improve their low-frequency performance. A simplified approach that relies on the fluid-equivalent theory was used together with the Transfer Matrix Method (TMM) to analyse different configurations, prediction results showing a good agreement when compared to experiments in an impedance tube over additive manufactured samples. Unlike other perforated-based solutions, the proposed system avoids addressing the cavity design while showing improved sound absorption features.

1. Introduction

Perforated panel absorbers are an excellent alternative to conventional porous media because of their structural features and remarkable sound absorption properties [1]. Many examples of noise reduction applications of these acoustic resonators can be found in the literature, such as muffler devices [2], noise barriers [3], or building isolation walls [4]. These systems typically consist of a flat panel with periodically arranged perforations backed by an air cavity, resulting in an acoustic resonator. When these perforations are reduced to submillimeter size, wide-band sound absorption of one or two octaves can be achieved from these so-called Micro-Perforated Panel absorbers (MPPs) [5]. In the pursuit of new designs that let further broaden their sound absorption bandwidth, some authors have proposed different solutions based on the series [6] and parallel [7] combination of different MPP absorbers, the production of MPPs with ultra-micro-perforations [8] or the use of micro-perforated partitions in the backing cavity [9]. Among these, multi-layer MPP arrangements are probably one of the most extensively investigated.

Numerous authors have studied the acoustic behavior of multi-layer perforated panel systems by using different approaches. For instance, Lee and Kwon [10] analyzed the sound absorption coefficient of engine exhaust muffler composed of multiple perforated panels by using the Transfer Matrix Method (TMM). On the other hand, Sakagami et al. [11] used electro-acoustical equivalent circuit analysis to predict the acoustic properties of a space absorber consisting of a double layer MPP without a rigid backing. Ruiz et al. [12] proposed the use of simulated annealing to find the proper combination of MPPs for a target sound absorption bandwidth by using the Impedance Translation Method (ITM). Later on, a similar procedure was proposed by Kim and Bolton [13] to optimize these systems both in terms of sound absorption and transmission loss by means of the TMM and the genetic algorithm. Bravo et al. [14] showed that the structural resonances of multi-layer structures made up of thin micro-perforated panels could also improve the absorption performance of these devices. In a work by Pieren and Heutschi [15], lightweight multilayer curtains were represented as discrete impedances similar to that of a perforated plate, the Equivalent Circuit Method (ECM) being used to predict their sound absorption. An extensive review of multi-layer MPPs as sound absorbers in buildings can be found in a recent work by Cobo and Simón [16]. Even though the high potential of these solutions as wide-band absorbers has been sufficiently proven, the still large

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space required to achieve an effective low-frequency sound absorber prompts the need for alternative designs.

This work proposes a multi-layer perforated panel absorber with oblique perforations both to improve the sound absorption performance and to reduce the total size of these resonator systems. As previously discussed by several authors [17,18], the use of oblique perforations can significantly enhance the low-frequency sound absorption when compared to conventional porous materials. In a recent work by the authors [19], a simplified approach that relies on the fluid-equivalent theory was proposed to study the acoustic behavior of acoustic resonators with oblique perforations, results showing a good agreement when compared to measurements in an impedance tube over additive manufactured samples. This approach together with the TMM is herein used to predict the acoustic properties of multi-layer perforated panel absorbers with oblique perforations. Theoretical predictions were compared to experiments on an impedance tube over different arrangements of samples with oblique perforations. Results showed that effective low-frequency sound absorption can be achieved by using the proposed systems without the need for addressing the backing cavity design and significantly reducing the total depth of the absorber.

This technical note is structured as follows: In Section 2, multi-layer perforated panel systems are described, the proposed fluid-equivalent model together with the corrections necessary to account for the oblique perforations being recalled. In Section 3, the TMM theory used to analyze the sound absorption performance of these devices is presented, along with a short description of the preparation of the samples and experimental setup used to verify the applicability of the model. In Section 4, experimental results for several multi-layer configurations are compared to the model predictions in terms of the sound absorption coefficient, an analysis of the effect of the perforation angle and the inter-panel/backing cavity depths on this parameter being also carried out, along with a brief discussion on the effective bandwidth of these absorbers. Finally, Section 5 summarizes the main conclusions of this work.

2. Background theory

2.1. Multi-layer perforated panel systems

Multi-layer perforated panel systems usually consist of a series arrangement of air-spaced perforated panels intended to achieve a wider effective absorption bandwidth than single panel absorbers. These assemblies also give rise to additional possibilities such as the tuning of multiple target frequencies if an appropriate combination of panel features and air cavity depths is chosen. Let consider for instance the multi-layer perforated panel system depicted in Fig. 1, which is composed of N panel-cavity subsystems backed by a rigid wall.

It can be seen that the absorber is composed of successively interconnected acoustic elements, where *PP* and *AC* refer to the perforated panels and the air cavities, respectively. Under plane wave incidence, assuming each acoustic element to be laterally infinite, continuity of pressure and particle velocity exists at each element interface. Consequently, each acoustic element can be characterized mainly by its geometrical characteristics in the case of the perforated panels and its depth in the case of the air cavities.

Many authors [5,20,21] have proposed theoretical models to predict the acoustic properties of perforated panels provided their geometrical characteristics are known beforehand. Once these properties are determined, it is straightforward to obtain the sound absorption performance of the whole assembly by using the TMM to be detailed in Subsection 3.1. The predictive model hereafter used to analyze the acoustic behavior of the absorber relies on the fluid-equivalent theory described next.

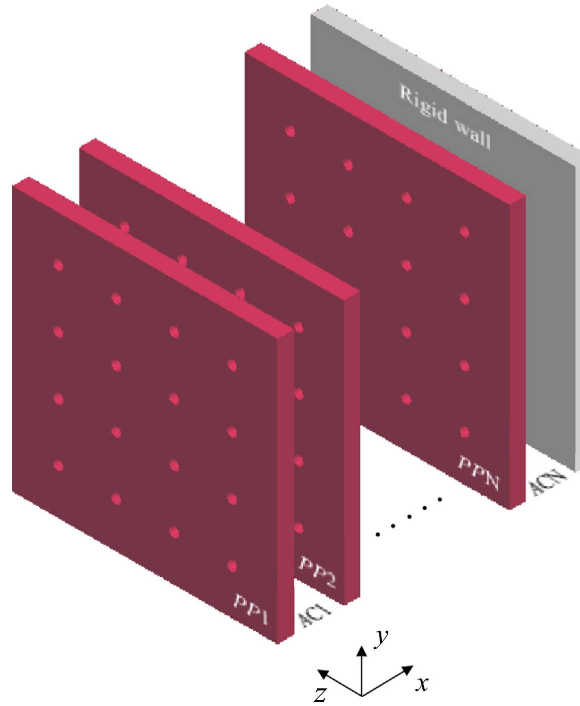

Fig. 1. Multi-layer perforated panel system composed of N panel-cavity subsystems backed by a rigid wall (AC: air cavity, PP: perforated panel).

2.2. Fluid equivalent to a perforated panel

As mentioned above, the acoustic properties of a perforated panel can be determined from its geometrical characteristics, to list: open area ratio (i. e. the perforation rate), the radius of the perforations, and panel thickness; viscothermal losses in the inner air depending mainly on these two latter parameters. Atalla and Sgard [21] proposed a simple model to describe the acoustic behavior of a perforated panel whose solid frame is motionless replacing the air inside the perforations by an equivalent fluid on the macroscopic scale. Thereby, for a rigid flat panel with uniform circular holes normal to its surface, the expression of the acoustic transfer impedance for wavelengths much larger than the dimensions of the panel can be simplified to

$$Z_{PP} = \frac{1}{\phi} j\omega\rho d \tag{1}$$

where ϕ is the open area ratio, ω the angular frequency, d the thickness of the panel, and ρ the effective density of the inner air, which can be written as

$$\rho = \rho_0\alpha_\infty \left(1 + \frac{\sigma\phi}{j\omega\rho_0\alpha_\infty} G_C(s)\right) \tag{2}$$

where ρ_0 is the air density, α_∞ the geometrical tortuosity, and σ the flow resistivity of the panel, with

$$G_C(s) = -\frac{s\sqrt{-j}}{4}\frac{J_1\left(s\sqrt{-j}\right)}{J_0\left(s\sqrt{-j}\right)}\left(1 - \frac{2}{s\sqrt{-j}}\frac{J_1\left(s\sqrt{-j}\right)}{J_0\left(s\sqrt{-j}\right)}\right) \tag{3}$$

where $s = R(\omega\rho_0\alpha_\infty/\eta)^{1/2}$, R is the radius of the perforations, η the dynamic viscosity of air, and J_0 and J_1 represent the Bessel functions of the first kind and zeroth and first orders, respectively.

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Note that thermal dissipation effects were neglected in Eq. (1), being this assumption valid for panels whose thickness and shape of the perforations are small [21]. Nevertheless, additional corrections must be done in the previous expressions to account not only for the dissipative and inertial effects resulting from the finite thickness of the panel but also for the perforation angle in the case under study.

2.3. Corrections for a perforated panel with oblique perforations

In a previous work by the authors [19], a simplified model that relies on the previous fluid-equivalent theory was proposed to describe the macroscopic behavior of perforated panels with oblique perforations. Briefly, the panel is replaced by an equivalent fluid whose acoustic properties can be retrieved from redefined macroscopic parameters for the air inside the oblique perforations. In this model, the surface resistance term $R_B = 2R_S$, where $R_S = (\eta\rho_0\omega/2)^{1/2}$, was added twice in the acoustic transfer impedance of the panel (Eq. (1)) to account for the viscous dissipation at its front and rear apertures (divided by ϕ to consider the surface of the panel); whereas an equivalent tortuosity was used to account for the angle of the perforations with respect to the normal of the panel surface, the following macroscopic parameters being redefined

$$\alpha_\infty = \frac{1}{\cos^2\theta} + 2\frac{\varepsilon_e}{d/\cos\theta} \tag{4}$$

$$\sigma = \frac{8\eta}{\phi R^2 \cos^2\theta} \tag{5}$$

where θ is the perforation angle, and $\varepsilon_e = (1 - 1.13\xi - 0.09\xi^2 + 0.27\xi^3)8R/(3\pi)$ is the correction length proposed by Jaouen and Bécot [22], which accounts both for the interaction between perforations and the effective length of the panel, with $\xi = 2(\phi/\pi)^{1/2}$.

Therefore, once the acoustic transfer impedance of a single perforated panel with oblique perforations is defined, it follows using a method to analyze an absorber system composed of multiple perforated panels and air cavities.

3. Materials and methods

3.1. Transfer Matrix Method (TMM)

The Transfer Matrix Method (TMM) is an extended plane-wave based methodology frequently used to study the acoustic properties of multi-layer systems for its simplicity and ease of use. This method not only simplifies the analysis of complex multilayer systems but also allows calculating acoustic field quantities in a simple way for the sake of their design and development. In this method, each acoustic element of Fig. 1 is represented using a generic transfer matrix $\mathbf{T_i}$ that relates the acoustic pressure and particle velocity at the upstream (sub-index u) and downstream (sub-index d) of the element [23]

$$\begin{bmatrix} p_{i,u} \\ v_{i,u} \end{bmatrix} = \mathrm{T_i}\begin{bmatrix} p_{i,d} \\ v_{i,d} \end{bmatrix} = \begin{bmatrix} T_{i,11} & T_{i,12} \\ T_{i,21} & T_{i,22} \end{bmatrix}\begin{bmatrix} p_{i,d} \\ v_{i,d} \end{bmatrix} \tag{6}$$

Assuming the upstream and downstream particle velocities in a thin perforated panel are the same [24], the above transfer matrix can be simplified for this type of sub-system to

$$\mathrm{T_{PP}} = \begin{bmatrix} 1 & Z_{PP} \\ 0 & 1 \end{bmatrix} \tag{7}$$

where Z_{PP} is the acoustic transfer impedance of the perforated panel including the corrections derived in Subsection 2.3.

On the other hand, the transfer matrix corresponding to an air cavity having a depth D can be represented by

$$\mathrm{T_{AC}} = \begin{bmatrix} \cos(k_0D) & jZ_0\sin(k_0D) \\ \frac{j}{Z_0}\sin(k_0D) & \cos(k_0D) \end{bmatrix} \tag{8}$$

where $Z_0 = \rho_0c_0$ and $k_0 = \omega/c_0$ are the characteristic impedance and the wave number in air, respectively, c_0 being the sound propagation velocity in air.

Hence, by successively multiplying the individual transfer matrices of all the elements of the multi-layer perforated panel system, the overall transfer matrix can be obtained

$$\mathrm{T_M} = \mathrm{T_{PP,1}T_{AC,1}T_{PP,2}T_{AC,2}\ldots T_{PP,N}T_{AC,N}} = \begin{bmatrix} T_{M,11} & T_{M,12} \\ T_{M,21} & T_{M,22} \end{bmatrix} \tag{9}$$

The normal incidence sound absorption coefficient of the whole absorber can thus be calculated as

$$\alpha = 1 - \left|\frac{Z_S - Z_0}{Z_S + Z_0}\right|^2 \tag{10}$$

where $Z_S = T_{M,11}/T_{M,21}$ is the surface impedance of the multi-layer system.

3.2. Sample preparation and experimental rig

Both the sound absorption performance of these multi-layer systems and the applicability of the previous modeling methodology were assessed by performing impedance tube measurements over additive manufactured samples. Specifically, circular samples (30 mm in diameter) having different perforation radius, open area ratios, and perforation angles, were prepared using the Projection micro-stereolithography (PμSL) printing technology [25,26] in the Ember 3D printer from Autodesk. Table 1 summarizes the geometrical characteristics of some of the manufactured samples. Subsequently, the sound absorption coefficient of different multi-layer arrangements of these samples was measured by means of the impedance tube apparatus BSWA SW470 following the procedure described in the ASTM E1050-12 standard [27]. A schematic representation of the prepared samples together with pictures thereof and a detailed view of a multi-layer arrangement mounted in the impedance tube are depicted in Fig. 2. Further details of both the sample preparation process and the experimental setup can be found in [19].

4. Results and discussion

4.1. Straight perforations vs oblique perforations

First, the advantages in terms of sound absorption and space reduction of using oblique perforations instead of straight ones in a multi-layer perforated panel absorber will be shown. To this end, the sound absorption coefficient of configurations composed of two panels having either straight ($\theta_{1,2} = 0°$) or oblique ($\theta_{1,2} = 60°$) perforations was measured. Both the inter-panel and backing cavities had the same depth $D_{1,2} = 5$ mm, the geometrical characteristics of the panels being those corresponding to PP#1 and PP#3 in Table 1. Furthermore, all the experimental results obtained using the impedance tube method described in the previous section were compared against theoretical predictions resulting from the proposed model. It should be noted that for simplicity only multi-layer systems composed of two panels were analyzed in this work even though, as stated above, the modeling methodology could be extended for cases having more panels. Fig. 3 shows the sound absorption coefficient for the two analyzed cases.

Table 1
Geometrical characteristics of the perforated panels under study.

	b (mm)	*d* (mm)	ϕ (%)	*R* (mm)	θ (°)
PP#1	13.2	4.8	3.5	1.4	0
PP#2		4.8	3.5	1.5	40
PP#3		5.0	4.0	1.5	60

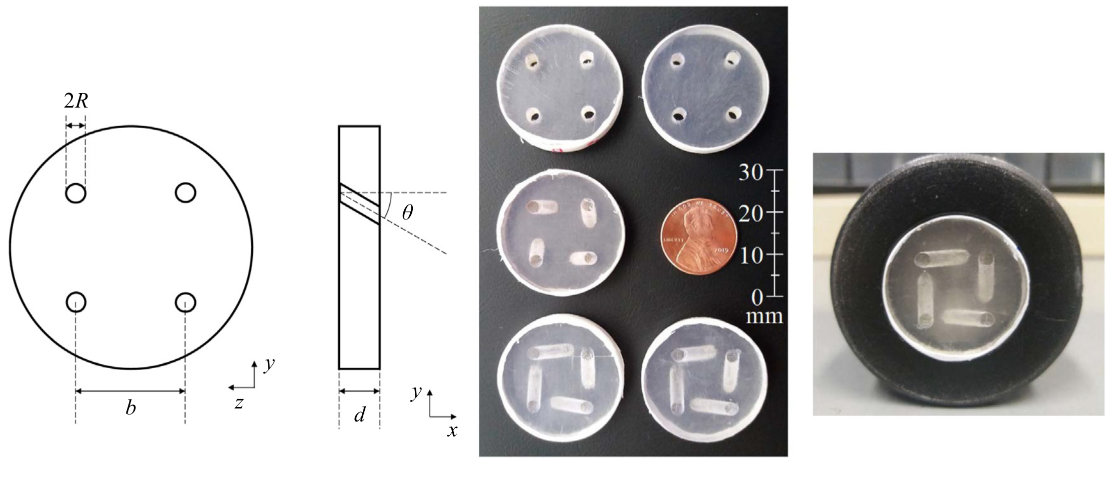

Fig. 2. Additive manufactured samples: (a) schematic representation; (b) picture of some samples (top: $\theta = 0°$, center-left: $\theta = 40°$, and bottom: $\theta = 60°$); and (c) detailed view of the mounting on the impedance tube.

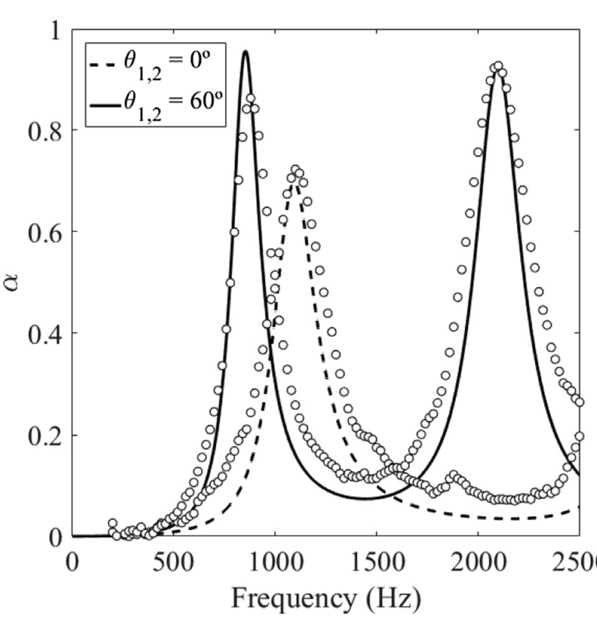

Fig. 3. Comparison of the analytical (lines) and experimental (circles) results for a multi-layer perforated panel system with straight ($\theta_{1,2} = 0°$) and oblique perforations ($\theta_{1,2} = 60°$). The geometrical characteristics of the panels are listed in Table 1.

Results indicate that using panels with oblique perforations not only significantly shifts the resonance peak to lower frequencies, but also increases its amplitude when compared to the system with straight ones. Given that the thickness, the open area ratio and the radius of the perforations of the panels, as well as the depths of the air cavities, are the same in both cases, a much lower frequency resonator was achieved by using oblique perforations, the total size necessary to absorb sound in this frequency range being thereupon reduced. As for the theoretical predictions, it can be seen that the model results follow the trends of the experimental data with reasonable agreement. In this regard, even though the locations of the resonance peaks match properly well, the amplitude values are overestimated for the configuration with oblique perforations. These differences may be attributed to the inner roughness resulting from the fabrication process for such intricate perforations, the influence of the printing technology in this regard and on the final dimensions being a common difficulty in additively manufactured porous media [28].

4.2. Influence of the perforation angle

In the following step, and to further illustrate the influence of the perforation angle on the sound absorption performance, multi-layer systems whose perforated panels had different perforation angles were analyzed. For this purpose, the sound absorption coefficient of systems in which the perforation angle of the second (rear) panel is changed while the first (front) panel is kept with straight perforations were tested. In Fig. 4, results for panels with perforation angles $\theta_{1,2} = 0°$ (PP#1), $\theta_2 = 40°$ (PP#2), and $\theta_2 = 60°$ (PP#3), whose geometrical characteristics are listed in Table 1, are shown.

In view of the results, it is evident that a frequency shift of the resonance peaks occurs as the perforation angle of the rear panel increases along with a remarkable rise of the peak absorption coefficient with respect to the reference straight case. These effects can be explained by the higher values of the tortuosity and flow resistivity resulting from an increase of the effective length of the panel (i. e. the distance that the acoustic wave travels between its ends). Regarding the model predictions, results show an acceptable agreement when compared with the measured values, differences being for the most part linked to the previously discussed manufacturing accuracy. It should be also pointed out that the analyzed

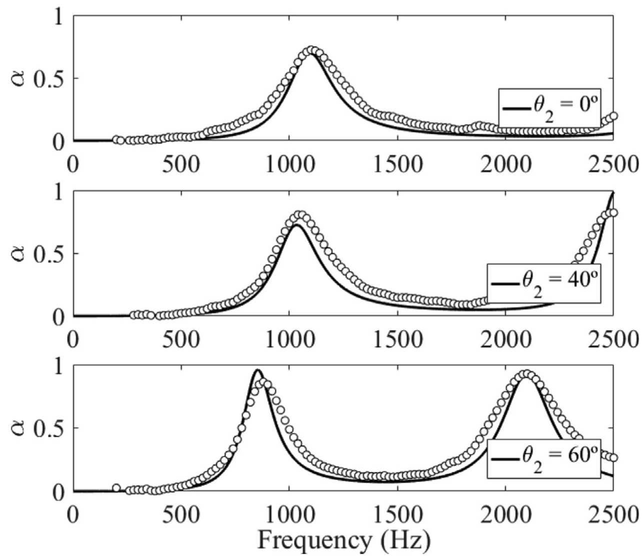

Fig. 4. Influence of the perforation angle of the rear panel (top: $\theta_2 = 0°$, center: $\theta_2 = 40°$, and bottom: $\theta_2 = 60°$) on the sound absorption coefficient of a multi-layer perforated panel system. Solid lines: analytical; circles: experiments.

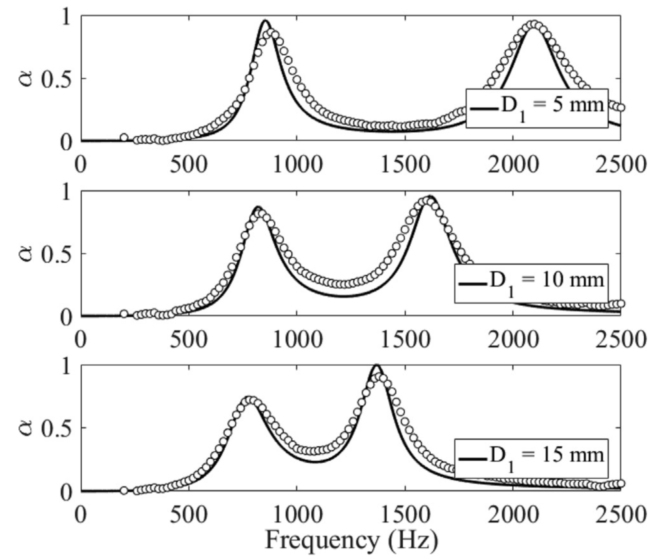

Fig. 5. Influence of the inter-panel cavity depth (top: $D_1 = 5$ mm, center: $D_1 = 10$ mm, and bottom: $D_1 = 15$ mm) on the sound absorption coefficient of a multi-layer perforated panel system. Solid lines: analytical; circles: experiments.

samples have a circular cross-section, which differs from the infinite lattice arrangement assumed by most analytical models as the one proposed. Alternatively, numerical methodologies that rely on the linearized Navier-Stokes equations [29,30] could be used to rigorously account both for the actual dimensions of the samples and the full viscothermal dissipation mechanisms.

All the same, the simplified approach herein proposed not only reveals the improved sound absorption performance and tuning capabilities of these systems but may also be very helpful to conceive new arrangements in different applications. For instance, in the typical case in building acoustics in which a regular panel must be used in the visible front surface to meet conventional aesthetic criteria, the rear panel may serve to effectively choose the target frequencies to absorb while keeping the same total space depth. In this regard, the proposed solution can more easily overtake possible space constraints when compared to simpler techniques that require using thicker panels or larger air cavity depths.

4.3. Influence of the inter-panel and backing cavity depths

So far, the systems analyzed were composed of panel-cavity sub-systems whose cavities had the same depth. To better understand the acoustic behavior of these multi-layer sound absorbers, configurations having different inter-panel and backing cavity depths were analyzed. In a first step, three distinct inter-panel cavity depths were tested ($D_1 = 5$ mm, 10 mm, and 15 mm) while the backing cavity was kept the same as in the previous cases ($D_2 = 5$ mm). The front and rear panels used for the measurements were PP#1 and PP#3, respectively. Fig. 5 shows the influence of changing the inter-panel cavity depth on the sound absorption coefficient of the multi-layer system.

Notice that an increase of the inter-panel cavity depth shifted the second resonance peak to lower frequencies while the first peak location barely changed even while its amplitude diminished probably due to proximity effects between resonances. It is noteworthy to highlight that the larger the inter-panel cavity depth the closer the resonance peaks get. As a result, the sound absorption in the intermediate frequency range improves, this being a very useful feature of the multi-layer system to achieve more general sound absorption in that region.

In a second step, the inter-panel cavity depth was kept to $D_1 = 5$ mm while different air backing cavity depths were analyzed ($D_2 = 5$ mm, 10 mm, and 15 mm), the panels used in the experiments being the same as in the previous analysis. Fig. 6 shows the effect of varying the backing cavity depth on the sound absorption coefficient of the whole system.

In this case, it was the first resonance peak that shifted to lower frequencies while the second resonance peak location slightly changed. This effect is explained by the fact that it was the panel having the largest backing space (i. e. inter-panel cavity plus second panel-cavity sub-system) which was modified. Therefore, the backing cavity is expected to be the one that defines the minimum absorption frequency provided that the same panels are used. On the other hand, prediction model again shows a relatively good

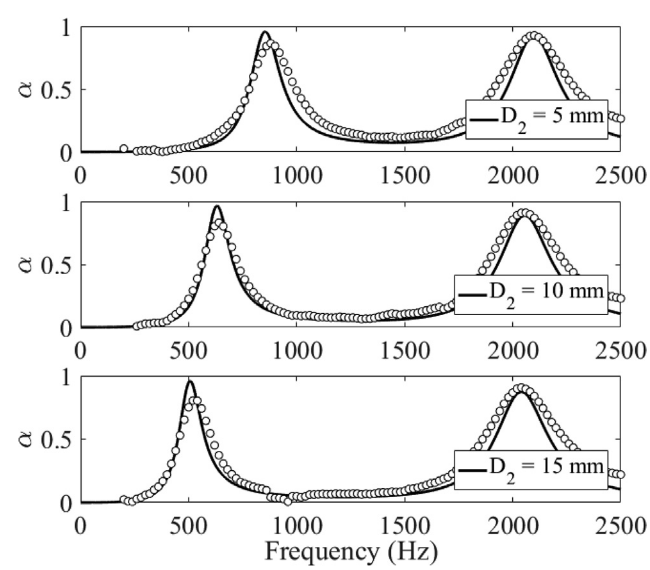

Fig. 6. Influence of the backing cavity depth (top: $D_2 = 5$ mm, center: $D_2 = 10$ mm, and bottom: $D_2 = 15$ mm) on the sound absorption coefficient of a multi-layer perforated panel system. Solid lines: analytical; circles: experiments.

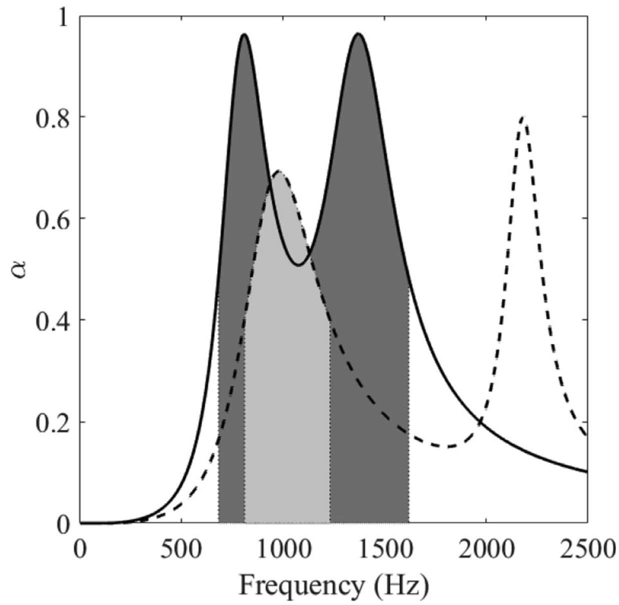

Fig. 7. Sound absorption coefficient curves and effective bandwidth (shadowed regions) of multi-layer perforated panel absorbers with straight (discontinuous line and light grey) and oblique (continuous line and dark gray region) perforations. The geometrical characteristics of both systems were: $d_1 = 5$ mm, $d_2 = 4$ mm, $D_1 = 16$ mm, $D_2 = 5$ mm, $\phi_1 = 5\%$, $\phi_2 = 3\%$, $R_1 = 0.3$ mm, $R_2 = 0.7$ mm, $\theta_1 = 0°$, and $\theta_2 = 0°/60°$ (straight/oblique cases).

agreement when compared to measurement data both in the inter-panel and backing cavity analysis, being therefore a tool of great interest in the preliminary design stage of these devices.

4.4. Effective bandwidth of multi-layer perforated panels with oblique perforations

Previous examples showed that the proposed resonators allowed both working in different one-third octave bands for more general sound absorption and improving the low-frequency performance while reducing the space requirements when compared to conventional ones (i. e. systems with straight perforations). Finally, a brief discussion on the improved broadband features of these absorbers in terms of their effective bandwidth is given. In Fig. 7, a comparison in terms of the sound absorption coefficient of two systems having the same geometrical characteristics ($d_1 = 5$ mm, $d_2 = 4$ mm, $D_1 = 16$ mm, $D_2 = 5$ mm, $\phi_1 = 5\%$, $\phi_2 = 3\%$, $R_1 = 0.3$ mm, $R_2 = 0.7$ mm) is shown, the only difference being one having panels with straight perforations ($\theta_{1,2} = 0°$) and the other using oblique perforations only in the rear panel ($\theta_1 = 0°$, $\theta_2 = 60°$). The effective bandwidth (i. e. frequency range delimited by the frequencies of half maximum absorption) for each case is depicted using shadowed regions (straight perforations: light grey; oblique perforations: dark gray).

As can be seen, the multi-layer perforated panel with oblique perforations overcomes that with straight ones both in the peak absorption amplitude and the effective bandwidth. To achieve a similar curve using conventional multi-layer arrangements may not only require using much smaller perforations but also much thicker panels or lower open area ratios, which may be a constraint for some specific applications, as commented in [19]. Nonetheless, further research must still be carried out on the development of inexpensive fabrication techniques that let produce these absorbers for their settlement in the acoustic materials industry.

5. Conclusions

Perforated panel absorbers may not only show excellent sound absorption properties but also a higher durability and mechanical strength than most conventional porous media. For this reason, the development of new designs that let further improve their sound absorption performance is of great interest in those noise control applications in which both acoustical and structural features are desired. In the seek for a simple but versatile solution that could be used in such scenarios, a multi-layer perforated panel absorber with oblique perforations was herein proposed. By knowing the geometrical characteristics of the panels and air cavities, fluid-equivalent theory along with the Transfer Matrix Method (TMM) were used to develop a simplified approach that let predict the sound absorption performance of these systems. The sound absorption coefficient of different additive manufactured samples was measured, results serving both to assess the simplified approach and to show the potential of these multi-layer systems as sound absorbers. Several conclusions were drawn from the above results: (i) the use of oblique perforations allows increasing the effective length of the panel thus reducing the space requirements to absorb low frequencies of conventional multi-layer perforated systems; (ii) there is no need to address the design of the cavities, thus overcoming requirements for engineering of alternative solutions rarely adopted in practice; (iii) the resonance frequencies of the system can be tuned without modifying the frontal panel, thus being of great interest in those applications in which decorative or aesthetic effects are important. Furthermore, the development of the proposed system is not limited to 3D printing technologies, as similar panels even if not so refined may still be manufactured using conventional techniques such as punching or milling to make the fabrication process affordable. Nevertheless, the rise of additive manufacturing techniques allows innovative designs difficult to conceive until recently to be fabricated, extending its use into the acoustic materials industry presumably being one of the challenges to be faced in the forthcoming years.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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