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Sound absorption assessment of variable perforated shapes for room acoustic design

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ABSTRACT

In room acoustics design, the sound quality within a room depends on several variables such as the size, shape, surface orientation, materials as well as background noise. Regarding the lining materials in multipurpose auditoriums, contemporary architectural trends require the development of new solutions, with novel materials that fulfil architects requests and provide simultaneously a suitable acoustic performance. These materials should therefore provide either different sound absorption or a sound diffusion coefficient in order to control reverberation, provide intelligibility and correct sound defects of rooms, for several types of use. In this paper a preliminary study is carried out, where we explore the use of different shapes to control reverberation using an analytical approach, where sound absorption coefficient is evaluated assuming normal incidence.

Keywords: Room acoustics, sound absorption, analytical approach, perforated shapes
I-INCE Classification of Subject Number: 35

1. INTRODUCTION

In room acoustics design, an important challenge for acoustic engineers is related with the acoustic performance of multi-purpose auditoriums which are typically designed to suite several performance requirements [1]. Within this intent, the analysis of several scenarios is usually performed individually and then an acceptable solution that may suite several situations is selected.

One way of providing a more appropriate acoustic performance for each function of the auditorium, is using variable absorption techniques to control reverberation time and other relevant acoustic parameters. The technique can be employed through the use of retractable curtains, hinged panels, acoustic banners, adjustable audience seats or movable reflectors [2, 3].

In terms of acoustical requirements for different purposes, such as conferences, or concerts, the same space should fulfil different needs. However, designing variable acoustic solutions just for a purpose may not cover all requirements defined for a

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specific purpose. For instance concert use refers to different types of music, like folk music and rock music which requires different acoustical characteristics.

When a multipurpose hall switches from conference use to concert use, reflective surfaces should be replaced with sound absorptive materials. Panels with acoustically differing faces configured to serve different functions can be developed and proposed as a variable acoustic solution [4]. In this case, sound absorption characteristics of selected materials are determined according to the specific volume of interest and defined uses.

If the volume of the space is assumed to be constant, changing sound absorption properties of materials may supply proper reverberation time [5]. Porous or fibrous materials, panel absorbers, or volume absorbers can be preferred as sound absorbent materials. The properties of porous materials (such as fibre length, density or material thickness), the air gap width behind panels and the lining separating porous material from the auditorium may be decisive in the characteristics of a variable acoustic system. If this lining is a multiple perforated panel, sound absorption performance of the system depends also on the properties of each perforated panel such as perforation type, diameter, central distance and perforation ratio

Therefore, by modifying some or all these parameters, a range of sound absorption coefficients provided by one such variable system is possible. Within this range, perforation can be arranged according to the hall needs from functional differences.

In this paper a preliminary study is carried out to assess sound absorption of perforated shapes that may be suitable for achieving a variable acoustic solution, for room acoustic design, making use of combinations of macro-perforated panels with different perforation rates and micro-perforated panels, porous materials and airgaps of varying thicknesses. With this propose an analytical model making use of the transfer matrix method to obtain sound absorption coefficient for normal incidence is used to evaluate different configurations using circular shaped perforated panels.

2. ANALYTICAL MODEL DESCRIPTION

The approach used in this paper to model the sound absorption of perforated panels is based on the conversion of the acoustic impedance of a single hole in an average value corresponding to the open area of the panel. The perforated panel is considered as a set of short tubes of similar length to the thickness of the panel, and the non-perforated material is assumed to be rigid. It is also assumed that the wavelength of the sound that propagates is sufficiently large compared with the cross-sectional dimension of the tube (i.e., hole). This method includes the terms due to viscosity of air, radiation (from a hole in a baffle), interactions between holes and the effects of reactance of the cavity.

The perforated panel is studied using the concept of the transfer matrix method [6], where the acoustic impedance along the normal direction of an interface of a material is determined using the continuity of particle velocity (on both sides of the interface) and knowing the acoustic properties of the medium (characteristic impedance, Z_{c_a}, and the wavenumber or propagation constant, k_a).

Knowing the acoustic impedance it is possible to determine the sound absorption coefficient and then estimate its value for diffuse field.

The arrangement of the absorber is shown in Figure 1. The system is considered as locally reacting, assuming the normal incidence of sound to the plane of the interface.

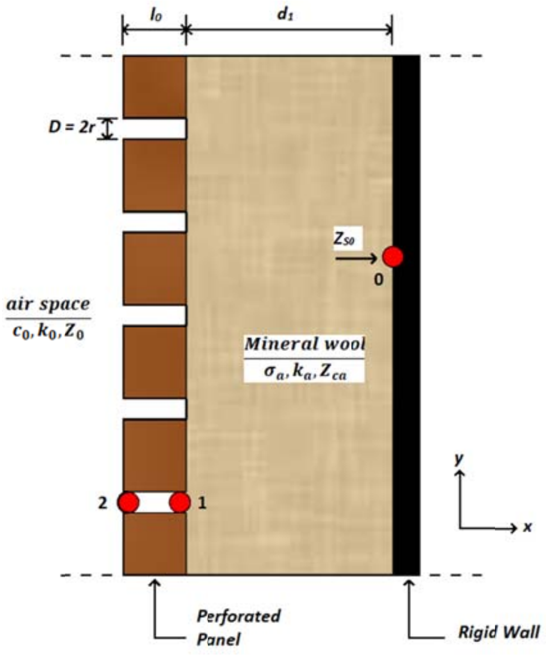


Figure 1 - Configuration of the perforated system

At point 0 the normal surface impedance is infinite ($Z_{s_0} = \infty$), since it is considered as a rigid wall. The normal surface impedance at point 1,

$$Z_{s_1} = -\mathrm{i}\, Z_{c_a} \cot\left(k_a d_1\right) \tag{1}$$

where Z_{c_a} is the characteristic impedance of the mineral wool, and k_a is the wavenumber (or propagation constant). So, in order to use this model, it is necessary to have the mineral wool characterized in respect to these physical quantities by means of measurement, as reported by Cox and D'Antonio [7], or using empirical predictions from regression analyses of measured data.

The surface impedance of the system (point 2) along the normal direction is:

$$Z_{s_2} = Z_{s_{panel}} + Z_{s_1} \tag{2}$$

where the normal surface impedance of a perforated panel corresponds the idea of the impedance of one hole (tube) being converted into a single averaged value corresponding to the fraction of perforated open area and it is given by:

$$Z_{s_{panel}} = \frac{Z_{s_{tube}}}{\varepsilon} \tag{3}$$

and, according to Crandall [8], the impedance of one hole (tube) is

$$Z_{s_{tube}} = \mathrm{i}\,\omega\rho_0\, l_0 \left[1 - \frac{2\, J_1\left(k_s r\right)}{\left(k_s r\right) J_0\left(k_s r\right)}\right]^{-1} + \left(2\sqrt{2\omega\rho_0\eta} + \rho_0 c_0 \pi^2 \left(\frac{2r}{\lambda}\right)^2 + \mathrm{i}\omega\rho_0\delta\right) \tag{4}$$

where ρ_0 is the air density, ω is the angular frequency, l_0 is the thickness of the perforated panel, r is the radius of the circular hole, η is the coefficient of air viscosity, λ is the wavelength, J_n is the n$^{\text{th}}$ order of Bessel function and $k_s = \sqrt{-\mathrm{i}\omega\rho_0/\eta}$ is the Stokes wave number.

The second term on the right hand side is the end correction, which also accounts for the interaction between the orifices via the expression (see [7] and [8])

$$\delta = \frac{16r}{3\pi}\left(1 - 1.47\sqrt{\varepsilon} + 0.47\sqrt{\varepsilon^3}\right) \tag{5}$$

The sound absorption coefficient for a sound incidence angle θ with respect to the normal of the surface is given by

$$\alpha(\theta) = 1 - \left|R(\theta)\right|^2 \tag{6}$$

where $R(\theta)$ is the reflection coefficient that can be expressed in terms of the normal surface impedance Z_{s_3} of the system:

$$R(\theta) = \frac{Z_{s_3}\cos\theta - Z_0}{Z_{s_3}\cos\theta + Z_0} \tag{7}$$

where $Z_0 = \rho_0 c_0$ is the acoustic impedance of the air.

3. PROPERTIES OF THE LAYERS COMPOSING ABSORBING SYSTEMS

The panel systems analysed consist of one or two layers of perforated panels with circular holes with thickness, diameter of the hole and perforation rates defined in Table 1, which are mounted over a resonating cavity whose thicknesses may vary between 0 and 150 mm. The resonating cavity may be partially filled with a porous material, with the properties of the mineral wool which are also defined in Table 1.

Table 1 – Properties of perforated panels and porous materials

ID	**Perforated panels**	**Thickness (mm)**	**Diameter of the hole (mm)**	**Perforation rate (%)**
MPA	Macro-Perforated	12	8	6.4
MPB	Macro-Perforated	12	6	3.6
MPC	Macro-Perforated	12	6	64
mP	Micro-Perforated	0.8	0.5	6.4
ID	**Porous material**	**Thickness (mm)**	**Density (kg/m^3)**	**Flow resistivity** Pa.s.m^{-2}
MW	Mineral Wool	40mm	40	28377

4. PARAMETRIC STUDY: ANALYTICAL RESULTS

In this section a parametric study is carried assuming different sets of configurations, with the aim of analysing the contribution of different layers in sound absorption of the system. In the following sub-sections, the influence of different components and configurations is therefore analysed.

4.1 Presence and position of the porous material

The first set of configurations was designed to evaluate the influence of the presence and position of the mineral wool placed inside the airgap with 150mm thickness of a system lined with a macro-perforated panel (MPA or MPB). Details regarding the configurations are displayed in Figure 1 and Table 2.

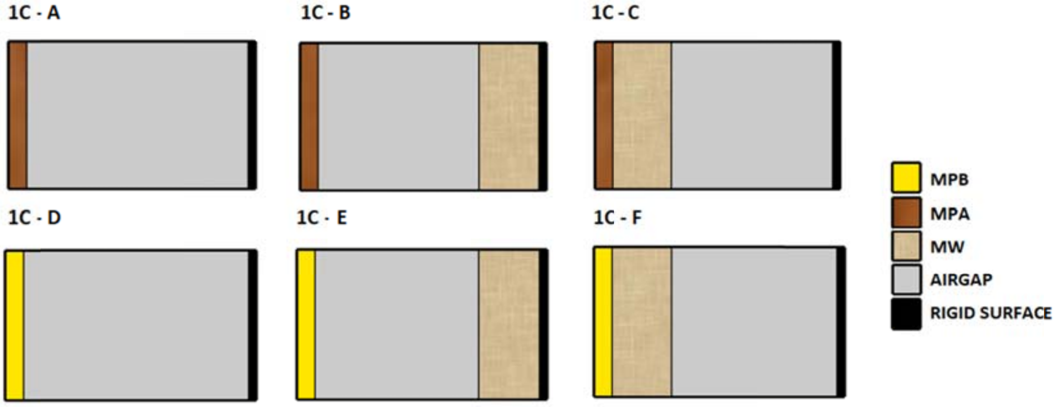


Figure 2 – Geometries used in the first set of configurations (configuration #1) to analyze the influence of the presence and position of the mineral wool

Table 2 – Definition of the different layers of each system of the first set of configurations

Configuration	**Layer 1**	**Layer 2**	**Layer 3**	**Layer 4**
1C - A	MPA	-	Airgap d1=150mm	-
1C - B	MPA	-	Airgap d1=110mm	MW
1C - C	MPA	-	MW	Airgap d1=110mm
1C - D	MPB	-	Airgap d1=150mm	-
1C - E	MPB	-	Airgap d1=110mm	MW
1C - F	MPB	-	MW	Airgap d1=110mm

Sound absorption coefficient regarding the different systems is displayed in Figure 3. In these plots it becomes apparent that when the mineral wool is placed immediately behind the perforated panel sound absorption displays higher values than those when this material is positioned immediately after the rigid surface.

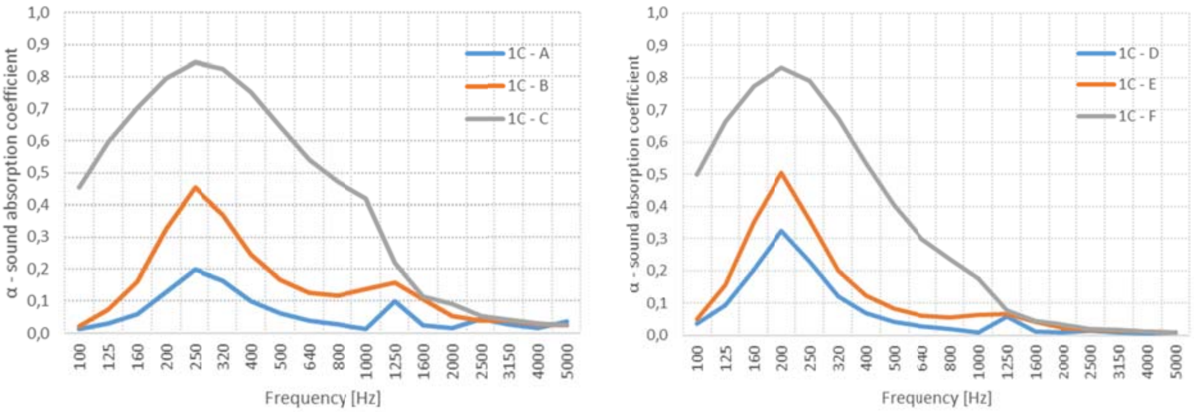


Figure 3 – Sound absorption coefficient provided by the geometries used in the first set of configurations (configuration #1) when using: a) Macro-perforated panel MPA; b) Macro-perforated panel MPB

4.2 Airgap thickness

In order to analyse the influence of the airgap thickness, a second set of configurations was defined (see Figure 4) assuming one macro-perforated panel (MPA) placed over an airgap of varying thickness, partially filled by a mineral wool layer which may be positioned in either the back of the perforated panel (configurations 2C-A to 2C-C) or lining the rigid cover (configurations 2C-D to 2C-F). Details on the different layers are displayed in Table 3.

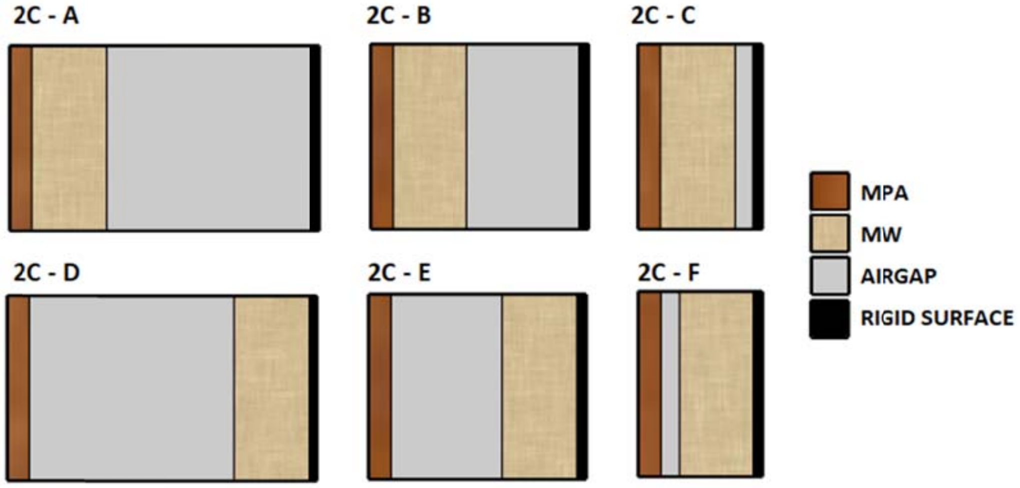
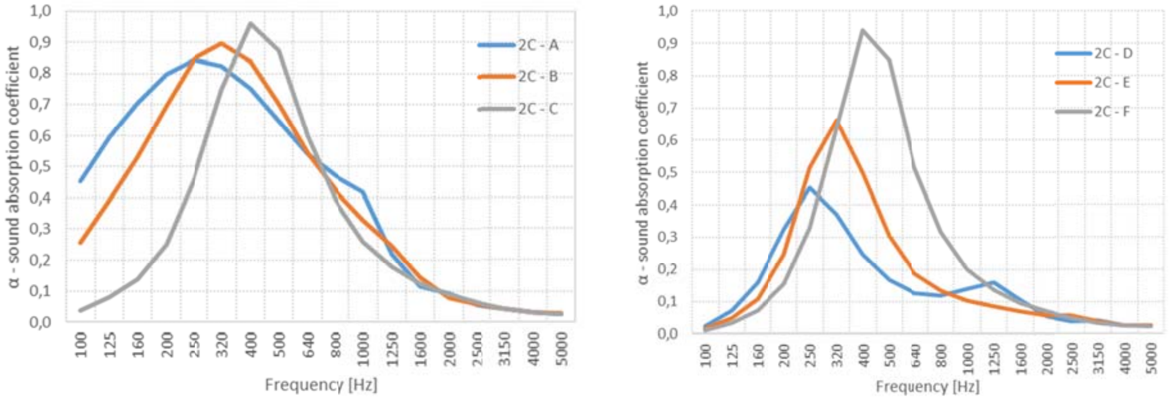


Figure 4 – Geometries used in the second set of configurations (configuration #2) to analyze the influence of the airgap thickness

Table 3 – Definition of the different layers for each system of the second set of configurations

Configuration	Layer 1	Layer 2	Layer 3	Layer 4
2C - A	MPA	-	MW	Airgap d1=110mm
2C - B	MPA	-	MW	Airgap d1=60mm
2C - C	MPA	-	MW	Airgap d1=10mm
2C - D	MPA	-	Airgap d1=110mm	MW
2C - E	MPA	-	Airgap d1=60mm	MW
2C - F	MPA	-	Airgap d1=10mm	MW

Figure 5 displays the sound absorption coefficients regarding Configurations #2. When the mineral wool is positioned on the back of the perforated panel (Figure 5a), we may notice that the peak of sound absorption moves to the lower frequencies when the airgap thicknesses increases, while its amplitude displayed a smooth decrease of about 10%. When the mineral wool is placed immediately after the rigid surface, the peak in sound absorption also moves to the lower frequencies but its amplitude significantly changes from about 0.95 to 0.40 when moving the airgap from 110mm thickness to 10mm.



a) b)

Figure 5 – Sound absorption coefficient provided by the geometries used in the second set of configurations (configuration #2): a)mineral wool placed against the perforated panel; b) mineral wool placed against the rigid surface.

4.3 Different perforation rates

In this subsection a comparison between varying perforation rates is performed by inserting a second perforated panel (MPB) behind the surface panel (PMA). This configuration was assigned as Configuration 3C-B and is displayed in Figure 6. In order to provide a reference result Configurations 3C-A and 3C-B were defined assuming that both perforated panels have similar perforation properties (see configuration 3C-A and

3C-C). Table 4 displays the properties of the different layers of the set of configurations #3.

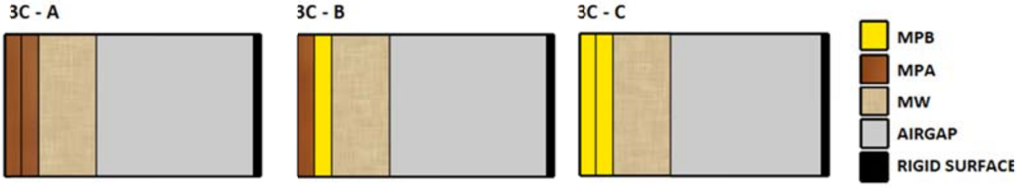


Figure 6 – Geometries used in the third set of configurations (configuration #3) to analyze the influence of the different perforation rates

Table 4 – Definition of the different layers for each system of the third set of configurations

Configuration	**Layer 1**	**Layer 2**	**Layer 3**	**Layer 4**
3C - A	MPA	-	MW	Airgap d1=110mm
3C - B	MPA	MPB	MW	Airgap d1=110mm
3C - C	MPB	-	MW	Airgap d1=110mm

The plot displayed in Figure 7 exhibits the sound absorption coefficient provided by the presence of a second perforated panel (MPB) positioned immediately behind the surface perforated panel (MPA) with a mineral wool lined against it and an airgap of 110 mm. From the analysis of this plot it can be seen that this panel displays a similar behaviour than that obtained for a single perforated panel with identical properties to the MPB one, but with thickness of 24mm.

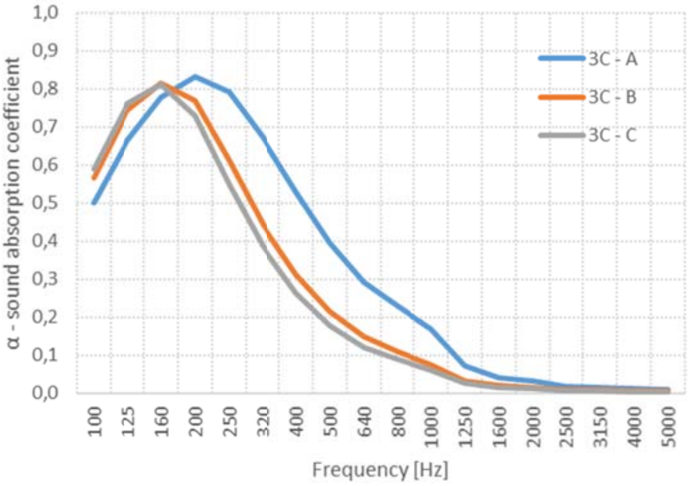


Figure 7 – Sound absorption coefficient provided by the geometries used in the third set of configurations (configuration #3)

4.4 Assembling a micro-perforated panel with a macro-perforated lining panel

In this sub-section we analyse the influence of combining a macro-perforated panel with a micro-perforated panel. With this aim, a set of configurations was defined (see Figure 8), first to analyse the sound absorption provided by each these panels individually, for two airgap thicknesses (t=0mm and t=110mm) (see Configurations 4C-A to 4C-D and 4C-G to 4C-H) and then we assembled them (see Configurations 4C-E to 4C-F and 4C-I to 4C-J). The result for a mineral wool (MN and MN/AG) is also displayed for reference. Table 5 provides the relevant properties of the layers.

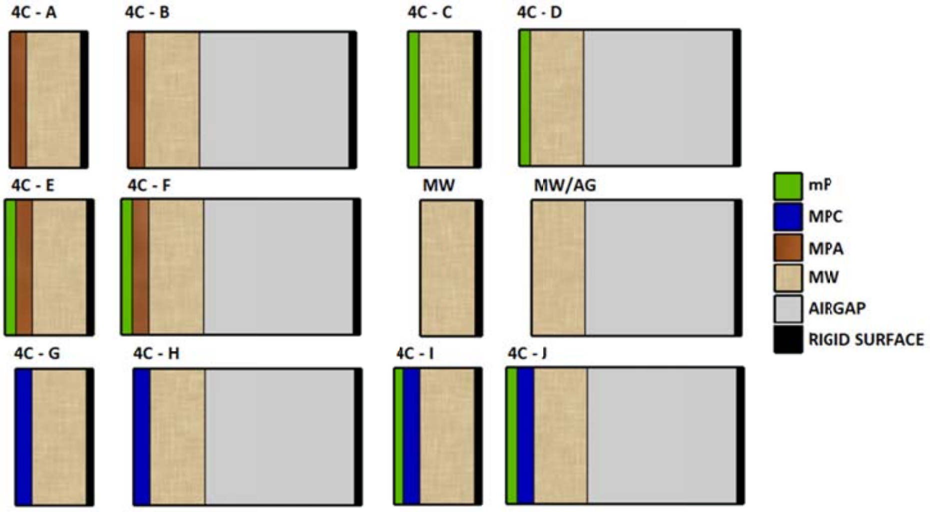
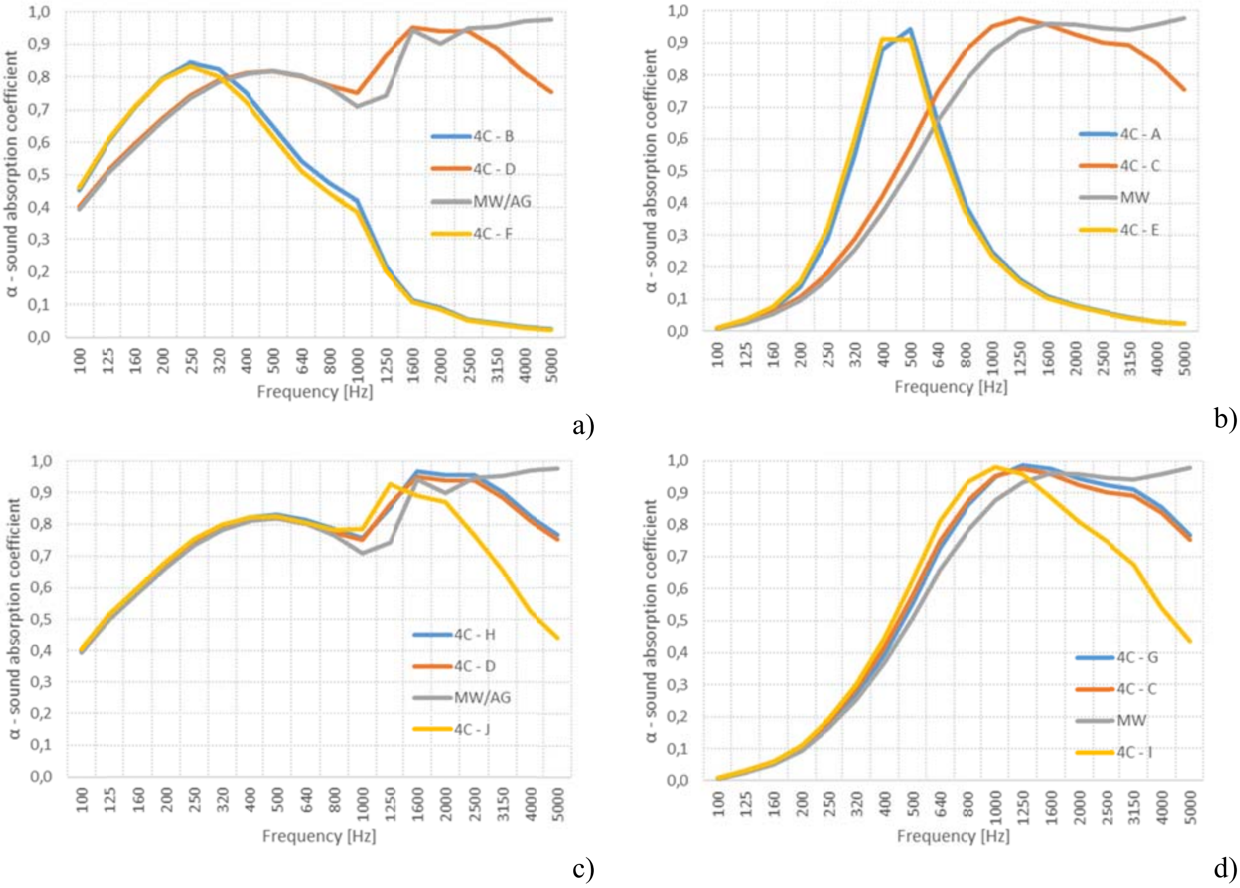


Figure 8 – Geometries used in the fourth set of configurations (configuration #4) to analyze the influence of macro-perforation and micro-perforation

Table 5 – Definition of the different layers for each system of the fourth set of configurations

Configuration	**Layer 1**	**Layer 2**	**Layer 3**	**Layer 4**
4C - A	MPA	-	MW	Airgap d1=110mm
4C - B	MPA	-	MW	-
4C - C	mP		MW	Airgap d1=110mm
4C - D	mP	-	MW	-
MW	MW	-	-	-
MW/AG	MW	-	-	Airgap d1=110mm
4C - E	mP	MPA	MW	-
4C - F	mP	MPA	MW	Airgap d1=110mm
4C - G	MPC	-	MW	
4C - H	MPC	-	-	Airgap d1=110mm
4C - I	mP	MPC	MW	Airgap d1=110mm

Figure 9 displays the sound absorption properties of the fourth set of configurations. From the analysis of these plots it can be seen that the micro-perforated panel provides sound absorption within the medium and high frequencies approaching the behavior of a mineral wool. When the micro-perforated is assembled to the macro-perforated MPA (Figures 9a and b), the sound absorption provided by this system is quite similar to that obtained for the macro-perforated panel. However when we increase perforation rate (MPC), sound absorption (see Figures 9c and d) approaches that provided by the micro-perforated solution.



a)

b)

c)

d)

Figure 9 – Sound absorption coefficient provided by the geometries used in the fifth set of configurations (configuration #5): a)and c) assuming an airgap with thickness d1=110mm; b) and d) assuming an airgap with thickness d1=0mm.

4.5 Interior macro-perforated panel lined with mineral wool placed in varying positions inside the airgap of a macro-perforated system

One last case was also analysed, where the perforated panel MPB lined with the mineral wool is placed in varying positions inside the airgap (see Figure 10 and details on the properties of the layers in Table 6).

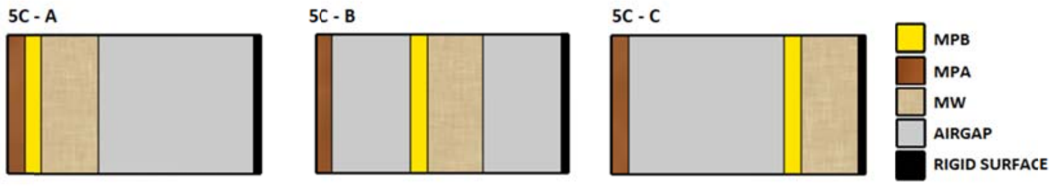


Figure 10 – Geometries used in the fourth set of configurations (configuration #5) to analyze the influence of an interior perforated panel lined with mineral wool in varying positions inside the airgap

Table 6 – Definition of the different layers for each system of the fifth set of configurations

Configuration	**Layer 1**	**Layer 2**	**Layer 3**	**Layer 4**	**Layer 5**
5C - A	MPA	MPB	MW	-	Airgap d1=110mm
5C - B	MPA	Airgap d1=50.5mm	MPB	Mineral wool	Airgap d1=50.5mm
5C - C	MPA	Airgap d1=110mm	-	MPB	Mineral wool

Figure 11 displays the results provided by set of configuration #5. In this plot we may notice that when the perforated panel MPB with the mineral wool moves to an intermediate position inside the airgap, the presence of two peaks, related to the resonating behavior of this multi-layered system is now observed. Consequently, a broader range of absorption is successfully obtained with this solution.

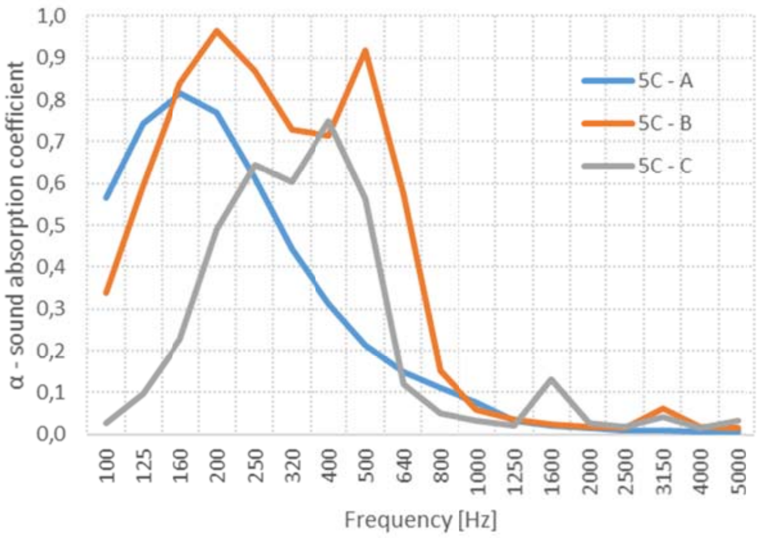


Figure 11 – Sound absorption coefficient provided by the geometries used in the fifth set of configurations (configuration #5)

4. CONCLUSIONS

In this paper a parametric study was carried out to analyse sound absorption of perforated shapes that may be suitable for achieving a variable acoustic solution, for room acoustic design, making use of combinations of macro-perforated panels with different perforation rates and micro-perforated panels, porous materials and airgaps of varying thicknesses. From the performed analysis we may identify the following conclusions for definition of guidelines for future design:

- Placing the porous material on the back of the perforated panel allows to increase sound absorption amplitudes;
- When increasing the airgap thicknesses from 0mm to 150mm it is possible to move the peak of sound absorption to lower frequencies;
- When assembling two macro-perforated panels of different perforations with the perforated panel with smaller diameter on the back, the behaviour of the system is similar to the macro-perforated panel with smaller diameter of the hole, placed on the back, but with thinness similar to the total width of the panel;
- Micro-perforated panel lining a macro-perforated panel with low perforation rates displays similar behaviour to that obtained for the macro-perforated panel.
- Inserting inside a perforated panel a second movable perforated panel lined with a porous material may increase the frequency range of sound absorption.

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