A theoretical approach on designing wideband acoustic absorbers

Ela Fasllija[1], **Semiha Yilmazer**[1], **Cengiz Yilmazer**[2]

[1]Department of Interior Architecture and Environmental Design, Bilkent University, Ankara, Turkey
(e.fasllija@bilkent.edu.tr, semiha@bilkent.edu.tr)

[2]CSY R&D and Architecture Engineering, Cyberplaza, Cyberpark, Bilkent, Ankara, Turkey
(cemsem64@hotmail.com)

Abstract

This study aims to synthesize the theoretical background required for the design of wideband acoustic meta-absorbers. For acoustic materials to have wideband absorption, especially in the low-frequency range, their design should include a combination of resonant mechanisms such as membranes and Micro-Perforated Panels (MPPs). The current work uses an electro-acoustical circuit model to understand the absorption mechanisms of such complex systems. Theories related to the resonance mechanism of MPPs have been widely discussed. Five variables affecting the resonance of one MPP structure are its holes' diameter, the distance between holes (perforation ratio), the thickness and area density of the panel material, and the cavity behind the structure backed by a rigid/absorptive wall. By tuning these variables, it is possible to achieve wideband absorption for desired frequencies. Moreover, parallel combinations of different MPPs showed to have a better performance at absorbing a broader frequency range.

Keywords: Micro-Perforated Panel, electro-acoustic circuit model, absorption coefficient, meta-absorber, parallel connection

1 Introduction

Good architectural acoustic design needs the right room volume, shape, and surface treatments, using an appropriate combination and placement of absorbers and diffusers. Getting the right amount of reverberation in a space is crucial to the design of most rooms, whether the aim is to make speech intelligible, reduce noise levels, make music sound beautiful or simply create a space acoustically pleasant. Reverberation time allows us to quantify how valuable spaces are regarding their potential function. It is linked to the materials used in that specific space, and consequently, material selections become of great importance in the acoustic project [1]. The primary method for reverberation control is absorption.

Absorbing materials such as fibrous and porous ones (mineral wool, fiberglass, acoustic plaster and gypsum, foam, etc.) are most effective in the mid-high frequency range due to their weak intrinsic dissipation properties [2]. On the other hand, for treating low-frequency problems, resonant structures (such as membranes or Helmholtz absorbers) are usually used [3]. Resonant absorbers are mass-spring systems with damping to absorb the system's resonant frequency [4]. The problem with these kinds of absorbers is that they usually only offer narrowband absorption. A series of absorbers must cover a wide bandwidth, each tuned to a different frequency range.

Recently, to expand the absorption bandwidth, a series of structured networks have been explored. Some combined structures of double or multi-layered MPPs and air cavities arranged along the sound direction were proposed [5-7]. These studies show that the absorption bandwidth is expanded to lower frequencies due to the additional multi resonance peaks. MPPs can be made of transparent or colorful plates or membranes, so they are also in demand by architects for sound quality control in auditoriums [5]. MPP absorbers are tagged as the "next generation" absorbing materials due to their vast potential compared to conventional porous materials [8]. A significant study by Yang et al. [9] used "the absorption by design" strategy, enabling customized solutions to complex room-acoustic problems. To implement the designed structure, they used 16 Febry Perot channels arrayed into an acoustic metamaterial in the shape of a cuboid with a square cross-section. By introducing a 3 mm sponge in front of the designed metamaterial unit, the absorption reaches 90% at 400 Hz and then increases to a nearly flat curve till 3000 Hz.

In this study, computational simulations are used to obtain insights into the effect geometry variations (d-diameter of the hole, b-distance between holes, t-thickness of the panel, D-distance from the back wall, and m-area density) of a single MPP have on its absorption coefficient in a frequency range from 125 to 3000 Hz. Furthermore, parallel-arranged MPPs with different variable combinations were tested. Results show that combinations of such kinds provide a better sound absorption performance and have a great potential in being used as wall/ceiling panels.

2 Theoretical background

2.1 Maa's model

In the 1970s, Maa [10] found that if the cross-sectional scale of the perforated holes is in the submillimeter range in contrast to conventional ones, which are in the millimeter range, then losses will occur due to viscous boundary effects in the perforations. Then such MPPs can exhibit significant absorption in the low-frequency range. The sound absorption performance of an MPP can be enhanced by placing it in front of a cavity with a reflecting wall at a specific distance.

The efficiency of MPPs depends if the diameter of the hole (d), the distance between the holes (b), the thickness of the panel (t), and the length (D) from the back wall are correctly designed. In this case, a low-mid frequency sound absorber can be achieved.

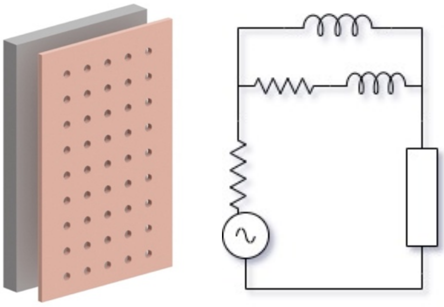

Figure 1. An MPP and its electro equivalent circuit

The acoustic impedance of a single MPP is a combination of the visco-thermal dissipation within the holes (Z_{hole}), the flow distortion in the perforation edges (Z_{edge}), the damping in the air cavity (Z_c), the vibrations of the panel (Z_{vib}) [11]. Z_{hole} and Z_{edge} constitute the MPP impedance Z_{MPP}. The impedance of the air cavity is calculated as a capacitance:

$$Z_c = -jZ_0{}^* \cot kD \tag{1}$$

The structural impedance of the panel, Z_{vib}, is achieved from the damping properties of the panel. Therefore, the total impedance of such as system is calculated as follows:

$$Z_{tot} = \frac{Z_{MPP}Z_{vib}}{Z_{MPP}+Z_{vib}} + Z_c \tag{2}$$

For a rigid panel, $Z_{vib}\rightarrow\infty$, resulting in:

$$Z_{tot} = Z_{MPP} + Z_c \tag{3}$$

Maa [10] developed a model measuring the Z_{MPP} for all perforation constant (k) values, and it is expressed as:

$$Z_{MPP} = \frac{32\eta t}{p\rho c d^2}\left(\sqrt{1+\frac{k^2}{32}} + \frac{\sqrt{2}}{32}k\frac{d}{t}\right) + \frac{\omega t}{\rho c}\left(1 + 1\Big/\sqrt{3^2+\frac{k^2}{2}} + 0.85\frac{d}{t}\right) \tag{4}$$

When $k = {}^{d}\!/_{2}\sqrt{{}^{\omega\rho}\!/_{\eta}}$ is the perforation constant, $\omega=2\pi f$ is the angular frequency, ρ= air density, c= sound velocity in air, p, d, t being the perforation ratio, diameter, and length of the hole respectively.

According to the electric equivalent circuit model, when n number of MPPs connected in parallel, their total impedance of the panel is calculated as :

$$Z = \left(\sum_{i=1}^{n}\frac{\emptyset_i}{Z_i}\right)^{-1} \tag{5}$$

When $\emptyset$ is the ratio each panel has on the overall surface panel.

Recently, a series of structures based on MPP in parallel or series have been explored to expand the absorption bandwidth. Some combined systems of double or multi-layered MPPs and air cavities arranged along the sound direction were proposed successively [6]. Moreover, researchers [7] have found that elongated tubes with porous materials attached to the perforated panel improved the low-frequency sound absorption.

3 Parametric study

3.1 Single-layer MPP

The following results belong to simulations related to a single layer MPP being tested for its absorption coefficient according to changes in one of its geometry parameters such as m for panel area density, d for hole diameter, p for perforation ratio (b for the distance between holes), t for panel thickness and D for cavity distance in the frequency range from 125 Hz to 3000 Hz.

3.1.1 Effect of area density on alpha

For a single layer MPP having holes of diameter d = 0.6mm, a distance between them of b = 3mm (p=3.14%), the thickness of the panel t = 15mm, and the back cavity of D = 5cm, five different construction materials with different area densities were tested. Their densities were as follow: m_1=0.22kg/m^2; m_2=0.45kg/m^2 ; m_3=0.67kg/m^2; m_4=5kg/m^2 and m_5=10kg/m^2.

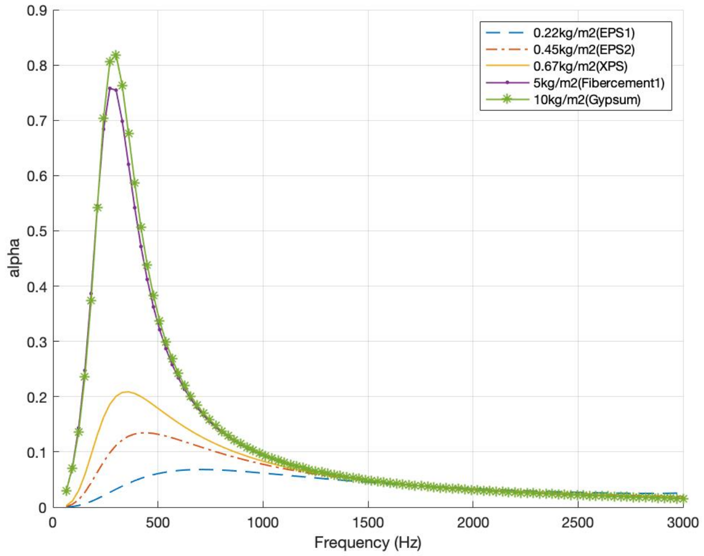

Figure 2. Effect of area density (m) on α

As inferred from Figure 2, increasing the higher area density materials offer a better absorption at the resonant frequency. The reason may be that when the panel is too light, panel vibration causes the relative velocity of the vibrating air in the hole to drop, and thus the absorption efficiency is reduced.

3.1.2 Effect of hole diameter on alpha

Figure 3 visually shows how the absorption coefficient of an MPP (t=15mm, D=5cm, and b=2mm) changes in the frequency spectrum according to the hole diameter (d) changes. A smaller hole shows a better absorption in the low frequency due to the viscous losses in the edges. Moreover, when d increases more than 0.7mm for this panel, the alpha value decreases even in mid-frequencies.

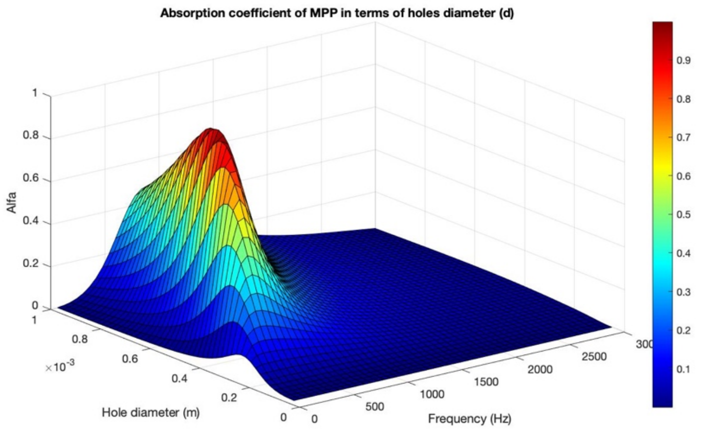

Figure 3. Effect of hole diameter (d) on α

3.1.3 Effect of perforation ratio on alpha

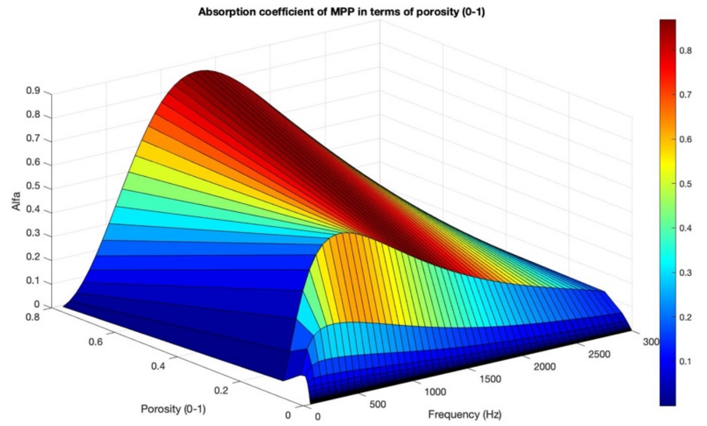

Figure 4. Effect of the perforation ratio (p) on α

The results in Figure 4 show that when the distance between holes (b) is increased (perforation ratio (p) is small), the material starts to behave more like a rigid material by reflecting the sound pressure in the low frequencies. Furthermore, the higher the open area, the higher the material's absorption coefficient after 1000 Hz for an MPP (t = 15mm, D = 5cm, d = 0.2mm).

3.1.4 Effect of panel thickness on alpha

Different values of t ranging from 5mm to 3cm related to the thickness of the panel are tested to understand its effect on the absorption coefficient of the MPP. The other parameters, such as hole diameter (d = 0.2mm); the distance between holes (b = 0.4 mm), and cavity distance D = 5cm, remained constant. As shown in Figure 5, panels with smaller thicknesses resembling the diameter of the microperforated holes exhibit a better absorption than thicker ones.

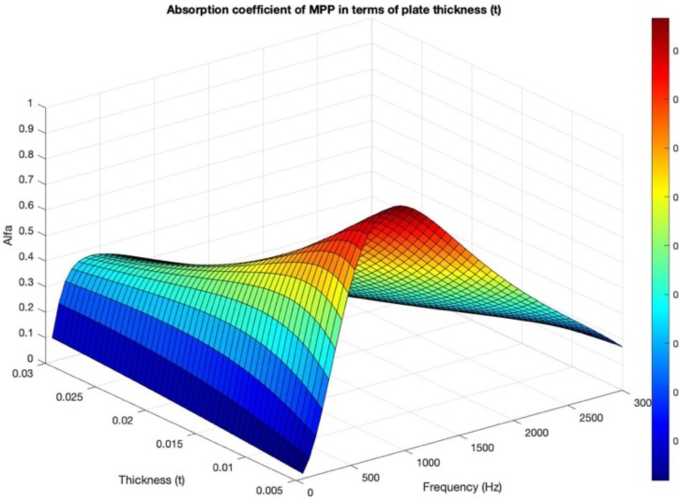

Figure 5. Effect of panel thickness' diameter on α

3.1.5 Effect of cavity length on alpha

Different values ranging from (2cm ≤ D ≤ 10cm) related to the cavity length are tested to understand its effect on the absorption coefficient of the MPP. The other parameters, such as hole diameter (d = 5mm), the distance between holes (b = 20 mm), and sheet thickness (t = 15mm), remained constant. As shown in Figure 6, the bigger the absorption performance in the low-frequency range, the better absorption is shown by the largest cavity length. When cavity length decreases, the resonant frequency shifts to higher frequencies. However, the length of the cavity is reciprocal to the frequency of the incoming wave by producing resonant frequencies.

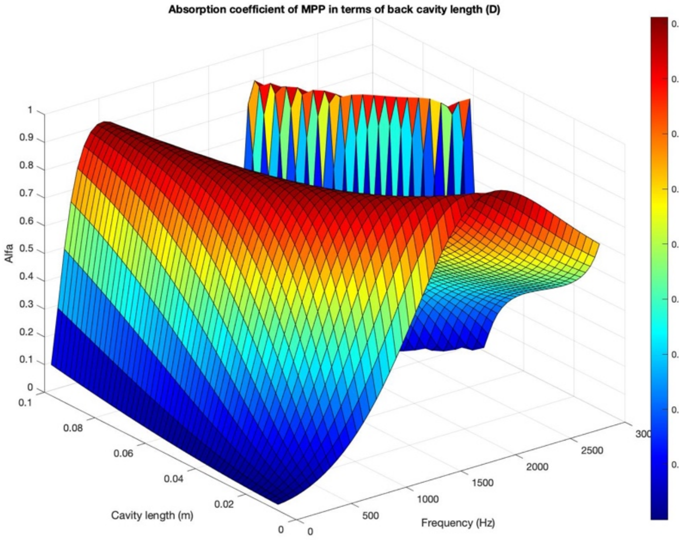

Figure 6. Effect of cavity length on α

3.2 Parallel arranged MPP panels

Three parallel arranged MPPs having different perforation ratios and the same cavity, as shown in Figure 7, are tested for their absorption coefficient. Their geometry variables are as follows: MPP1 $d1$ = 1mm, $b1$ = 6mm, $t1$ = 1cm, $D1$ = 5cm; MPP2 $d2$ = 0.8mm, $b2$ = 3mm, $t2$ = 1cm, $D2$ = 5cm ; MPP3 $d3$ = 0.9mm, $b3$ = 2.1mm, $t3$ = 1cm, $D3$ = 5cm and the ratio each panel occupies in the overall panel is 1/3. The results show that each MPP has a different resonance frequency (MPP1 at 310 Hz, MPP2 at 480 Hz, and MPP3 at 750 Hz. When combined in parallel, they exhibit a wideband absorption of an alpha value over 0.5 from 270 Hz to 900 Hz (See Figure 8).

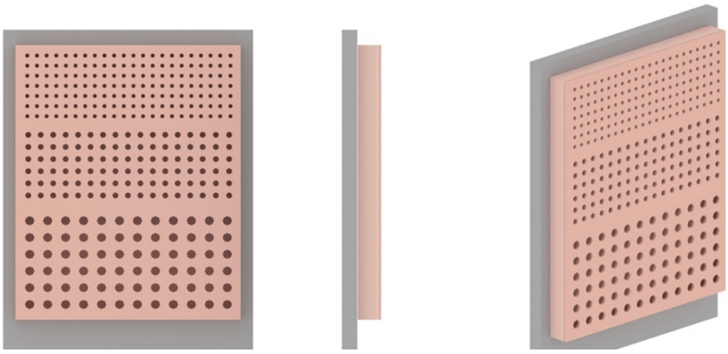

Figure 7. Parallel arranged MPP-s with the same back air cavity

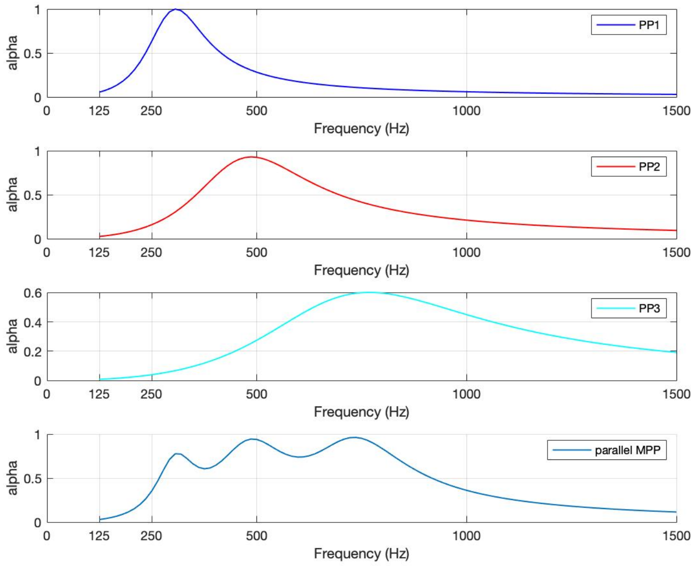

Figure 8. Alpha values for MPP1,MPP2,MPP3 and all of them connected in parallel

Lastly, three MPPs having different perforations and geometries are tested for their absorption coefficient from 125 to 1500 Hz (See Figure 9). Their features were for; MPP1 $d1$ = 1mm, $b1$ = 7mm, $t1$ = 1cm, $D1$ = 6cm; MPP2 $d2$ = 0.7, $b2$ = 3mm, $t2$ = 1cm, $D2$ = 4.2cm and MPP3 $d3$ = 0.8mm, $b3$ = 2.1mm ,$t3$ = 1cm, $D3$ = 2.5mm.

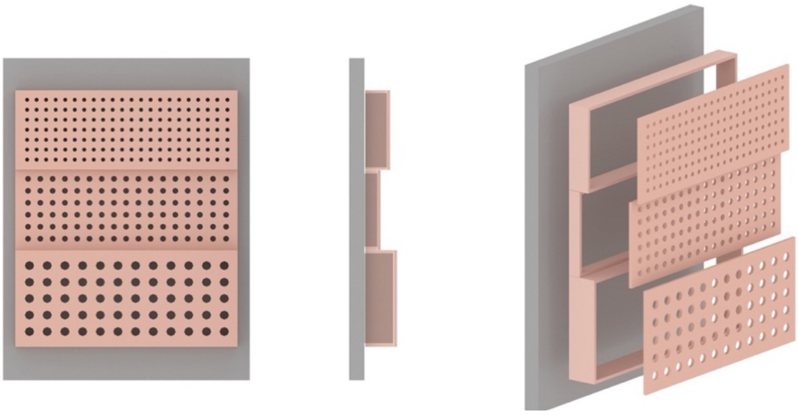

Figure 9. Parallel arranged MPPs having different back cavities

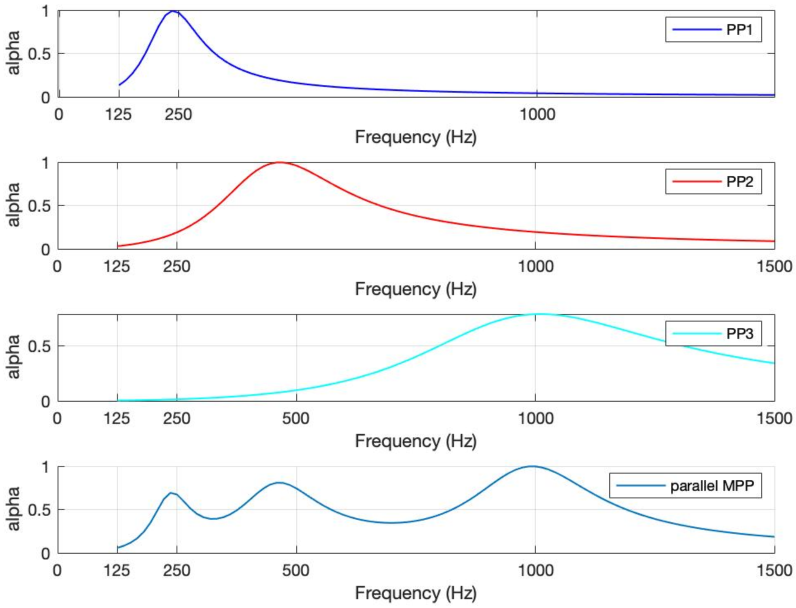

Figure 10. The absorption coefficient of MPP1, MPP2, MPP3
and their combination in parallel with different cavities

In the current structure, it is observed in Figure 10 that decreasing the distance of back cavities shifts the resonant frequency to higher frequencies broadening the absorption bandwidth (alpha ≥ 0.5 till 1200 Hz) but having some abrupt downfalls at 300 and 750 Hz. Therefore, an optimized design of this structure may be helpful in further studies.

4 Conclusions

This work shows the potential of MPPs, which can exhibit a wider absorption band than conventional building materials when correctly designed. Each parameter and its intertwined relations affect the absorption coefficient factor of the material and, therefore, the overall absorption in the room. Since the acoustic performance of parallel-connected MPPs depends on 4N parameters, it is difficult to know a priori the combination of these parameters providing the maximum absorption within a prescribed frequency band. Authors have used several optimization algorithms such as simulated annealing [11], genetic algorithm [12], and Particle Swarm Optimization [13]. After achieving some optimized parameters for specific panels, it can be manufactured and therefore can be used as a wall/ceiling panel in architectural applications. Absorptive panels are used as an acoustic treatment when it's crucial to improve sound quality within an environment. By installing absorptive or diffusive panels in space, the level of undesirable noise, in the form of echo and reverberation, is reduced. An environment with inadequate acoustics negatively affects a space's environmental comfort, behavior, and productivity [14]. When high absorption of specific frequencies is required, innovative material panels that integrate resonant mechanisms with building materials' intrinsic properties providing the ideal reverberation desired for any room, should be further investigated. Investigations of this kind from the architect's point of view help the latter make informed decisions for incorporating better sound within the project's design, ultimately delivering a better user experience.

References

[1] González, A. E. How Do Acoustic Materials Work? *The acoustics of Materials*, (2019), DOI: 10.5772/intechopen.82380.

[2] Kumar, S., & Lee, H. P. The Present and Future Role of Acoustic Metamaterials for Architectural and Urban Noise Mitigations. *Acoustics*, *1*(3), 2019, 590–607.

[3] Kuttruff, H. (1991). *Room acoustics*. Taylor & Francis, London, 1st edition, 1991.

[4] Cox, T. J., & D'Antonio, P. *Acoustic absorbers and diffusers: theory, design, and application*. Boca Raton: CRC Press, 2009.

[5] Fuchs, H. V., & Zha, X. Micro-perforated structures as sound absorbers–a review and outlook. *Acta acustica united with acustica*, *92*(1), 2006, 139-146.

[6] Sakagami, K., Nagayama, Y., Morimoto, M., & Yairi, M. Pilot study ON wideband sound ABSORBER obtained by combination of two different MICROPERFORATED panel (MPP) absorbers. *Acoustical Science and Technology*, *30*(2), 2009, 154–156.

[7] Li, D., Chang, D., & Liu, B. Diffuse Sound Absorptive Properties of Parallel-Arranged Perforated Plates with Extended Tubes and Porous Materials. *Materials*, *13*(5), 2020.

[8] Toyoda, M., & Takahashi, D. Sound transmission through a microperforated-panel structure with subdivided air cavities. *The Journal of the Acoustical Society of America*, *124*(6), 2008, 3594–3603.

[9] Yang, M., Chen, S., Fu, C., & Sheng, P. Optimal sound-absorbing structures. *Materials Horizons*, *4*(4), 2017, 673-680.

[10] Maa, D. Y. Theory and design of microperforated panel sound-absorbing constructions. *Scientia Sinica*, *18*(1), 1975, 55-71.

[11] Ruiz, H., Cobo, P., Dupont, T., Martin, B. & Leclaire, P. Acoustic properties of plates with unevenly distributed macro perforations backed by woven meshes. *The journal of the acoustical society of America*, *132* (5), 2012, s. 3138–3147.

[12] Qian Y.; Zhang J, "Optimization Design of Serial-Parallel Coupled Micro-Perforated Panel Absorbers by Genetic Algorithm," *2018 IEEE 4th International Conference on Control Science and Systems Engineering (ICCSSE)*, 2018, pp. 217-220, DOI: 10.1109/CCSSE.2018.8724824.

[13] Lu, C.-H., Chen, W., Zhu, Y.-W., Du, S.-Z. & Liu, Z.-E. (2018). Comparison Analysis and Optimization of Composite Micro-perforated Absorbers in Sound Absorption Bandwidth. *Acoustics Australia*, *46* (3), s. 305–315. doi:10.1007/s40857-018-0140-0

[14] Mujan, I., Anđelković, A. S., Munćan, V., Kljajić, M., & Ružić, D. Influence of indoor environmental quality on human health and productivity-A review. *Journal of cleaner production*, *217*, 2019, 646-657.