



Optimum Design of Multi-layered Micro-perforated Panel Sound Absorbers in Combination with Porous Materials in an Arbitrary Frequency Range

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ABSTRACT

Optimum design of sound absorbers with optimum thickness and maximum sound absorption has always been an important issue to noise control. The purpose of this paper is an achievement of optimum design for micro-perforated panel (MPP) and its combination with a porous material and air gap to obtain maximum sound absorption with maximum overall thickness up to about 10 cm in the frequency range of (20-500 Hz), (500-2000 Hz) and (2000-10000 Hz). For this purpose, the genetic algorithm is proposed as an effective technique to solve the optimization problem. By using the precise theoretical models (i.e. simplified Allard's model and Atalla *et al.*'s model) to calculate the acoustic characteristics of each layer consisting of MPP, porous material, and airgap, we obtained more precise optimized structures. The transfer matrix method has been used to investigate the sound absorption of structures. To verify the operation of the programmed genetic algorithm, the results obtained from the optimization of the MPP absorber are compared with others that show the accuracy and efficiency of this method. After ensuring the accuracy of the proposed programmed genetic algorithm with more precise theoretical models to achieve the characteristics of each layer, new structures were obtained that have a much better sound absorption coefficient in the desired frequency range than the previous structures. The results show that the sound absorption coefficient can be reached to 0.67, 0.96, and 0.96 in the mentioned first, second, and third frequency range, respectively by optimum design parameter choosing of a composite structure.

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NOMENCLATURE

f	Frequency (Hz)	d	Diameter of the holes (mm)
w	Angular frequency (rad/s)	D	Depth of air gap (cm)
L	The thickness of the porous material (cm)	Greek Symbols	
Z_s	The specific acoustic impedance of the MPP (Rayls)	$\rho_0 c_0$	The characteristic impedance of the air (kg/m ² s)
t	The thickness of the panel (mm)	σ	Flow resistivity of the porous material (Pa · s/m ²)
R_s	The surface resistance of the vibrating air inside each hole	\mathcal{E}_e	Final correction coefficient
p	Perforation rate (%)	μ	Kinetic coefficient of air
Z_{in}	Input specific acoustic impedance (Rayls)	α	Sound absorption coefficient

1. INTRODUCTION

Noise pollution is an unpleasant sound that is significantly harmful to general health and it's become one of the most important environmental issues in

modern life [1-5]. Control of noise, especially, in three frequency ranges, e.g. low-frequency (20 Hz-500 Hz), mid-frequency (500 Hz-2000 Hz), and high-frequency (2000 Hz-10000 Hz) is important [6-9]. Porous materials [10] are the most applicable types of sound absorbers

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used in noise control in high frequencies [11-14]. To increase the sound absorption in low frequencies, the thick layer of the porous absorber is needed and it takes up a lot of space. They are cheaper sound absorbers than other types of absorbers but have three major drawbacks:

- 1) They do not have adequate sound absorption in low and mid frequencies with low thickness;
- 2) They do not have adequate strength against the impact and pressure;
- 3) The separated particles from them are entered into the air and the ventilation system and thus damage human health.

In previous works, we optimized a flat multi-layer porous sound absorber by using a multi-objective genetic algorithm for application in an anechoic chamber [15]. Due to the above disadvantages for porous sound absorbers, the achieved design was only suitable for use in certain places such as anechoic rooms and music studios, not in residential and public buildings.

Hence the use of a Micro perforated panel (MPP) as a strength sound absorber in front of the porous absorber was considered by the researchers [16-19].

MPPs were introduced by Maa [20-22] for the first time. The disadvantage of this type of sound absorber is the narrow frequency range of absorption. Due to an increase in the frequency range of absorption, some suggestions have been proposed such as the use of multi-layered MPPs in succession [23-27] and the use of porous material behind the MPP [16-19].

Researchers are interested to produce sound absorbers suitable for low-frequency noise control. To increase the sound absorption in low frequencies, the insertion of the flexible plate driven by a concentrated force on the back of the MPP is used [28]. Basirjafari [29] enhanced the Helmholtz resonator sound absorption only in low-frequency by Fibonacci sequence according to the nature inspiration, for the first time.

Literature review shows that the multi-layered sound absorbers composed of porous materials and MPPs are mostly used for noise control, due to their high environmental compatibility, high strength, beautiful facing, low-cost manufacturing, simple installation, and the adjustable frequency bandwidth of sound absorption. Although, the thickness of each layer, the arrangement of layers, selection of material for each layer, determination of MPP parameters such as thickness, hole diameter, and porosity play important roles to design an optimum multi-layered sound absorber for an arbitrary frequency range of absorption.

On the other hand, a genetic algorithm is an effective tool for optimization. By using the genetic algorithm, the type of arrangement, and the characteristics of each layer in the multi-layered sound absorber can be determined in such a way that the maximum absorption coefficient of

sound is obtained in a special thickness.

The purpose of this paper is to optimize the MPPs structure and porous material by using the more precise theoretical models (i.e. simplified Allard's model [14] and Atalla *et al.*'s model [30]) than previous researches [16, 23, 26] to calculate their acoustical characteristics, and their arrangement in combination with an air gap to have a maximum average of sound absorption coefficient in desired frequency ranges with a maximum overall thickness of 10 cm.

Three frequency ranges including the first range (20 Hz - 500 Hz), the second one (500 Hz - 2000 Hz), and the third one (2000 Hz - 10000 Hz) are selected for optimization. To this aim, the use of a genetic algorithm has been proposed as an effective tool in optimization problems. By using precise theoretical models, the genetic algorithm can give a more precise optimized structure.

2. MATHEMATICAL MODEL

In this paper, the transfer matrix of a multi-layered structure composed of an MPP, porous material, and the air gap is used to calculate its sound absorption coefficient, as described in the previous paper [16]. The previous method has been used with the difference that the simplified Allard's model is used to calculate the characteristic impedance and the propagation constant of porous material [14] because it is more accurate than the others. Atalla *et al.* [30] model is used for calculating the acoustic impedance of MPPs as:

$$Z_s = (t + 2\varepsilon_e) \left[(1 + j) \frac{4R_s}{pd} + \frac{jw\rho_0}{p} \right] \quad (1)$$

$$\varepsilon_e = 0.425d(1 - 1.14\sqrt{p}) \quad (2)$$

$$R_s = \sqrt{\frac{\rho_0 w \mu}{2}} \quad (3)$$

In the above equations, Z_s is the specific acoustic impedance of the MPP, t is the thickness of the panel, ε_e is the final correction coefficient, R_s is the surface resistance of the vibrating air inside each hole, p is the perforation rate, d is the diameter of the holes, w is the angular frequency, and μ is the kinetic coefficient of air. The sound absorption coefficient can be obtained [16]:

$$\alpha = \frac{4Re\left(\frac{Z_{in}}{\rho_0 c_0}\right)}{\left[1 + Re\left(\frac{Z_{in}}{\rho_0 c_0}\right)\right]^2 + \left[\text{Im}\left(\frac{Z_{in}}{\rho_0 c_0}\right)\right]^2} \quad (4)$$

in which, Z_m an input specific acoustic impedance and $\rho_0 c_0$ is the characteristic impedance of the air.

It can be seen that several factors affect the sound absorption coefficient of a multi-layered sound absorber composed of MPP, porous material, and air gap. For example, the absorption coefficient of the MPP depends on four factors: the diameter of the holes, the thickness of the panel, the porosity, and the depth of the air gap behind the panel. Also, the absorption coefficient of the porous absorber depends on different factors: porosity, tortuosity, Young's modulus, airflow resistivity, and the thickness of the porous material layer, which airflow resistivity and the thickness of the porous material layer is just considered in the simplified Allard's model.

With the right choice of these quantities, suitable absorption can be achieved within the desired frequency range. The number and arrangement of layers also affect the sound absorption of the structure. Therefore, for optimal structural design, the type of arrangement, and the determination of the proper characteristics of each layer is very important. Because examining the effect of each of the above factors on adsorption efficiency requires the design, fabrication, and test of several laboratory samples, the trial, and error-based method is very costly and time-consuming. Therefore, the genetic algorithm is used to optimize the sound absorption of the mentioned multi-layered structure, with commercial porous materials whose specifications are given in Table 1 of our previous paper [15]. By using the genetic algorithm, the type of arrangement, and the characteristics of each layer are determined in a way that the maximum sound absorption coefficient for the absorber with a certain thickness is obtained.

The used parameters of the genetic algorithm in this paper are as follows:

1. The maximum number of generations is 20.
2. The population size in each generation is 328.
3. The generation gap is equal to 0.5, which means that 50% of the population in each generation is replaced and the mutation rate is 5% means that in each generation, 5% of the population is jump.
4. In this case, the fitness function is the sound absorption coefficient. The transfer matrix method described in the previous section should be used to calculate it.

The design parameters are the type and thickness of the porous absorber layer, the micro-perforated panel thickness, the holes diameter, the porosity, and the air gap thickness.

3. RESULTS AND DISCUSSION

Because in industrial applications, optimal absorber design is required for optimum performance in the

desired frequency range, the purpose of this section is to optimize the multi-layered sound absorber composed of an MPP, porous material, and air gap for achieving the highest average of sound absorption coefficient in three frequency ranges including first range (20 Hz - 500 Hz), second range (500 Hz - 2000 Hz) and the third range (2000 Hz - 10000 Hz).

For this purpose, a genetic algorithm has been used as an effective tool for optimization problems. For the implementation of the genetic algorithm, MATLAB software has been used. In the first step, a double-layer MPP and a three-layer MPP sound absorber have been optimized by the genetic algorithm and compared with the results reported by Ruiz et al. [26] to verify the programmed genetic algorithm. At the second step, a single layer MPP and a double-layer MPP have been optimized in the mentioned three frequency range by genetic algorithm. Finally, the multi-layered sound absorber has been optimized by the genetic algorithm in the same three mentioned frequency ranges.

3.1. Analytical Method Verification To verify the mathematical model, the sound absorption coefficient of the single-layer micro-perforated panel and composite absorber was calculated by the transfer matrix method and compared with the experimental results illustrated in Figures 1 and 2. Sound absorption coefficients were examined in impedance tube, according to ASTM E 1050 90 and ISO 10543-2.

In Figure 1, the experimental result has been reported by Ruiz et al. [26] for the sound absorption coefficient of single layer micro-perforated panel absorber with characteristics of $t = 1$ mm, $d = 0.25$ mm, $p = 3.4\%$, and air gap with the thickness of 1.1 cm. As shown in Figure 1, the results of the proposed theory for the single-layer

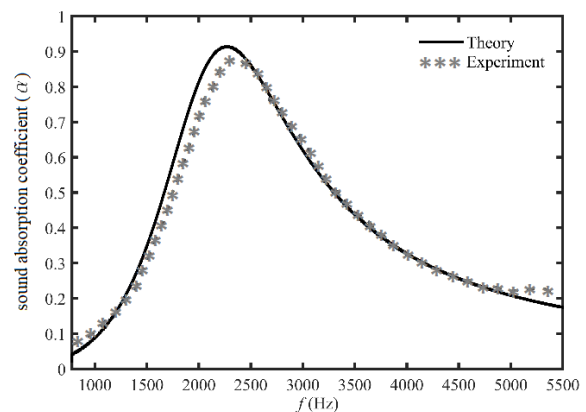


Figure 1. Comparison of the present theoretical result with the experimental result reported in [26] for the sound absorption coefficient of single layer micro-perforated panel absorber versus frequency; characteristics of MPP are $t = 1$ mm, $d = 0.25$ mm, $p = 3.4\%$, and thickness of air gap is 1.1 cm

MPP correspond to the experimental results with an average error of 5.8%.

In Figure 2, the experimental result has been reported by Davern [18] for the sound absorption coefficient of composite absorber consists of three layers with characteristics of the first layer: MPP absorber with $t = 6.3$ mm, $d = 0.75$ mm, $p = 4.7\%$; second layer: porous absorber with $\sigma = 16000$ Pa.s/m², $L = 2.5$ cm; third layer: air gap with $D = 2.5$ cm thickness. As shown in Figure 2, the results of the proposed theory for the triple-layer MPP correspond to the experimental results with an average error of 15.7%.

3. 2. Verification of the Programmed Genetic Algorithm

As mentioned before, the absorption coefficient of the MPP sound absorber depends on four quantities: the diameter of the holes, the thickness of the panel, the porosity of the panel, and the air gap thickness between the panel and the wall.

To verify the performance of the programmed genetic algorithm for optimizing acoustic absorbers, the optimization results of MPP absorbers were compared with the optimization results reported by Ruiz et al. [26].

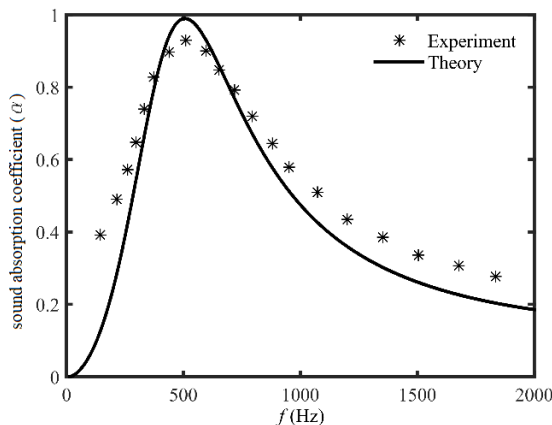


Figure 2. Comparison of the present theoretical result with experimental result reported in [18] for sound absorption coefficient of composite absorber versus frequency (first layer: MPP absorber with $t = 6.3$ mm, $d = 0.75$ mm, $p = 4.7\%$; second layer: porous absorber with $\sigma = 16000$ Pa.s/m², $L = 2.5$ cm; third layer: air gap with $D = 2.5$ cm thickness)

They have used the Atalla model [30] to calculate the sound absorption coefficient of the MPPs. Because it is more accurate than other models. Also, they used the Simulated Annealing algorithm (SA) to optimize it. Therefore, in this paper, to compare the optimization results, the Atalla model is used to calculate the sound absorption coefficient. The relations of this model are given in Equations (1) to (3).

Also, to compare the programmed genetic algorithm results with the Simulate Annealing algorithm (SA) which Ruiz et al. [26] used to optimize the sound absorber structure, the specification of the micro-perforated panel (the diameter of holes, the thickness of the panel, the porosity, and the air gap spacing) is limited by the Ruiz method [26], which is shown in relation (5).

$$t_i = 1\text{ mm}, d_i \in [0.25, 0.75]\text{ mm}, p_i \in [3.4, 8.5]\%, D_i \in [1, 5]\text{ cm} \tag{5}$$

In this regard, t_i is the thickness of the panel, d_i is the diameter of the holes, p_i is the porosity, D_i is the air gap thickness, and the subscript i represents the number of each layer. The optimization results by using the genetic algorithm and Simulate Annealing algorithm (SA) for double-layer MPP are given in Table 1 and for three-layer MPP are given in Table 2. According to Tables 1 and 2, the obtained results for the average sound absorption in comparison with Ruiz’s results clearly show the validity of the programmed genetic algorithm.

After ensuring the accuracy of the proposed programmed genetic algorithm with more precise theoretical models (i.e. simplified Allard’s model [14], and Atalla *et al.* model [30]) to achieve the characteristics of each layer, new structures will be proposed that have a much better sound absorption coefficient in the desired frequency range than the previous structures.

3. 3. MPP Sound Absorber Optimization

In the structural design of the N-layer micro-perforated panel, the sound absorption coefficient depends on the 4N quantities. The specifications of the panels are limited according to Equation (6).

$$t_i \in [0.5, 5]\text{ mm}, d_i \in [0.1, 1]\text{ mm}, p_i \in [1, 15]\%, \sum D_i \leq 10\text{ cm} \tag{6}$$

TABLE 1. Comparison between the optimization results of the present genetic algorithm and the results of simulated annealing of [26] for double-layer micro-perforated panel absorber with the same thickness $t_1 = t_2 = 1$ mm

Optimization method	1st. layer parameters			2nd. layer parameters			The average sound absorption coefficient in 800-6400 Hz
	d_1 (mm)	p_1 (%)	D_1 (cm)	d_2 (mm)	p_2 (%)	D_2 (cm)	
Simulated annealing [26]	0.25	8.4	1	0.25	3.5	1	0.65
Genetic algorithm (present work)	0.25	8.5	1	0.25	3.4	1	0.66

TABLE 2. Comparison between the optimization results of the present genetic algorithm and the results of simulated annealing of [26] for three-layer micro-perforated panel absorber with the same thickness $t_1 = t_2 = t_3 = 1 \text{ mm}$.

Optimization method	1st. layer parameters			2nd. layer parameters			3rd. layer parameters			The average sound absorption coefficient in 800 -6400 Hz
	d_1 (mm)	p_1 (%)	D_1 (cm)	d_2 (mm)	p_2 (%)	D_2 (cm)	d_3 (mm)	p_3 (%)	D_3 (cm)	
Simulated annealing [26]	0.25	8.5	1	0.25	4.55	1	0.25	3.4	1.3	0.74
Genetic algorithm (present work)	0.25	7.8	1	0.25	4.71	1	0.25	3.5	1.7	0.73

In practical applications of noise control, the limitation of occupied space by the sound absorber is a very important problem. The total thickness of the sound absorber is considered to be about 10 cm, most of which is air gap or porous material and is therefore very light or low cost.

In Equation (6), the maximum thickness for the total air gap is 10 cm. Tables 3 and 4 show the optimal specifications and the average sound absorption coefficient of the structure consisting of a single layer MPP (see Figure 3(a)) and double-layer MPP (see Figure 3(b)) for the desired frequency ranges, respectively.

Figures 4 and 5 show the absorption coefficient of the optimal structures in Tables 3 and 4, respectively, in terms of frequency.

According to the results of optimizing the structure of a single layer MPP, as shown in Figure 4, the genetic algorithm in each frequency range adjusts the structure characteristics so that the first resonance frequency of the structure occurs in the same range.

The optimal structure No. 1 has the highest sound absorption coefficient of 0.99 at a resonant frequency of 288 Hz. As can be seen, this structure has six resonances in the frequency range of 1 Hz to 10000 Hz, in which the

value of the absorption coefficient decreases at higher resonant frequencies.

The optimal structure No. 2 has the highest sound absorption coefficient of 0.98 at the resonant frequency of 1005 Hz. The optimal structure thickness of No. 1 is more than 3 times of No. 2 and has an average sound absorption coefficient of 21% less than the structure No. 2 in the frequency range of 500 Hz to 2000 Hz.

Therefore, increasing the thickness of the structure in the second frequency range is not necessary and if there is not considerable noise in the frequency lower than 500 Hz, structure No. 1 can not be used.

The optimal structure No. 3 has the highest sound absorption coefficient of 0.86 at a resonant frequency of 4008 Hz. As can be seen, due to the increase in the frequency range of sound absorption, the absorption coefficient of structure No. 3 in the resonance frequency has decreased by 13%. Also, the average sound absorption coefficient in this frequency range has decreased by 12.7% compared to the first frequency range and 36.4% compared to the second frequency range. Therefore, a structure consisting of a single layer of MPP is weaker in absorbing high-frequency audible sound compared to low- and mid-frequencies.

TABLE 3. Optimization of the sound absorption coefficient for single layer micro-perforated panel absorber.

Structure number	Frequency bandwidth (Hz)	Optimal design parameters				The average sound absorption coefficient
		t (mm)	d (mm)	p (%)	D (cm)	
1	20 – 500	1.5	0.1	1.9	10	0.62
2	500 – 2000	1.5	0.1	5.3	3	0.75
3	2000 - 10000	0.7	0.1	8.5	1	0.55

TABLE 4. Optimization of the sound absorption coefficient for a double-layer micro-perforated panel absorber.

Structure number	Frequency bandwidth (Hz)	Optimal design parameters								The average sound absorption coefficient
		t_1 (mm)	d_1 (mm)	p_1 (%)	D_1 (cm)	t_2 (mm)	d_2 (mm)	p_2 (%)	D_2 (cm)	
1	20 - 500	4.5	1	1.9	5	3.9	0.1	1.2	5	0.64
2	500 - 2000	2.1	0.1	14.9	3.4	4.2	0.1	7.5	2.1	0.94
3	2000 - 10000	0.5	0.1	12	1	0.8	0.1	8	1	0.78

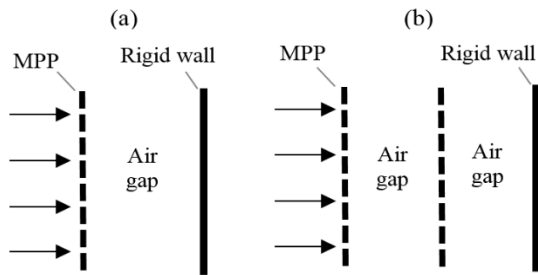


Figure 3. (a) single layer, (b) double-layer micro-perforated panel (MPP)

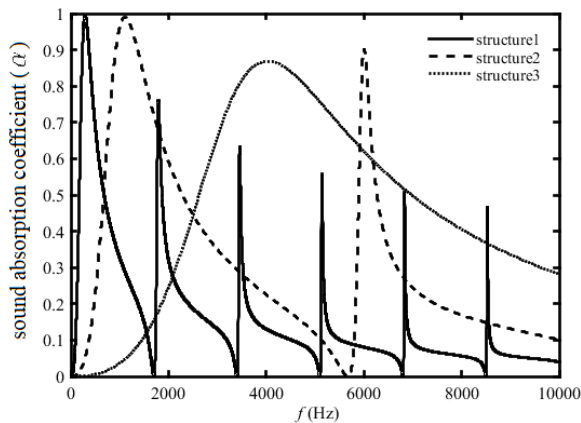


Figure 4. The sound absorption coefficient of optimum structures 1, 2, and 3 that are described in Table 3, for double-layer micro-perforated panel versus frequency

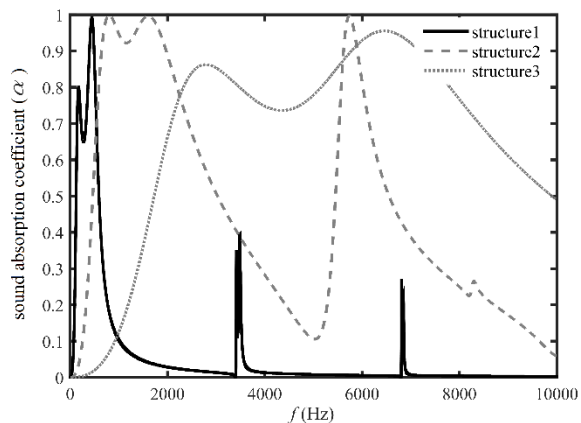


Figure 5. The sound absorption coefficient of optimum structures 1, 2, and 3 that are described in Table 4, for single-layer micro-perforated panel versus frequency

The average absorption coefficient of the proposed double-layer structure by Ruiz et al. [26] by assuming the fixed thickness of each layer, whose specifications are listed in Table 1, was 0.65 in the frequency range of 800 to 6400 Hz, with a total thickness of 22 mm. Whereas we considered the thickness of the MPP as a variable

quantity in the genetic algorithm and according to Table 3, by differentiating the aforementioned frequency interval, we achieved two different single-layer structures No. 2 and 3. Structure No. 2 with a thickness of 31.5 mm, provides an average absorption coefficient of 0.82 in the frequency range of 800 to 2000 Hz, and structure No. 3 with a thickness of 10.7 mm, provides an average absorption coefficient of 0.64 in the frequency range of 2000 to 6400 Hz.

Comparing Ruiz's proposed double-layer structure with our proposed single layer structures shows that according to the frequency spectrum of noise in a room, with a suitable arrangement of the structures Nos. 2 and 3 on the surfaces of the room can be achieved the average absorption coefficient of 0.73 in the frequency range of 800 to 6400 Hz, which is 12.3% better than the average absorption coefficient of the Ruiz's proposed structure.

Considering that our proposed structures are single layer, it has less manufacturing cost than Ruiz's proposed double-layer restructure, and also due to less average total thickness of 21.1 mm which is less than his structure, the average space it occupies is 4.1% lower.

The average absorption coefficient of the proposed triple-layer structure by Ruiz et al. [26] by assuming the fixed thickness of each layer, whose specifications are listed in Table 2, was 0.74 in the frequency range of 800 to 6400 Hz, with a total thickness of 36 mm.

Comparing his proposed triple-layer structure with our proposed single layer structures in Table 3, we find that with a suitable layout of these two structures Nos. 2 and 3 on the surfaces of the room, with a maximum thickness of 31.5 mm, i.e. 12.5% less than the total thickness of the Ruiz's proposed structure, can be achieved the average absorption coefficient of 0.73 in the frequency range of 800 to 6400 Hz, which with good accuracy is almost equal to the average absorption coefficient of the Ruiz's proposed structure.

Considering that our proposed structure is single-layer, it has advantages over the proposed Ruiz's triple-layer structure, including:

1. It has less manufacturing cost than the proposed Ruiz's structure.
2. Due to the lower average thickness than the proposed Ruiz's structure, the average space it occupies is 4.1% lower.
3. The diameter of MPP holes in our proposed structure is 60% reduced compared to the proposed Ruiz's structure, which is more resistant to dust passage, and as a result, over time, the space behind the perforated panel becomes less filled and polluted with dust.
4. Considering that the average thickness of the MPP in our two proposed single-layer structures is 1.1 mm. Whereas in the proposed Ruiz's triple-layer structure is used three MPP layers with an overall thickness of

3 mm. His proposed structure compared to our proposed structure, after installation on the surfaces of the room, increases the final weight of the building by 63.3% more, which is clearly, the lighter structure is more desirable and safer in earthquakes.

According to the given results for optimizing the structure of the double-layer MPP, as shown in Figure 5, using two layers of the micro-perforated panel creates the first and second resonant frequencies.

In optimized structures, the genetic algorithm in each frequency range arranges the structure specifications in such a way that the first and second resonant frequencies of the structure occur within that range. From the comparison of the optimal structure of the number 1 in Table 3 with the optimal structure of number 1 in Table 4, it can be seen that by adding single layer MPP to the single-layer structure of MPP without increasing the total thickness of 10 cm, only 3.2% has been added to the average coefficient of sound absorption in the frequency range of 20 Hz to 500 Hz. Therefore, for this frequency range, the single-layer MPP structure is more economical than the double-layer MPP. Comparison of the optimal structure No. 2 in Table 3 with the optimal structure No. 2 in Table 4 shows that by adding a perforated layer to a single-layered structure, 3 cm is added to the total thickness of structure No. 2 and the total thickness is increased to 6.13 cm, and the average sound absorption coefficient is improved by 25.3% in the frequency range of 500 Hz to 2000 Hz. Therefore, for this frequency range, the double-layer MPP structure is more appropriate than a single-layer one. According to Figure 5 for structure No. 3, it can be seen that in the optimal double-layer structure, despite the increase in the absorption frequency bandwidth, the amount of absorption at the resonance frequencies has not decreased. Besides, the use of double-layer MPP created two resonances in the frequency range of 2000 Hz to 10000 Hz, which has resulted in a 41.8% improvement in the average sound absorption coefficient of the double-layer MPP structure compared to the single-layer structure in the frequency range of 2000 Hz to 10000 Hz.

According to the results for optimal structures including single-layer and double-layer MPPs, it can be said that to improve the amount of absorption coefficient in the frequency range of 20 Hz to 500 Hz, it is necessary to increase the overall thickness of the structure.

Also, the arrangement of the three proposed structures in Table 4, with an average total thickness of 33% more than the three structures in Table 3, improves the average sound absorption coefficient in the room at all frequencies by about 23% and reaches about 80%.

3. 4. Optimization of a Composite Sound Absorber

To compare the results of this section with the

optimization results of the previous section, the specifications of the MPP are according to Equation (6), except for the maximum allowable depth of air gap which is considered in this section is 5 cm. The porous materials whose specifications are given in Table 1 of our previous paper [15] are used, and the maximum allowable thickness of the porous material is 5 cm. Therefore, the maximum allowable thickness for the entire air gap and porous material is 10 cm.

To accurately model the MPP and porous material, Atalla's model [30] and Allard's model [14] have been used, respectively. The optimal structural characteristics and the average sound absorption coefficient of the composite sound absorber in the three frequency range of low-, mid-, and high-frequencies are listed in Table 5. Also, the sound absorption coefficient of the optimal structures presented in Table 5 is shown in Figure 6 in terms of frequency.

According to the results of the optimization of the composite sound absorber in Table 5 and its comparison with Tables 3 and 4, it can be seen that for low-frequency range, the composite sound absorber in comparison with the single and double-layer MPP structure with the same overall thickness, has better sound absorption. Also, the use of porous material behind the MPP, due to good absorption in the high-frequency range, improves the absorption bandwidth in the composite sound absorber.

Comparison of sound absorption efficiency in optimal single-layer MPP structure which is obtained in Table 3 and composite sound absorber according to Table 5 shows that using the 5 cm of porous material behind the MPP, without a considerable increasing the thickness of the whole structures, improves the average sound absorption coefficient by 8% in the first frequency range, 28% in the second frequency range and 74.6% in the third frequency range.

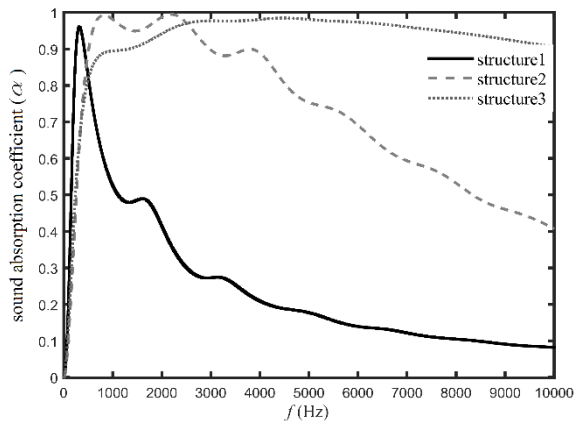
Figure 6 in comparison with Figures 4 and 5 shows that, as expected, porous material has a greater effect on improving the sound absorption coefficient at high frequencies.

Comparison of sound absorption efficiency of the optimal structure of double-layer MPP which is obtained in Table 4 and composite absorber according to Table 5, considering the high cost of making micro-perforated panels, shows that the use of 5 cm porous material behind the MPP, in addition, to reduce the manufacturing cost, improves the average sound absorption coefficient of the structure up to 4.7% in the first frequency range, up to 2% in the second frequency range and up to 23% in the third frequency range.

Therefore, it can be concluded that the use of a composite sound absorber is very suitable for sound absorption in a wider frequency range. According to the results of composite sound absorber optimization, the

TABLE 5. Optimization of the sound absorption coefficient for the composite absorber.

Structure number	Frequency bandwidth (Hz)	Optimal design parameters						The average sound absorption coefficient
		t (mm)	d (mm)	p (%)	D (cm)	σ (Pa.s/m ²)	L (cm)	
1	20 - 500	5	0.1	9	5	6229	5	0.67
2	500 - 2000	1.5	0.9	14	3.6	10100	5	0.96
3	2000 - 10000	0.5	0.2	15	2.8	21600	5	0.96

**Figure 6.** The sound absorption coefficient of optimum structures 1, 2, and 3 that are described in Table 5, for composite absorber versus frequency

genetic algorithm in all three mentioned frequency ranges determines the maximum allowable thickness of the optimal structures with a thickness of 5 cm of porous material. Therefore, it can be said that increasing the thickness of the porous material in the composite sound absorber improves the average sound absorption coefficient in all three mentioned frequency ranges.

For future work, more accurate models such as the Johnson-Champoux-Allard (JCA) model [31] can be used to determine the acoustic characteristics of porous materials.

4. CONCLUSIONS

In this paper, the optimal design of the multi-layered sound absorber composed of porous materials and the micro-perforated panel with an overall maximum thickness of up to 10 cm is presented by using the genetic algorithm for three frequency ranges. The desired frequency range includes the first range (20 Hz-500 Hz), the second range (500 Hz-2000 Hz), and the third range (2000 Hz-10000 Hz). Briefly, the results can be summarized as follows:

- The optimal design of the single-layered micro-perforated panel is only appropriate in the frequency

range of 20 Hz to 500 Hz.

- By using the precise theoretical models, we obtained single layer structures with 4.1% lower space occupation and less manufacturing cost in comparison with Ruiz's proposed double-layer structure enhance the average absorption coefficient up to 12.3% in the frequency range of 800 to 6400 Hz.
- By using the precise theoretical models, we obtained single layer structures with 41.4% lower space occupation, less manufacturing cost, 60% cleaner, and 63.3% lighter and safer in comparison with Ruiz's proposed triple-layer structure provide the same amount of the average absorption coefficient in the frequency range of 800 to 6400 Hz.
- By adding a layer to a single-layer structure MPP, the average sound absorption coefficient improves up to 25.3% in the frequency range of 500 Hz to 2000 Hz.
- The use of 5 cm porous material behind the MPP in the composite absorber, in addition, to reducing the manufacturing cost in comparison with double-layer MPP, improves the average sound absorption coefficient of the structure up to 23% in the frequency range of 2000 Hz to 10000 Hz.

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Persian Abstract

چکیده

طراحی بهینه‌ی جاذب صوت با ضخامت مطلوب و حداکثر جذب صدا، همیشه مسئله مهمی در کنترل نویز بوده است. هدف از این مقاله، دستیابی به طراحی بهینه برای پانل‌های میکروسوراخ‌دار و ترکیب آن با مواد متخلخل و فاصله هوایی برای به‌دست‌آوردن حداکثر جذب صدا با حداکثر ضخامت کلی تا حدود ۱۰ سانتی‌متر در محدوده‌ی فرکانس‌های (۲۰ تا ۵۰۰ هرتز)، (۵۰۰ تا ۲۰۰۰ هرتز) و (۲۰۰۰ تا ۱۰۰۰۰ هرتز) است. برای این منظور، الگوریتم ژنتیک به عنوان یک روش مؤثر برای حل مسئله‌ی بهینه‌سازی پیشنهاد شده است. با استفاده از مدل‌های نظری دقیق همچون مدل آلارد و مدل آتالا برای محاسبه‌ی مشخصات آکوستیکی هر لایه شامل پانل میکروسوراخ‌دار، ماده متخلخل و فاصله هوایی، الگوریتم ژنتیک ساختارهای بهینه‌شده‌ی دقیقتری ارائه داده است. از روش ماتریس انتقال برای بررسی جذب صدای ساختارها استفاده شده است. برای تأیید عملکرد الگوریتم ژنتیک برنامه‌ریزی شده، نتایج بدست‌آمده از بهینه‌سازی جاذب میکروسوراخ‌دار با سایر تحقیقات مقایسه شده است که دقت و کارایی این روش را نشان می‌دهد. پس از اطمینان از درستی عملکرد الگوریتم ژنتیک برنامه‌نویسی شده با مدل‌های نظری دقیقتر برای محاسبه‌ی مشخصات آکوستیکی هر لایه، ساختارهای جدیدی بدست آمده‌اند که ضریب جذب صوتی بهتری نسبت به ساختارهای قبلی در محدوده‌ی فرکانسی موردنظر دارند. نتایج نشان می‌دهد که با انتخاب بهینه‌ی پارامترهای طراحی، ضریب جذب صوت در محدوده‌ی فرکانسی اول، دوم و سوم به ترتیب به ۰/۶۷، ۰/۹۶ و ۰/۹۶ می‌رسد.