Journal of Electronic Research and Application, 2025, Volume 9, Issue 2
http://ojs.bbwpublisher.com/index.php/JERA
ISSN Online: 2208-3510
ISSN Print: 2208-3502

Research on Optimization of Microperforated Acoustic Structures Based on Genetic Algorithm

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Abstract: Microperforated panels (MPP) are widely used in noise control applications due to their excellent sound absorption performance. However, traditional single-layer MPPs suffer from a narrow sound absorption bandwidth, making it difficult to meet the demands for broadband sound absorption. To address this limitation, this study proposes a design approach for double-layer MPPs optimized using a genetic algorithm (GA). By optimizing structural parameters such as perforation diameter, panel thickness, perforation ratio, and cavity depth, the sound absorption performance of the double-layer MPP is significantly enhanced. The results demonstrate that the optimized double-layer MPP achieves an average sound absorption coefficient of 0.71 across the 100–5000 Hz frequency range, with a peak absorption coefficient exceeding 0.8 at 500 Hz, outperforming conventional sound-absorbing products of the same category.

Keywords: Microperforated panels; Genetic algorithm; Sound-absorption

Online publication: March 28, 2025

1. Introduction

Microperforated Panels (MPP) are acoustic structures made from thin plates, which were first proposed by Professor Ma Da Yu in 1970 [1,2]. Since then, he established the classical theoretical model for MPPs, and based on this model, numerous research achievements have been made in the structural optimization of MPPs in recent years [3]. Compared with traditional sound-absorbing materials, MPPs have the advantages of being lightweight, easy to clean, and durable [4], making them widely used in the field of sound absorption and noise reduction [5]. To enhance the sound absorption performance of MPPs, Meng *et al.* [6] proposed a composite structure combining Acoustic Black Hole (ABH) with MPP, overcoming the limitations of length and bandwidth of sound wave suppression in current ABHs. Zhao *et al.* [7] introduced a Mechanical Impedance Plate (MIP) into the traditional MPP structure and installed Helmholtz resonators on the MIP, thereby improving low-frequency sound absorption performance. Chu *et al.* [8] proposed a multi-layer micro-perforated panel structure based on convoluted space, which achieved high absorption (always exceeding 90%) in the frequency range of 400–5000 Hz. Zhang *et al.*

[9] proposed a micro-perforated sandwich-polyurethane composite structure based on Triply Periodic Minimal Surfaces (TPMS). The results showed that filling the TPMS micro-perforated core layer with strong sound-absorbing polyurethane material could broaden the relative sound absorption bandwidth in the mid-low frequency range, shift the peak sound absorption frequency towards the low-frequency direction of 294 Hz, and widen the relative sound absorption bandwidth by 23.86%.

In addition, some scholars have also investigated the effects of structural parameters of MPPs on sound absorption performance. Chen *et al.* [10] studied a double-cavity resonant composite sound absorption structure based on micro-perforated plates. Using the COMSOL impedance tube model, they analyzed the effects of various structural parameters on sound absorption and sound insulation performance. Xie *et al.* [11] designed a micro-perforated honeycomb metasurface panel (MHMP) with different hole diameters. Through impedance tube tests, they evaluated the effects of MPP hole diameter and thickness on the sound absorption performance of MHMP. Rafique *et al.* [12] proposed a composite structure of micro-perforated plates (MPP) composed of non-uniform MPPs (IMPPs) backed by J-shaped cavities of different depths. The results showed that as the length, volume of the backing cavity, and thickness of the IMPP increased, the low-frequency sound absorption peak shifted towards lower frequencies.

With the widespread application of MPPs in architectural acoustics, some scholars [13] have found that optimization algorithms can significantly enhance the sound absorption performance of MPPs. Therefore, this paper proposes a design method for optimizing the structural parameters of double-layer MPPs using a genetic algorithm, aiming to significantly improve their sound absorption performance. By optimizing parameters such as hole diameter, plate thickness, perforation rate, and cavity depth, and verifying the results using numerical simulations with COMSOL software, it was found that the optimized double-layer MPP achieved an average sound absorption coefficient of 0.71 in the frequency range of 100–5000 Hz, with a sound absorption coefficient exceeding 0.8 at 500 Hz, outperforming traditional sound-absorbing products of the same category.

2. Theoretical model of double-layer micro-perforated panels

In **Figure 1**, D_1 –The distance between the two layers of MPP; D_2 –The distance between MPP2 and the wall. Based on the equivalent circuit, the acoustic impedance of the double-layer series micro-perforated panel structure can be derived as follows:

$$Z = R_1 + j\omega M_1 + \frac{Z_{D1}(R_2 + j\omega M_2 + Z_{D2})}{R_2 + j\omega M_2 + Z_{D1} + Z_{D2}} \quad (1)$$

Where R_1 and R_2 are the acoustic resistances of the MPPs, $M_{1,}$ and M_2 are the acoustic masses of the MPPs, $Z_{D1,}$ and Z_{D2} are the acoustic impedance of the cavities behind the MPPs, and ω is the angular frequency.

When the sound wave is incident perpendicularly, the sound absorption coefficient of the micro-perforated panel is:

$$\alpha = 1 - \left|\frac{Z - \rho c}{Z + \rho c}\right|^2 \quad (2)$$

Where p is the air density, c is the speed of sound.

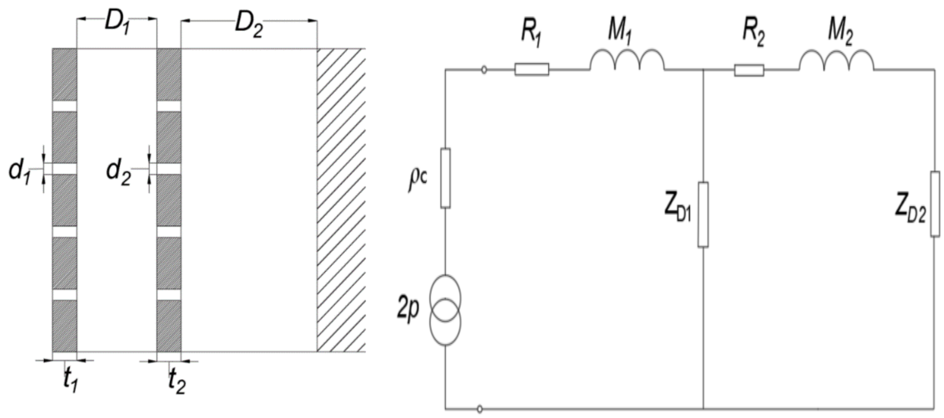

Figure 1. Double-layer micro-perforated panel sound absorption structure. Left: Schematic diagram of the double-layer micro-perforated panel structure; Right: Equivalent circuit diagram

3. Genetic algorithm optimization

A genetic algorithm-based optimization model is established, with the main objective of maximizing the sound absorption coefficient at 500 Hz and achieving the fullest average sound absorption coefficient in the frequency range of 100–5000 Hz. The objective function is defined as:

$$max\,(A) = max\,\alpha\,(f_0) + \int_{f_1}^{f_2} \alpha(f)\,df \tag{3}$$

Where f_0 is 500 Hz, f_1 and f_2 are the lower and upper-frequency limits, respectively

During the optimization process, the decision variables and constraints are determined as follows:

0.1 mm ≤ t1 ≤ 1 mm, 0.1 mm ≤ t2 ≤ 1 mm, 0.1 mm ≤ d1 ≤ 1 mm, 0.1 mm ≤ d2 ≤ 1 mm , 10 mm ≤ D1 ≤ 100 mm, 10 mm ≤ D2 ≤ 100 mm, 0.05 % ≤ σ1 ≤ 5 %, 0.05 % ≤ σ2 ≤ 5 %.

The genetic algorithm parameters are set as follows: population size of 50, termination generation of 100, mutation probability of 0.1, and crossover probability of 0.7. The optimization results are shown in **Table 1**:

Table 1. Optimization of structural parameters for double-layer micro-perforated plates

Layer	Hole diameter (mm)	Plate thickness (mm)	Perforation rate (%)	Cavity depth (mm)
Layer 1	0.18	0.51	4.48	19.54
Layer 2	0.11	0.10	1.31	77.93

4. Optimization structure simulation

Based on the optimized structural parameters obtained using the genetic algorithm, the sound absorption coefficient of the double-layer micro-perforated panel was simulated using COMSOL software. To verify the accuracy of the simulation method, a micro-perforated panel was selected for comparison between simulation and experimental results. The dimensions of the panel are 100 cm in length, 2 cm in width, and 10 cm in height, with the basic structural parameters shown in **Table 2**.

Table 2. Structural parameters of microperforated panel

Type	Hole diameter (mm)	Plate thickness (mm)	Hole spacing (mm)	Cavity depth (mm)
Single-layer MPP	0.35	0.8	4	100

In COMSOL, the simulation model of the sound absorber was established with the micro-perforated panel positioned 1 m above the ground. Considering the negligible effect of the support on the simulation, the support was omitted from the model. Each pair of micro-perforated panels was spaced 10 cm apart. The room boundaries were set as rigid acoustic boundaries, and the area above the micro-perforated panel was defined as a perfectly matched layer and an acoustic air domain. The acoustic air domain was set with a background pressure field. The simulation model is shown in **Figure 2**. The type of pressure field was defined by the user, with the incident sound pressure set as:

$$p_{inc} = e^{-j(k_x \cdot x + k_y \cdot y + k_z \cdot z)} \tag{4}$$

Where $k_z = -k_0 \cos(\theta)$, $k_x = k_0 \sin(\theta)\cos(\phi)$, and $k_y = k_0 \sin(\theta)\cos(\phi)$are the wave numbers in the x, y, and z directions, respectively, and $k_0 = \omega/c$ represents the wave number. The oblique incidence sound absorption coefficient is given by:

$$\alpha(\theta) = 1 - |R|^2 \tag{5}$$

Where $R = P_{scat}/ P_{inc}$ is the reflection coefficient and P_{scat} is the scattered sound pressure. The weighted average sound absorption coefficient is calculated as:

$$w(\theta_i) = \frac{\sin\theta_i \cdot \cos\theta_i}{\sum_{j=1}^{N} \sin\theta_j \cdot \cos\theta_j} \tag{6}$$

$$\alpha_{avg} = \sum_{i=1}^{N} \alpha(\theta_i) \cdot w(\theta_i) \tag{7}$$

Where α_{avg} is the weighted average sound absorption coefficient, $w(\theta_i)$ is the weight factor, and N is the number of sampling points.

The simulation was conducted by defining the variables according to the above formulas. The angle of incidence (as shown in **Figure 3** was varied from 0° to 78° with a step size of 10°. The sound absorption coefficients obtained at nine angles were averaged to produce the final average sound absorption coefficient curve, which was compared with the sound absorption coefficient measured using the reverberation room method. The experimental setup is shown in **Figure 4**.

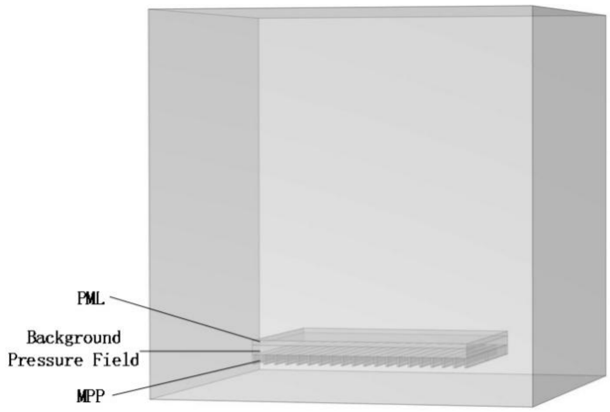

Figure 2. Simulation model

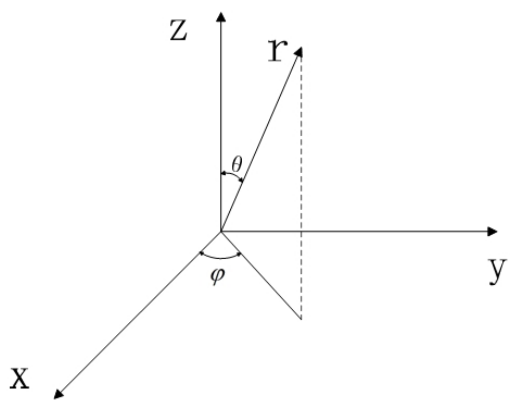

Figure 3. Oblique incidence schematic diagram

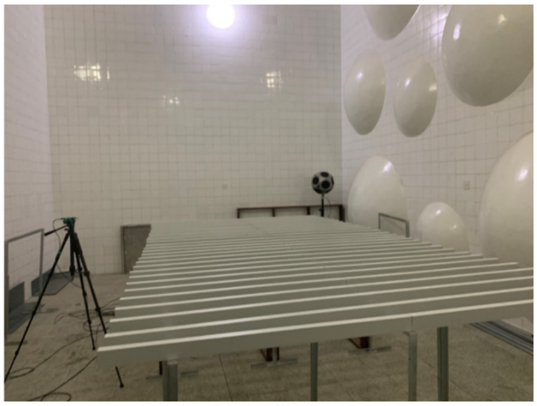

Figure 4. Reverberation room method for sound absorption coefficient testing

As shown in **Figure 5**, the red curve represents the experimental results, while the blue curve represents the simulation results. Both curves reach a peak sound absorption coefficient at around 800 Hz. Although the simulated peak is slightly lower than the experimental peak, and the simulated sound absorption coefficient is slightly higher than the experimental result at the anti-resonant frequency of 2000 Hz, the overall trends of the sound absorption effects are consistent, with the curves fitting well. This verifies the accuracy of the simulation.

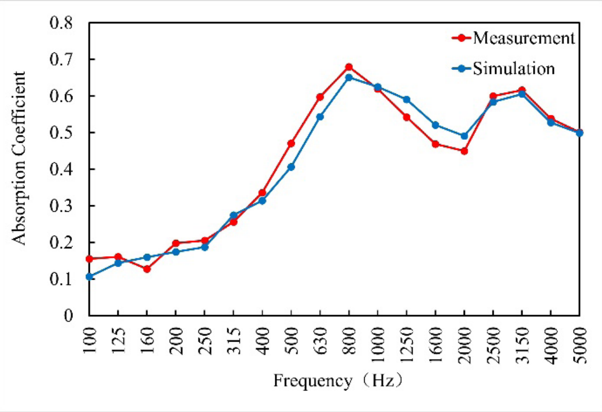

Figure 5. Comparison of simulated and experimental sound absorption coefficient curves

Based on the structural parameters optimized using the genetic algorithm, the sound absorption coefficient of the double-layer micro-perforated panel was simulated using COMSOL software. The simulation results (see **Figure 6**) show that the optimized double-layer micro-perforated panel achieved a sound absorption coefficient of over 0.8 at 500 Hz, with the coefficient approaching 1.0 near the resonance frequency of 1250 Hz. The sound absorption coefficient also remained high during anti-resonance.

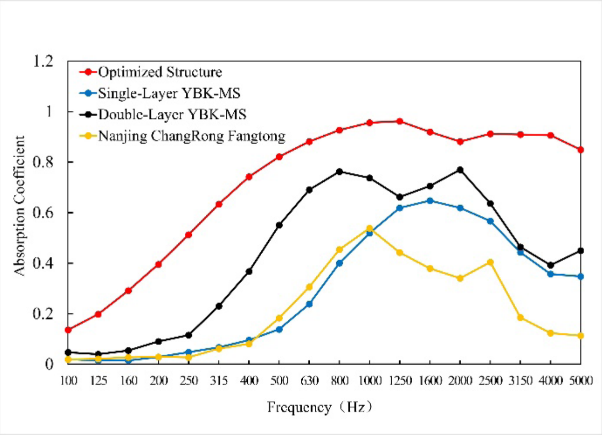

Figure 6. Comparison of simulated and experimental sound absorption coefficient curves

Furthermore, by comparing the optimized sound absorption coefficient curve with those of commercially available micro-perforated sound-absorbing products of similar specifications, it is evident that the optimized structure not only exhibits a higher sound absorption coefficient at 500 Hz but also demonstrates good sound absorption performance at low frequencies (250 Hz). The sound absorption effect is significantly enhanced across all frequencies, with a notable expansion of the sound absorption frequency band. This results in a more robust sound absorption coefficient curve within the common noise frequency range.

5. Conclusion

This paper significantly enhances the sound absorption performance of double-layer MPP through the optimization of their structural parameters. The optimized double-layer MPP achieves an average sound absorption coefficient of 0.71 across a broad frequency range of 100–5000 Hz, demonstrating excellent broadband sound absorption capability. Specifically, at 500 Hz, the sound absorption coefficient is enhanced to above 0.8, surpassing the sound absorption performance of conventional MPP products available on the market. Moreover, this optimized design effectively broadens the sound absorption bandwidth, with a synchronized enhancement in sound absorption capability, particularly in the low-frequency range (e.g., at 250 Hz), thereby addressing the deficiencies of traditional MPP in low-frequency sound absorption.

Disclosure statement

The authors declare no conflict of interest.

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