Distribution and Influence of Optimal Structural Parameters to Low-frequency Sound Absorption Property of the Microperforated Panel Absorber

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Abstract. Noise pollution is a global problem, no matter in developed or developing countries, which makes the noise reduction one research focus all over the world. Microperforated panel (MPP) absorber is supposed as a potential and practical candidate for effective noise reduction, particularly in the urban area. Influence of the optimal structural parameters to low-frequency sound absorption performance of the MPP absorber are studied in this research. The theoretical sound absorption model provides the foundation for the further analysis, and the cuckoo search algorithm is treated as the technique support. Influences of the optimal structural parameters for thin/normal/ thick MPP absorbers are studied by the combination of theoretical modeling and cuckoo search optimization with the total thickness of the MPP absorber ranging from 10 mm to 60 mm with the interval of 10 mm, from which it can be concluded that the major influent factor is total thickness of the MPP absorber. For a given total thickness of the MPP absorber, no matter what thickness of the panel is, it can always achieve appropriate structural parameters by optimization to obtain similar best sound absorption performance, which will be favorable to design and develop practical MPP absorbers.

1. Introduction
Noise pollution [1], together with air pollution [2], water pollution [3], and solid waste pollution [4], has become the major environmental pollution that affects people’s daily life and health, especially in the urban area, and it is an important influencing factor that restricts the sustainable development of economy and hinders the further improvement of people’s life quality [5, 6]. It can be judged from the “China Environmental Noise Prevention and Control Annual Report 2019” that the average acoustic environment quality in the urban area is significantly worse than that in the whole country, especially at night, which is reported by the Ministry of Ecology and Environment of the People’s Republic of China. The noise pollution is a global problem, no matter in the developed or developing countries [7, 8], which makes the noise reduction a research focus all over the world.

Many sound absorbing materials and structures have been developed for the noise reduction, such as the porous material [9], microperforated panel (MPP) [10], acoustic metamaterial [11], and so on. Taking the production cost, manufacturing efficiency, preparation process, optional variety of material, service life, and the other influencing factors into account, the MPP absorber is supposed as the most practical product for noise reduction, because it has the following remarkable advantages. Firstly, the sound absorption mechanism of MPP absorber is well revealed, and its theoretical sound absorption model can be accurately constructed according to the Maa’s theory [10, 12], which make it possible to develop the appropriate sound absorber for the different conditions. On the contrary, it was difficult to
build the accurate sound absorption model for most of acoustic metamaterials. Secondly, the sound absorption effect of MPP has little relationship with material type of the used plate, which indicates that many types of MPP absorbers can be developed for variable application scenarios, and they are easy to manufacture, transport, install, maintain, replace, clean, and so on. By contrary, most of the fabrication processes for the porous material lead to the environmental pollution inevitably, and the complex structure of acoustic metamaterial limits its practical application. Thirdly, the noise in the low frequency range was more difficult to reduce than that in the middle or high frequency range, and MPP absorber has advantage on this point relative to that of the porous material. Although the acoustic metamaterial can obtain a better sound absorption performance in certain low frequency range, its bandwidth is difficult to enlarge. Therefore, MPP absorber is supposed as a potential and practical candidate for the effective noise reduction, particularly in the urban area.

2. Theoretical modeling

Schematic diagram of the MPP absorber is shown in the Figure 1, and its structural parameters are also marked, which consists of the thickness of the panel $t$, diameter of the hole $d$, distance between the neighboring holes $b$, and length of the cavity $D$. Meanwhile, total thickness of the MPP absorber $L$ is summation of thickness of the panel $t$ and length of the cavity $D$, as shown in the Figure 1.

![Schematic diagram of the MPP absorber and its structural parameters.](image)

According to the Maa’s theory [10, 12], absorption of acoustic wave is realized based on resonance principle, and its sound absorption coefficient $\alpha$ can be derived through the calculation of the total transfer matrix $T$, as shown in the Eq. (1). Here $T_{11}$ and $T_{21}$ are two elements of the total transfer matrix $T$, which can be calculated by the transfer matrix $T_{\text{MPP}}$ of the MPP and that $T_{\text{cavity}}$ of the cavity, as shown in the Eq. (2); $\rho$ and $c$ are density of the air and acoustic velocity in the air at room temperature and atmospheric pressure, which are 1.225 kg/m$^3$ and 340 m/s respectively.

$$\alpha = \frac{4 \Re \left( \frac{T_{11}}{T_{21}} \cdot \frac{1}{\rho c} \right)}{1 + \Re \left( \frac{T_{11}}{T_{21}} \cdot \frac{1}{\rho c} \right)^2 + \Im \left( \frac{T_{11}}{T_{21}} \cdot \frac{1}{\rho c} \right)^2}$$  \hspace{1cm} (1)

$$TT = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} = T_{\text{MPP}} \cdot T_{\text{cavity}}$$  \hspace{1cm} (2)

Transfer matrix $T_{\text{MPP}}$ of the MPP and that $T_{\text{cavity}}$ of the cavity can be calculated by the Eqs. (3) and (4) respectively. In the Eq. (3), $Z_s$ is the acoustic impedance of MPP, which consists of the acoustic resistance $R$ and acoustic mass $X$, as shown in the Eq. (5), and they can be calculated by the Eqs. (6) and (7) respectively. In the Eq. (4), $\omega$ is the angular frequency of acoustic wave, which can be calculated by the Eq. (8); $j$ is the symbol of imaginary unit, $j^2 = -1$.

$$T_{\text{MPP}} = \begin{bmatrix} 1 & Z_s \\ 0 & 1 \end{bmatrix}$$  \hspace{1cm} (3)
3. Parameters optimization

The cuckoo search algorithm is a novel metaheuristic search algorithm and constructed based on the obligate brood parasitic behavior of some cuckoo species, which has been used to optimize parameters of sound absorber [13-16]. Therefore, the optimal structural parameters of MPP absorber are achieved by cuckoo search algorithm firstly, which provides basement for further analysis. Through establishing the optimized object of $b$ and $d$, the optimization target, and the constraint conditions, the cuckoo search algorithm for optimization of the structural parameters of MPP absorber can be conducted, and its flow diagram is shown in the Figure 2. Through calculation of the objective value, update of the next generation solution, achievement of the superior solution, and judge whether the superior solution is satisfied, the final optimal solution is obtained by the iterative computation.

\[ T_{\text{cavity}} = \begin{bmatrix} \cos\left(\frac{\omega D}{c}\right) & j\rho c \sin\left(\frac{\omega D}{c}\right) \\ \frac{j}{\rho c} \sin\left(\frac{\omega D}{c}\right) & \cos\left(\frac{\omega D}{c}\right) \end{bmatrix} \]  

\( Z_s = R + jX \)  

\[ R = \frac{32(\mu + \nu) \rho}{\varepsilon} \frac{t}{d^2} k_n \]  

\[ X = \frac{\omega \rho \nu}{\varepsilon} k_n \]  

\[ \omega = 2\pi f \]  

4. Results and discussions

Distributions of the optimal structural parameters with the different constraint conditions are shown in the Figure 3. For the purpose of better observation, the horizontal axis in Figure 3 uses the logarithmic coordinate, which is marked with thickness of the panel $t$. It could be judged from Figure 3(a) that optimal diameter of the hole $d$ gradually increases along with increase of thickness of the panel $t$ or
along with increase of the total thickness of the MPP absorber \( L \). On the contrary, optimal distance between the neighboring holes \( b \) gradually increases along with increase of thickness of the panel \( t \) (except when the total thickness of the MPP absorber \( L \) is 10 mm) or along with increase of total thickness of the MPP absorber \( L \). Normally, the fabrication cost increases along with decrease of diameter of the hole \( d \) or along with decrease of distance between the neighboring holes \( b \). Thus, increase of the optimal diameter of the hole \( d \) and decrease of the optimal distance between the neighboring holes \( b \) indicate that fabrication cost of the optimal MPP absorber is almost equal for different conditions with variable thickness of the panel \( t \) and variable total thickness of the MPP absorber \( L \). It is interesting to note that optimal distance between the neighboring holes \( b \) actually increases when thickness of the panel \( t \) is larger than 3 mm and total thickness of the MPP absorber \( L \) is 10 mm, which is different from the other conditions. The major reason for this phenomenon is supposed that the optimal distance between the neighboring holes \( b \) is larger than total thickness of the MPP absorber \( L \) of 10 mm in this case, and it reaches its minimum value when thickness of the panel \( t \) is 3 mm and the corresponding length of the cavity is 7 mm.

Figure 3. Flow diagram of the cuckoo search algorithm for optimization of the structural parameters.

Distributions of optimal sound absorption performance of the optimized MPP absorbers are shown in the Figure 4. It could be found that the optimal average sound absorption coefficients in the Figure 4(a) and the optimal peak sound absorption coefficients in Figure 4(b) are almost equal for different conditions with variable thickness of the panel \( t \) and variable total thickness of the MPP absorber \( L \). The similar exception also appears when total thickness of the MPP absorber \( L \) is 10 mm. Thus, it
could be concluded that the major influence factor to low-frequency sound absorption performance is total thickness of the MPP absorber $L$, and the other parameters can be adjusted accordingly.

![Graph showing the relationship between optimal sound absorption performance and thickness](image)

5. Conclusions
Influence of the optimal structural parameters to low-frequency sound absorption performance of the MPP absorber are investigated in this research. The theoretical sound absorption model provides the foundation for the further analysis, and the cuckoo search algorithm is treated as the technique support. Influences of the optimal structural parameters for thin/normal/thick MPP absorbers are studied by the combination of theoretical modeling and cuckoo search optimization with the total thickness of the MPP absorber ranging from 10 mm to 60 mm with the interval of 10 mm, from which it can be concluded that the major influencing factor is total thickness of the MPP absorber $L$. For a given total thickness of the MPP absorber $L$, no matter what thickness of the panel $t$ is, it can always achieve the appropriate structural parameters by optimization to obtain similar best sound absorption performance, so thickness of the panel $t$ can be established for the requirements in physics or mechanics firstly, which is favorable to design and develop practical MPP absorbers.

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