

Study on Sound Absorption Performance of Micro-Perforated Panel Structures with Unequal Cavity Depths

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Abstract

For conventional micro-perforated panel sound absorption structures, achieving satisfactory broadband sound absorption performance usually requires multiple sound absorption units to be connected in series. However, such configurations struggle to provide effective broadband sound absorption under space-constrained conditions. To address this issue, this study takes a stepped multi-cavity micro-perforated panel structure as the basis and further improves the performance of the sound absorption structure by fully utilizing the redundant space within the stepped cavities. An improved structure connecting the long cavity and the redundant space is proposed. The effectiveness and reliability of the proposed structure have been preliminarily validated through theoretical calculations and simulation analyses. The results show that the structure achieves effective sound absorption in the frequency range of 700 Hz to 3250 Hz with a sound absorption coefficient above 0.8 at a total thickness of only 50 mm. While maintaining excellent broadband performance, it also exhibits certain low-frequency sound absorption capabilities.

Keywords

Micro-Perforated Panel, Stepped, Broadband, Sound Absorption

1. Introduction

While people enjoy the convenience brought by the rapid development of science and technology, they also suffer from the hazards of technological products, among which noise pollution is one. At present, the primary means of noise control is sound absorption; thus, high-performance sound absorption structures will undoubtedly minimize the impact of pollution to the greatest extent.

Current research on sound absorption is still mainly focused on micro-perforated panel structures, and the major research directions can be divided into two categories. The first is low-frequency sound absorption. Due to the long wavelength of low-frequency noise, conventional sound absorption structures can only achieve satisfactory absorption of low-frequency noise by increasing their structural dimensions. However, such enlargement reduces structural applicability and is therefore undesirable. For instance, Wu F *et al.* [1] designed a hybrid sound absorption structure based on micro-perforated panels and coiled channels, and verified its low-frequency sound absorption performance through experimental analysis. Ma X Y *et al.* [2] discussed the design of micro-perforated panels (MPPs) and their passive sound absorption performance for low-frequency acoustic waves. Their results showed that adjusting the size and arrangement of MPPs can significantly optimize low-frequency sound absorption. Other researchers [3]-[6] have also conducted extensive relevant studies. The second category is broadband sound absorption. It is undoubtedly more practical to develop structures that can effectively absorb noise over multiple frequency ranges. Zhou X *et al.* [7] investigated the broadband sound absorption performance of micro-perforated sandwich panels with hierarchical honeycomb cores under high sound pressure levels. Their results indicated that such composite structures exhibit excellent sound absorption characteristics over a broad frequency range. Guo Z *et al.* [8] proposed a hierarchical porous acoustic metamaterial that enhances broadband sound absorption capability through synergistic effects; this is also the research direction chosen by most scholars [9]-[11]. Nevertheless, a balance between low-frequency and broadband sound absorption structures has not yet been achieved, and their respective advantages remain incompatible in practical performance. In response to this issue, some scholars have begun to investigate low-frequency broadband sound absorption structures that can satisfy both broadband absorption and satisfactory low-frequency performance.

To achieve low-frequency broadband sound absorption, Bucciarelli F *et al.* [12] introduced a prototype multi-layer micro-perforated panel structure, which realized the absorption of low-frequency and broadband sound waves through a multi-layer design. Carbajo J *et al.* [13] designed a multi-layer perforated panel absorber with inclined perforations to achieve broadband sound absorption. Experimental results show that the structure possesses both low-frequency and broadband sound absorption capabilities. Yan S L *et al.* [14] extended the sound absorption bandwidth by using back cavities of micro-perforated panels with different cross-sectional areas, optimizing the low-frequency and broadband sound absorption performance. This method effectively broadened the sound absorption bandwidth, especially in the low-frequency range. Other researchers have also conducted relevant studies [15]-[19]. However, all the above structures suffer from the drawback of relatively complex configuration. Therefore, this paper proposes a relatively simple low-frequency broadband sound absorption structure: a connected stepped micro-perforated panel structure with unequal cavity depths, which is abbreviated as UD-MPP in the following text for convenience. The proposed struc-

ture enhances the equivalent back cavity depth by utilizing the redundant spaces of stepped, multi-layered, and other structural configurations without increasing the overall thickness, thereby achieving a significant improvement in sound absorption performance.

2. Theoretical Model

2.1. Basic Structure

The UD-MPP structure consists of two parallel cavities with different depths. The two cavities share a single perforated panel, forming a stepped micro-perforated panel structure. Hereinafter, the deeper cavity is referred to as the long cavity, and the shallower one as the short cavity. Connecting the long cavity with the extra space corresponding to the depth difference between the long and short cavities yields the UD-MPP structure designed in this study. Its configuration is shown in **Figure 1**.

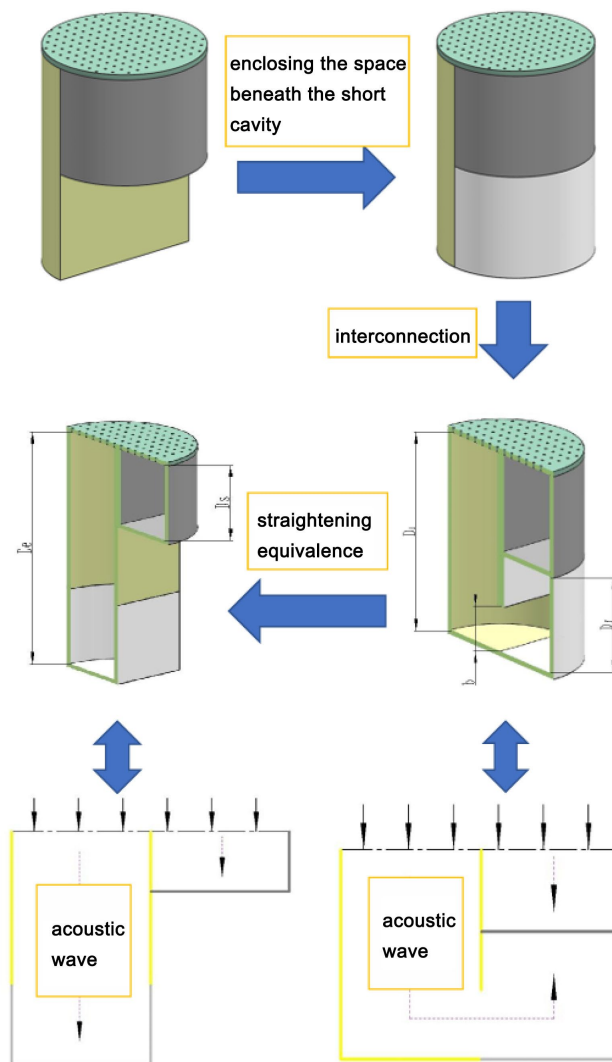


Figure 1. Schematic diagram of directly connected micro-perforated panel structure with unequal cavity depths.

The depth of the redundant space is $D_f = D_l - D_s$, the width of the partition opening is b , and its length is equal to the diameter of the perforated panel. When the opening area S_p is equal to the corresponding perforated panel area S_l of the long cavity, that is: $S_p = S_l \Rightarrow db = \pi d^2/8 \Rightarrow b = \pi d/8$ the new equivalent depth of the long cavity becomes $D_e = 2D_l - D_s$. The detailed structure is shown in the figure. Meanwhile, for the convenience of subsequent description, all parameters involved are listed uniformly in **Table 1**.

Table 1. Parameter definition comparison.

Parameter	Symbol
redundant space depth	D_f
equivalent cavity depth	D_e
width of the opening	b
opening area	S_p
Perforated panel area of the long cavity	S_l

Meanwhile, to facilitate subsequent calculations and simulations, the definitions and baseline values of the key parameters are specified, as presented in **Table 2**.

Table 2. Parameter definitions and baseline values.

Parameter	parameter definition	baseline values
panel diameter	d	29 mm
perforation ratio	p_m	6%
hole diameter	d_m	0.2 mm
panel thickness	t_m	1 mm
long cavity	D_l	50 mm
short cavity	D_s	10 mm

2.2. Theoretical Calculation of Sound Absorption Coefficient

In the theoretical calculation of this structure, the width of the connection is set to $b = \pi d/8$. The interaction between adjacent micro-perforated holes is neglected, and the vibration of the panel as well as the effects of thermoviscous acoustics are not taken into account. Based on the electro-acoustic analogy method, the electro-acoustic analogy diagram shown in **Figure 2** can be drawn.

In the figure, Z_{De} represents the new equivalent back-cavity impedance after connection, with a back-cavity depth of 20 mm. According to the rigorous theory and design derivation of micro-perforated panel absorbers proposed by Ma Da-You [20], the acoustic impedance of the equivalent cavity can be expressed as:

$$Z_{De} = -j \cot\left(\frac{\omega D_e}{c}\right) \quad (1)$$

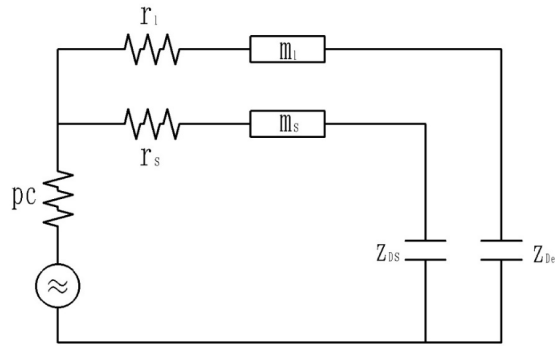


Figure 2. Electro-acoustic analogy diagram of the directly connected structure with unequal cavity depths.

The acoustic impedance of the equivalent cavity sound absorption structure is

$$Z_e = Z_{ml} + Z_{De} \tag{2}$$

Thus, the acoustic impedance of the directly connected sound absorption structure with unequal cavity depths is

$$Z_e = \left(\frac{a_l}{Z_e} + \frac{a_s}{Z_s} \right)^{-1} \tag{3}$$

By substituting into the formula for the sound absorption coefficient, the sound absorption coefficient curves can be plotted using MATLAB and compared with those of the non-connected structure, as shown in the figure. It can be seen from **Figure 3** that after connecting the closed space, although the overall effective sound absorption coefficient of the structure decreases slightly, the sound absorption frequency band is broadened. The first absorption peak shifts to low frequencies by 411 Hz, achieving a low-frequency sound absorption effect at 650 Hz, which is a direct result of the increased equivalent cavity depth after connection. The high-frequency part is also broadened outward by a frequency range of 185 Hz. Moreover, the effective sound absorption coefficient can be improved by reasonably setting the structural parameters.

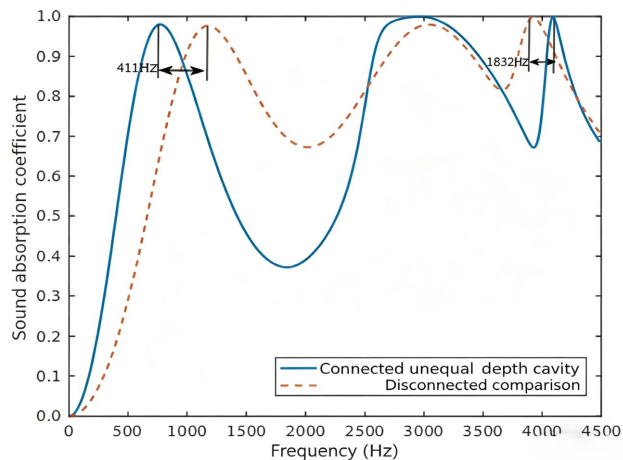


Figure 3. Comparison between the connected equivalent cavity depth structure and the unconnected structure.

3. Simulation Analysis

For the above calculations, a simulation model of the connected unequal-cavity-depth sound absorption structure and a model of the equivalent cavity-depth structure were established using COMSOL Multiphysics. The model is primarily based on the simplified derivation of Crandall's analysis of sound waves in Rayleigh microtubes, while incorporating a built-in end correction for acoustic impedance, ensuring reliable sound absorption calculation results [21]. After completing the modeling, a background pressure field was added above the perforated panel, which thus became the interior of the structure. The internal perforated panel and the relevant hard acoustic field boundaries were then set accordingly. Since the structure is primarily intended for mid-to-low frequency noise absorption, the mesh was generated using the software's default "Normal" size for free tetrahedral elements (as shown in **Figures 2-6**), which fully satisfies the criterion of one-sixth of the minimum wavelength. The resulting simulation outcomes are presented in **Figure 4**.

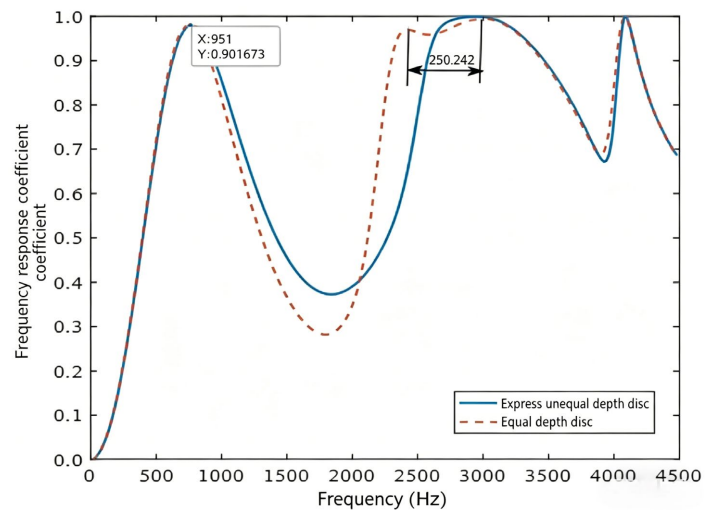


Figure 4. Comparison of sound absorption coefficients between the connected folded cavity and the straightened equivalent cavity.

It can be seen from **Figure 4** that the two curves are in complete agreement in the ranges of 0 - 761 Hz and 2650 - 4500 Hz. This indicates that the built-in folded cavity can achieve the sound absorption performance that only large-size structures can reach without increasing the structural thickness, broadening the sound absorption frequency band while maintaining a certain absorption effect. In the range of 761 - 2650 Hz, there is a slight difference between the two curves, which shows that the thermal effect caused by the sound wave propagation direction in the built-in folded cavity still exerts a certain influence on the sound absorption coefficient.

Meanwhile, the impedance derived by electro-acoustic analogy is substituted into the sound absorption coefficient formula, and then compared with the simulation results above, yielding the curves shown in **Figure 5**.

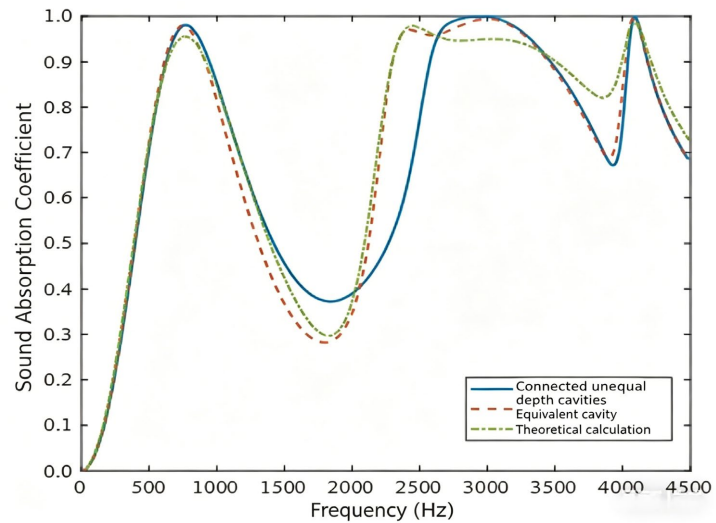


Figure 5. Comparison between simulation results and theoretical calculation results.

It can be seen from the figure that the three curves are in good agreement within the entire frequency range, which indicates that the electro-acoustic analogy method is completely feasible for calculating the connected micro-perforated panel sound absorption structure with unequal cavity depths and the equivalent cavity micro-perforated panel sound absorption structure. However, slight differences appear among the connected unequal cavity depths, equivalent cavity depth, and theoretical calculation results after 2061 Hz. This is because the wavelength shortens as the frequency increases, and the sound wave propagates laterally in the connected region, resulting in an obvious thermal effect that shifts the resonant frequency backward. After passing the resonant frequency, the curves begin to coincide again, which shows that the thermal effect is more significant near the resonant frequency.

4. Effect of Short Cavity Depth Variation on the Sound Absorption Coefficient

Section 3 has preliminarily verified that the theoretical calculation and simulation analysis methods adopted are accurate for investigating the sound absorption performance of directly connected micro-perforated panel sound absorption structures with unequal cavity depths. Within the studied frequency range, the obtained sound absorption coefficient curves show four resonant sound absorption peaks and achieve effective sound absorption at the low frequency of 761 Hz, whereas the sound absorption effect is relatively poor between 1000 Hz and 2500 Hz. Next, the influence of the variation in short cavity depth D_s on the sound absorption coefficient will be investigated, with the aim of further improving the sound absorption performance of this structure.

On the premise that the overall dimensions of the structure remain unchanged, when the short cavity depth D_s varies, it can be known from the formula that the redundant space depth D_f and the equivalent depth D_e will also change,

thus exerting a coupled effect on the sound absorption coefficient. To ensure that the variation of the short cavity depth does not affect the connection width b , Set $D_f \geq b$, with b taking values according to calculations. The specific variation of the short cavity depth is shown in **Table 3**.

Table 3. Values of short cavity depth variation after direct connection.

Parameters	Initial value	Step size	Final value
D_s	5 mm	5 mm	25 mm

The simulation results are shown in **Figure 6**. It can be seen that there is no obvious variation pattern of the sound absorption coefficient with the change of the short cavity depth. Nevertheless, it can still be observed from the figure that the corresponding frequencies of the first absorption peak of the curves are basically coincident, which indicates that when the frequency is sufficiently low, a small increase in the equivalent cavity depth has an insignificant effect on improving the low-frequency performance of the sound absorption structure.

Moreover, within this frequency range, when D_s is set to 5 mm, 10 mm, and 15 mm, the curves all exhibit four absorption peaks. Among them, the sound absorption effect is the best at 15 mm and the worst at 5 mm. It can be concluded that the resonance effect is the strongest when D_s ranges from 10 mm to 15 mm. When D_s is set to 20 mm and 25 mm, only three absorption peaks appear, but under the current parameters, the effective sound absorption bandwidth is superior to that of the cases with four absorption peaks. In particular, at a cavity depth of 20 mm, effective sound absorption is achieved in the frequency range of 700 Hz to 3250 Hz, with a sound absorption coefficient exceeding 0.8.

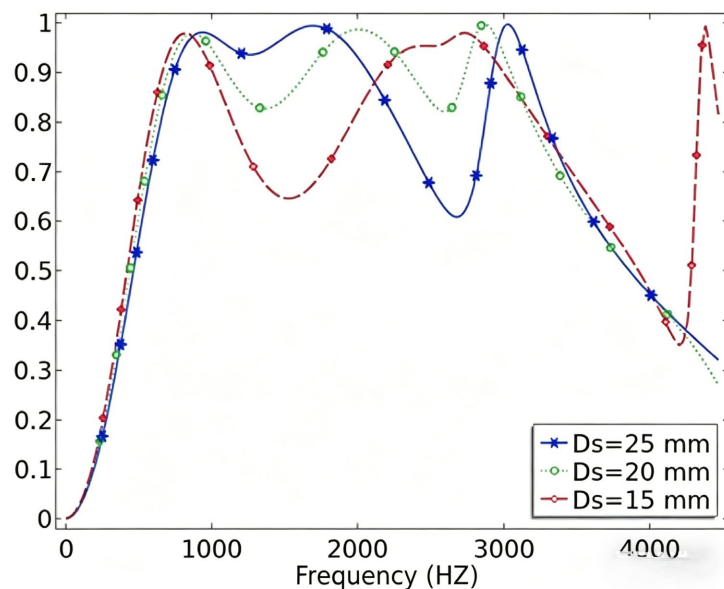


Figure 6. Simulation of sound absorption performance of structures with varying short cavity depths.

5. Conclusions

Based on the stepped micro-perforated panel structure, this paper fully utilizes the redundant space present in the shorter cavities when the cavity depths are unequal. By rationally exploiting this redundant space, the performance of the sound absorption structure is further improved.

Through the research, it has been found that under a total thickness of 50 mm, the proposed structure achieves effective sound absorption in the frequency range of 700 Hz to 3250 Hz, with a sound absorption coefficient exceeding 0.8. However, this represents the absorption performance contributed by only three resonance absorption peaks; undoubtedly, a configuration with four resonance absorption peaks holds greater potential. Subsequent research can be directed toward optimizing the sound absorption performance of four resonance absorption peaks to achieve even better absorption results.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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