Study on sound absorption properties of fiber materials and perforated components and their composite structures with different structural parameters

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Abstract. Fiber materials and perforated components are often used as basic structural units, which are widely used in the field of environmental noise reduction and automotive noise reduction. In this work, the effects of different structural parameters on the sound absorption properties of fiber materials, perforated components and their composite structures are studied. The sound absorption coefficients of fiber materials, perforated elements and their composite structures with different structural parameters were simulated by COMSOL finite element software. The transfer function method is used to measure the sound absorption in the impedance tube. The simulation results are in good agreement with the experimental results. The results show that the thickness of sound absorption material has a great influence on the sound absorption coefficient. The perforation rate is an important factor affecting the sound absorption performance of perforated components. When the perforation rate is high, it hardly absorbs sound. With the increase of aperture and wall thickness, the sound absorption performance increases in low frequency band and decreases in medium and high frequency bands. The non-periodic oscillation of sound absorption coefficient occurs with the change of cavity thickness.

Keywords. Fiber materials; Perforated components; composite structure; structural parameters; sound absorption performance.

1. Introduction

Fiber materials can be widely used as sound-absorbing materials in noise pollution control. In addition, sound-absorbing materials also have different intricate and internal structures that make materials’ fabrication and acoustic modelling complicated. General fiber sound absorption refers to the friction, resonance and viscous resistance between air and pore wall when sound wave enters the material, which weakens the sound energy, as mentioned in Ref [1]. Perforated plate was put forward by the famous scientist of China and academician Ma Dayou of Chinese Academy of Sciences in the 1960s, as in Ref [2-3]. It is the earliest sound lining material developed in China and widely used in noise control engineering. Thin plates, such as steel plate, aluminum plate, plywood and plastic plate, are perforated according to a certain aperture and perforation rate, leaving a certain thickness of air
behind, thus forming a resonant sound absorption structure of perforated plates. Lin Lei et al. [4] established the theoretical analysis model of the micro-perforated-sound absorption composite structure for predicting and optimizing the sound absorption performance of the structure. Pei Chunming et al. [5] gave the calculation method of sound absorption coefficient of composite structure of sound absorption material and micro-perforated plate. Therefore, this paper studies the effect of structural parameters of fiber materials, perforated components and their composite structures on their sound absorption performance, which provides a theoretical basis and practical guidance for noise control.

2. Theoretical basis

2.1. Acoustic properties of sound absorbing materials

The internal structure of sound absorbing materials is different and complex. When describing their acoustic characteristics, they are assumed to be equivalent fluids with complex sound velocity and density. Among them, the complex wave number and complex characteristic impedance of sound absorbing materials are as follows:

$$k_a = \frac{k}{k_0} = \left(1 + a_1 E^{-\alpha_1}\right) - ja_2 E^{-\alpha_2};$$

$$z_a = \frac{z}{z_0} = \left(1 + b_1 E^{-\beta_1}\right) - jb_2 E^{-\beta_2};$$

In above formula, $E$ is a dimensionless parameter, $E = \rho_0 c_0 k_0 = 2\pi f / c_0$, is the wave number in the air, $z_0 = \rho_0 c_0$, is air characteristic impedance. Once one obtained complex wave number and complex characteristic impedance, the complex sound velocity and complex density of sound absorbing material can be evaluated by mathematical arrangements.

$$c_\tilde{a} = \frac{2\pi f}{k}$$

$$\tilde{\rho} = \frac{z}{c}$$

2.2. Acoustic characteristics of perforated components

Taking perforated plate structure as an example, its acoustic characteristics are expressed by acoustic impedance $Z_p$.

$$Z_p = \frac{\Delta p}{V} = R_p + jX_p$$

In equation (5), $\Delta p$ is the sound pressure difference inside and outside the perforated plate structure; $V$ is the average particle velocity at the orifice.

The formula for calculating the acoustic resistivity of perforated plates is given by Bauer [6]:

$$R_p = \frac{R_h}{\phi} = \frac{\sqrt{8\rho_0 \mu \omega (1 + t_w / d_h) / z_0}}{\phi}$$
In equation (6), $\phi$ is the porosity of the plate, $\mu$ is the dynamic viscosity coefficient of the fluid, $d_h$ is the diameter of the holes in the plate, and $t_w$ is the wall thickness of the plate. The formula for calculating the acoustic reactance is as follows:

$$X_p = k(t_w + \alpha d_h) / \phi$$  \hspace{1cm} (7)

When the number of holes is large, the influence of the interaction between holes on the end correction coefficient should be considered. The formula for calculating the end correction factor of perforated plate is given by Mechel [7]:

$$\alpha = \begin{cases} 
0.85 \left[1 - 2.34 \left(\frac{\phi}{\pi}\right)^{1/2}\right] + 0.25 \left(\frac{\phi}{\pi}\right)^{1/2} & \text{if } \frac{\phi}{\pi} \leq 0.25 \\
0.668 \left[1 - 1.9 \left(\frac{\phi}{\pi}\right)^{1/2}\right] + 0.25 \left(\frac{\phi}{\pi}\right)^{1/2} & \text{if } \frac{\phi}{\pi} > 0.25 
\end{cases}$$  \hspace{1cm} (8)

2.3. Acoustic characteristics of composite structure of sound absorbing materials and perforating elements

For resistive mufflers, one side of the perforated tube is air medium and the other side is sound absorbing material. The acoustic impedance of perforation (without flow) can be expressed as:

$$\zeta_p = R_s + jk \left(1 + \frac{\zeta}{\zeta_s}\right) \frac{\phi}{d_h}$$  \hspace{1cm} (9)

In equation (9), $\zeta$ and $\zeta_s$ represent the characteristic impedance of sound-absorbing material and air respectively; $k$ and $k_s$ represent the wave number of sound-absorbing material and air respectively.

3. Analogue simulation

3.1. Sound absorbing performance simulation of sound absorbing materials

In this subsection, the theoretical calculation principle and approach of sound absorption coefficient are based on two-microphone transfer function method. The sound absorption coefficient curve of the sound absorption material with different material thickness and cavity thickness was simulated and analyzed by COMSOL. The material flow resistance was set at 4896 $p a \cdot s / m^2$. The simulation results are shown in figure 1.
3.2. Space considerations Sound absorption performance simulation of perforated components

Using the control variable method, COMSOL software was used to study the effects of different structural parameters such as perforation rate, aperture, wall thickness and cavity thickness on the sound absorption performance of the sound absorbing structure of the perforated plate. The simulation results are shown in figure 2.

3.3. Sound absorbing performance simulation of composite structure of sound absorbing materials and perforating elements

The composite structure diagram of sound absorbing material and perforating element are shown in figure 3. Different structural parameters, including material thickness, perforation rate, aperture, wall
thickness and cavity thickness, are studied by COMSOL software. The sound absorption coefficient curves are obtained by simulation. The simulation results are shown in figure 4.

**Figure 3.** Schematic diagram of composite structure of sound absorbing material and perforated component.

**Figure 4.** Absorption coefficients of composite structures with sound absorbing materials and perforating elements under different structural parameters: (a) perforation rates; (b) apertures; (c) wall thicknesses; (d) material thicknesses; (e) cavity thicknesses.
4. Experimental test

4.1. Sound absorbing performance test of sound-absorbing materials

Using an impedance tube material sound absorption test system (Beijing SW series) and taking glass fiber cotton as the test object, the sound absorption coefficients of different material thicknesses and different cavity thicknesses were measured. The tested results are shown in figure 5.

![Figure 5](image)

**Figure 5.** Measured curves of sound absorption coefficients of different material thicknesses and cavity thicknesses: (a) material thicknesses; (b) cavity thicknesses.

4.2. Perforated component sound absorption performance test

In experimental test, the sound absorption coefficients of perforated panels under different structural parameters are measured. The results are shown in figure 6.

![Figure 6](image)

**Figure 6.** Measured curves of sound absorption coefficients of perforated panel sound absorption structures with different structural parameters: (a) perforation rates; (b) apertures; (c) wall thicknesses; (d) cavity thicknesses.
4.3. Sound absorbing performance simulation of composite structure of sound absorbing materials and perforating elements

In experiment, glass fiber cotton and perforated plate are used as sound absorption components. The sound absorption coefficient curves of composite structure of sound absorption material and perforated element with different structural parameters were measured, respectively. The measurement results are shown in figure 7.

![Figure 7](image)

**Figure 7.** Measured curves of sound absorption coefficients of composite structure of sound absorbing material and perforating element under different structural parameters: (a) perforation rates; (b) apertures; (c) wall thicknesses; (d) cavity thicknesses; (e) different thicknesses of sound absorption material.

5. Conclusions

Through COMSOL simulation and experimental measurements, the influences of different structural parameters obtained on the sound absorption properties of the sound absorbing materials, the perforated components and their composite structures are investigated and conclusions are summarized as follows:
Provided that the flow resistance of material keeps constant, the sound absorption coefficient of material will be improved with the increase of thickness of material, especially in low frequency range; given that thickness and flow resistance rate of material are set to be constant, the sound absorption coefficient of material follows a non-periodic oscillation that begins to occur as the thickness of cavity increases.

The perforation rate is one of main factors affecting the sound absorption coefficient of perforated element. As perforation rate increases, the sound absorption coefficient of perforated element drops sharply, and when perforation rate arises, the sound absorption coefficient turns out to be extremely low. With the increase of aperture, the sound absorption coefficient of the perforated component decrease in high frequency band and gradually rises in middle-high frequency bands; with the increase of wall thickness, component sound absorption performance at middle-high frequency bands continue to increase, but the high frequency band starts to decrease. When the thickness of cavity increases, the sound absorption coefficient appears to vibrate and the vibration period decreases continuously, and the peak shifts to lower frequency band.

For the combinations of sound absorbing material and perforated component, if the perforation rate is lower, the sound absorption performance at low frequencies is obviously better than that in high frequency band; with the increase of aperture and wall thickness, sound absorption coefficient of low-middle frequency bands increase continuously and the peak of sound absorption coefficient shifts to lower frequency band; with the increase of material thickness, the peak of sound absorption coefficient starts to move to low frequency band and overall curve tends to be smooth; with the increase of thickness of cavity, the sound absorption coefficient curve of middle-high frequency bands appears more regular. As a result, the oscillation period becomes short gradually, and sound absorption coefficient at low frequencies increases accordingly.

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