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ESTIMATION OF THE ABSORPTION PERFORMANCE OF POROUS MATERIAL/MPP COMPOUND STRUCTURE

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The model of the specific acoustic impedance of the porous material/MPP compound structure was established in this paper, and then the relations between the compound structure and the single absorbers were built based on the acoustic impedance model. Some qualitative conclusions were thereby gained through the analysis on the single structures, such as the compound structure and the micro-perforated panel absorber usually resonate at different frequency. All these conclusions were verified by the experimental results. Besides, it is very complicated to calculate the absorption coefficient of the compound structure directly, but predicting the absorption coefficient in low frequency range is very meaningful for the compound structure in engineering. Therefore, based on the theoretical and experimental research on the porous material/MPP compound structure, a model was proposed for predicting the absorption coefficient of the compound structure in low frequency range. According to the model, the absorption coefficient of the compound structure can be predicted by the absorption coefficients of the single structures, and the prediction of the absorption coefficient of the porous materials and micro-perforated panel absorbers are relatively simple. The prediction results and the measured results have a good agreement.

Keywords: compound structure, acoustic impedance, absorption coefficient

1. Introduction

Porous materials and micro-perforated panels (MPPs) have been used in many noise control applications [1]. Porous materials have good performance in high frequency range, and MPPs have good performance near the resonant frequency, which are always in low frequency range. For porous materials, the sound energy is attenuated mainly by the friction [2], but the micro-perforated panel absorber is based on the Helmholtz resonator which can be regarded as a mass-spring system [3]. Researchers have found that the acoustic impedance of porous materials is closely related to its physical parameters such as flow resistivity, tortuosity [4, 5], and the semi-empirical models are used to calculate the acoustic impedance [6, 7]. Maa was the first researcher who proposed developing effective perforated absorbers by reducing the hole diameters to sub-millimeter size, starting from Crandall’s short tube wave equation, Maa laid the theory of micro-perforated absorbers using electro-acoustic analogy [8, 9]. MPPs can be available in severe environment and they are more durable than common traditional sound-absorbing materials [10], as a consequence, various efforts have been made to improve the theory of micro-perforated panel absorbers [11-14].

For that MPPs are efficient in narrow frequency bandwidth around the resonance frequency, many researches are oriented to enlarge the frequency bandwidth. Many compound structures are with great prospects [15]. When porous material lay before MPP absorber, the compound structure show good performance in sound abatement, but the research on this structure is still very limited at present.

The acoustic impedance model of the porous material/MPP compound structure has been established in this paper. Theory analysis revealed some primary properties of the compound structure, such as the compound structure's resonant frequency is not always the same as the MPP absorber, experimental results verified these conclusions. A model was also proposed to predict the compound structure's absorption coefficient, and the prediction results agree well with experimental results.

2. Porous material/MPP compound structure

The schematic diagram of porous material/MPP compound structure is shown in Fig. 1, as the figure shows, porous material lies before the MPP absorber. Additionally, if the porous material has a large thickness, for most porous materials, its performance would be very good in low frequency range, then the MPP absorber would make little contribution to the compound structure, which would make the compound structure meaningless. Hence, we suppose the thickness of the porous material is not so large in the following discussion.

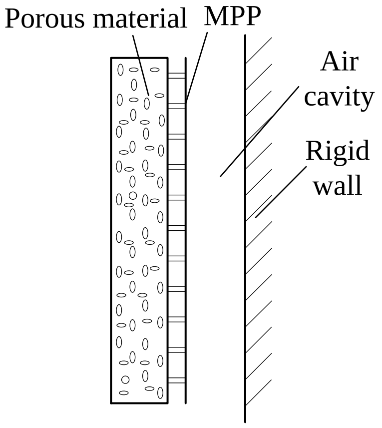

Figure 1: Porous material/MPP compound structure.

2.1 Theoretical models

Firstly, consider the MPP absorber, whose acoustic impedance can be expressed as:

$$Z_m = \rho_0 c_0 \left(r + j\omega m - j\cot\left(\frac{\omega D}{c_0}\right)\right) \tag{1}$$

$$r = \frac{32\eta t}{\rho_0 c_0 d^2 \sigma}\left(\sqrt{1+\frac{k_p^2}{32}} + \frac{\sqrt{2}}{32} k_p \frac{d}{t}\right) \tag{2}$$

$$\omega m = \frac{\omega t}{\sigma c_0}\left(1 + \left(9 + \frac{k_p^2}{2}\right)^{-1/2} + 0.85\frac{d}{t}\right) \tag{3}$$

$$k_p = d\sqrt{\omega \rho_0 / 4\eta} \tag{4}$$

Where ρ_0 is the density of air, c_0 is the speed of sound in air, η is the coefficient of kinematic viscosity of air, t is the thickness of the panel, d is the diameter of the hole, σ is the perforation ratio, ω is the circular frequency, D is the depth of the back cavity.

Then, consider the acoustic impedance of the porous material, when the porous material backed with rigid wall, the acoustic impedance can be expressed as:

$$Z_p = -j\rho c \cot kl \tag{5}$$

Where ρ is the density of the material, c is the sound speed in the material, l is the thickness of the material, $k = \omega / c - j\alpha_0$ is wave number and α_0 is the coefficient of the sound energy consumed by the material, its value would increase along with the increasing of the circular frequency ω. The normalized specific impedance can be expressed as:

$$\frac{Z_p}{\rho_0 c_0} = \gamma A + j\gamma B \tag{6}$$

$$A = \frac{sh2\alpha_0 l}{ch2\alpha_0 l - \cos\frac{2\omega l}{c}} \tag{7}$$

$$B = \frac{-\sin\frac{2\omega l}{c}}{ch2\alpha_0 l - \cos\frac{2\omega l}{c}} \tag{8}$$

$$\gamma = \frac{\rho c}{\rho_0 c_0} \tag{9}$$

Finally, the surface impedance of the compound structure can be gained, it can be expressed as:

$$Z_s = \rho c \frac{Z_m + j\rho c \tan kl}{\rho c + jZ_m \tan kl} \tag{10}$$

The specific acoustic impedance can be expressed as:

$$Z = \gamma \frac{Z_m / \rho_0 c_0 + j\gamma \tan kl}{\gamma + jZ_m \tan kl / \rho_0 c_0} = \frac{Z_{rs} Z_{r0} + \gamma^2}{Z_{rs} + Z_{r0}} \tag{11}$$

Where $Z_{rs} = Z_m / \rho_0 c_0 = R_p + jI_p$, $Z_{r0} = Z_p / \rho_0 c_0 = R_c + jI_c$.

And Z can be written as:

$$Z = Z_R + jZ_I \tag{12}$$

Where Z_R is the normalized specific acoustic resistance, and Z_I is the normalized specific acoustic reactance. Each term can be expressed as:

$$Z_R = \frac{\left(R_p + R_c\right)\left[\gamma^2 + \left(R_p R_c - I_p I_c\right)\right] + \left(I_p + I_c\right)\left(R_p I_c + I_p R_c\right)}{\left(R_p + R_c\right)^2 + \left(I_p + I_c\right)^2} \tag{13}$$

$$Z_I = \frac{\left(R_p I_c + I_p R_c\right)\left(R_p + R_c\right) - \left(I_p + I_c\right)\left[\gamma^2 + \left(R_p R_c - I_p I_c\right)\right]}{\left(R_p + R_c\right)^2 + \left(I_p + I_c\right)^2} \tag{14}$$

2.2 Analysis and discussions

The direct relations between the normalized specific acoustic resistance Z and frequency f is much more complicated, but the relations between R_p, I_p, R_c, I_c and f are clearly, so we can establish the relations between Z and f indirectly through R_p, I_p, R_c, I_c.

It is easily known that R_p is r of Eq. (2), from Eq. (2) we can know that $R_p > 0$, and the value of R_p would increase along with the increasing of frequency f though it would affected by the parameters of the MPP such as the thickness of the panel and perforation ratio. The general trend of the value of R_p in low frequency range is increasing slightly along with the increasing of frequency as shown in Fig. 2(a).

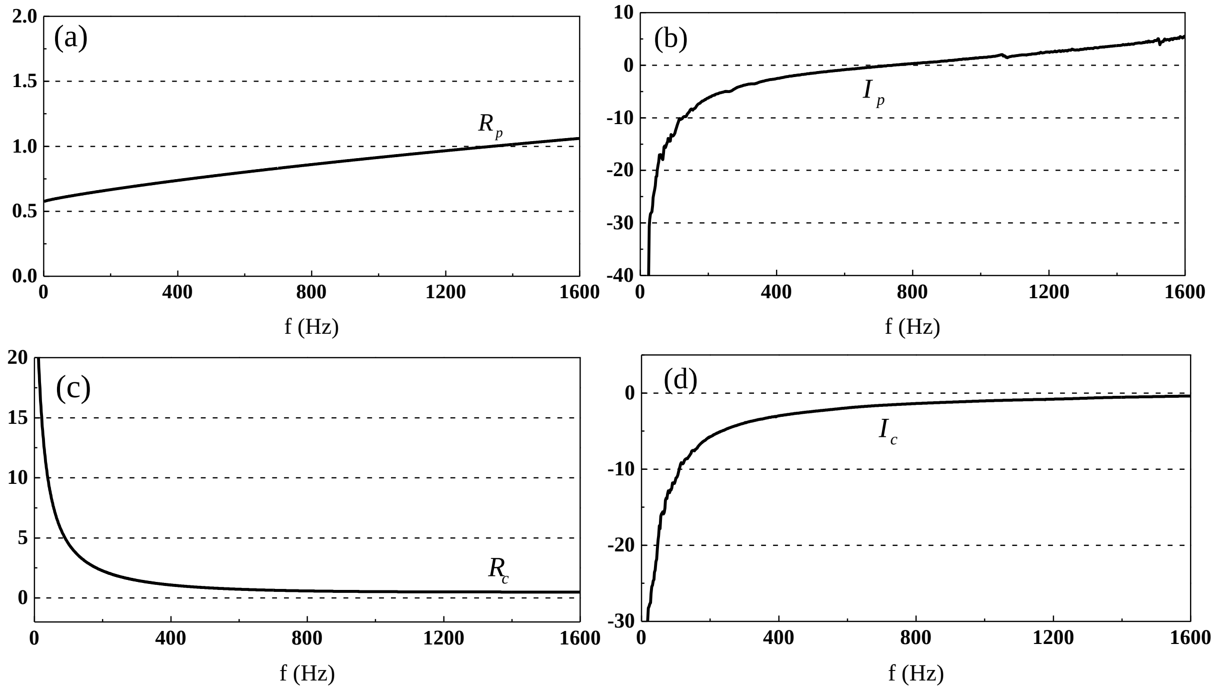

Figure 2: General trend of the value of R_p, I_p, R_c, I_c, (a) R_p; (b) I_p; (c) R_c; (d) I_c.

For $I_p = \omega m - \cot(\omega D / c_0)$, when $\omega D / c_0 < \pi$, the value of I_p would increase along with the increasing of frequency *f*, when I_p equals to zero, the absorption coefficient of the MPP absorber will reach to the peak value. And of course, the value of I_p is also related to other parameters, such as the thickness of the panel and the diameter of the hole, the general trend of the value of I_p is increasing along with the increasing of frequency as shown in Fig. 2(b).

As the real part of the acoustic impedance, $R_c = \gamma A$, it is always positive. Because the absorption coefficient can be expressed as $\alpha = 4Z_r / \left((1+Z_r)^2 + Z_i^2\right)$, where Z_r is the real part of the impedance and Z_i is the imaginary part of the impedance, it is obvious that Z_r have the same sign with α, and α is always positive, so Z_r is always positive. According to Eq. (7), in low frequency range, the general trend of the value of R_c is downwards quickly at beginning, then almost maintains at a certain value as shown in Fig. 2(c).

$I_c = \gamma B$, because $R_c > 0$ and $sh2\alpha_0 l > 0$, so $ch2\alpha_0 l - \cos(2\omega l / c) > 0$ according to Eq. (7). That is to say the denominator of I_c is positive, and whether the value of I_c is positive or negative is decided by the numerator. When $\omega l / c < \pi$, the value of I_c would change to positive from negative gradually depending on the sine function of the numerator. But when the thickness of the porous material is not large, most of them would reach to the peak value of the absorption coefficient at the frequency over 2 kHz, so the value of I_c will always negative in low frequency range, and the general trend of the value of I_c is increasing along with the increasing of frequency as shown in Fig. 2(d).

2.3 Results

It is easily known that $I_p < 0$, $I_c < 0$ and $Z_I < 0$ in lower frequency range from the above discussion, when the frequency reach to f_p, the MPP absorber would be resonant , so, $I_p = 0$, and the imagine part Z_I can be expressed as $Z_I = I_c\left(R_p{}^2 - \gamma^2\right)/\left(\left(R_p + R_c\right)^2 + I_c{}^2\right)$, then whether the value of Z_I is negative or positive is determined by R_p and γ. The value of R_p would smaller than γ for most porous materials in low frequency range. $Z_I > 0$ when $R_p < \gamma$, for Z_I is a continues function of frequency, so there is a f' smaller than f_p made $Z_I = 0$. That means the resonance frequency of the compound structure would move to the left side compared with the single MPP absorber. Similarly, if $R_p = \gamma$, then $Z_I = 0$, the compound structure have the same resonance frequency with the single MPP absorber.

Along with the increasing of the frequency, the value of I_p will much larger than γ, R_p, R_c, I_c, so Z_R and Z_I can be expressed as:

$$Z_R = \frac{R_p\left(\frac{\gamma}{I_p}\right)^2 + R_c\left(\frac{\gamma}{I_p}\right)^2 + R_c\left(\frac{R_p}{I_p}\right)^2 + R_p\left(\frac{R_c}{I_p}\right)^2 + R_p\left(\frac{I_c}{I_p}\right)^2 + R_c}{\left(\frac{R_p + R_c}{I_p}\right)^2 + \left(1 + \frac{I_c}{I_p}\right)^2} \approx R_c \tag{15}$$

$$Z_I = \frac{I_c\left(\frac{R_p}{I_p}\right)^2 + I_p\left(\frac{R_c}{I_p}\right)^2 - I_p\left(\frac{\gamma}{I_p}\right)^2 - I_c\left(\frac{\gamma}{I_p}\right)^2 + I_p\left(\frac{I_c}{I_p}\right)^2 + I_c}{\left(\frac{R_p + R_c}{I_p}\right)^2 + \left(1 + \frac{I_c}{I_p}\right)^2} \approx I_c \tag{16}$$

That means the specific acoustic impedance of the compound structure is approximately equal to the single porous material in high frequency region. The acoustic performance of the compound structure is similar to porous material.

3. Experimental results

Experiments have been done to verify whether the conclusions gained in the preceding section are right or not. The absorption coefficients were measured by two-microphone impedance measurement tube type 4206, in the frequency ranges from 50 Hz to 1.6 kHz. The porous materials used in the experiments are melamine with thickness of 40 mm, and the MPPs are made of aluminum, the parameters of the MPPs are shown in Table 1, the air cavity of the compound structure is 40 mm. The experimental results are shown in Fig. 3.

Table 1: parameters of the MPP

Sample	t (mm)	d (mm)	σ (%)
a	1.4	1	1
b	1	1	3.14
c	0.5	0.8	1

It can be seen from Fig. 3 that the resonance frequency of the compound structure moves to the left compared with the single MPP absorber. In the high-frequency range, the absorption coefficients of the compound structures are close to the absorption coefficient of the porous material. So, the analysis conclusions are consistent with the experimental results.

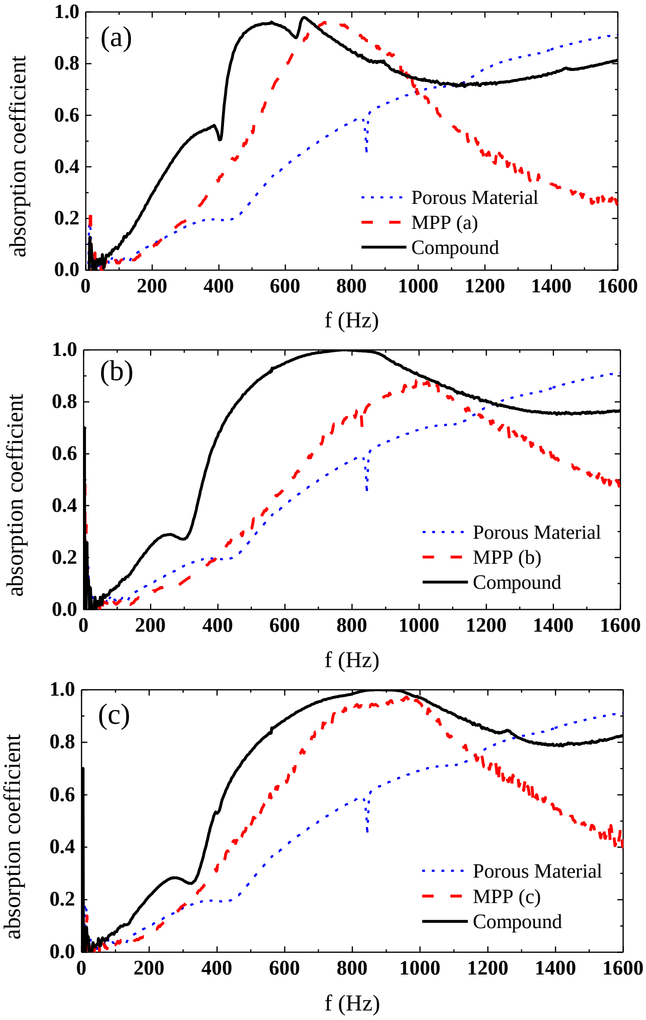

Figure 3: Experimental results, (a) sample a of MPP; (b) sample b of MPP; (c) sample c of MPP.

4. Absorption coefficient predicting

The specific acoustic impedance of the compound structure is relatively complex, so it is difficult to calculate the absorption coefficient directly. Compared with the compound structure, research on porous materials and MPP absorbers are much more sufficient and perfect, therefore, a single sound-absorbing structure has better designability, and the calculation of the absorption coefficient of a single sound-absorbing structure is much more convenient and accurate. Thus, using the absorption coefficient of the single sound-absorbing structures to predict the compound structure's absorption coefficient is very meaningful.

Absorption coefficient α is defined as $\alpha = 1 - ER/EI$, where EI is the energy incident to the materials, ER is the reflected energy. For the compound structure, the sound waves firstly go through the porous material, part of the sound energy would be consumed, then the rest of the sound energy would be incident to the surface of the MPP, and part of the incident energy would be consumed by the MPP absorber. If the absorption coefficient of the porous material is α_1 and the absorption coefficient of the MPP absorber is α_2, the absorption coefficient of the compound structure can be approximately expressed as:

$$\alpha = \alpha_1' + \alpha_2' - \alpha_1' \alpha_2' \tag{17}$$

Where α_1', α_2' are related to α_1, α_2, but not α_1, α_2, because for the compound structure, the porous material and the MPP absorber will effect each other, so their absorption coefficients would change. Then the α_1' and α_2' can be approximately expressed as:

$$\alpha_1'(f) = 4 * \alpha_1(f)/5 \tag{18}$$

$$\alpha_2'(f) = \alpha_2\left(f + \frac{\alpha_{cross}}{5} f_{cross}\right) \tag{19}$$

Where f_{cross} is the frequency when $\alpha_1 = \alpha_2$ and $f_{cross} > f_p$, α_{cross} is the absorption coefficient at frequency f_{cross}.

Figure 4 shows the comparison of the calculated results and the measured results. As can be seen from Fig. 4, the calculated results show a good agreement with the measured results. So, the proposed model can be used to predict the absorption coefficient of the compound structure.

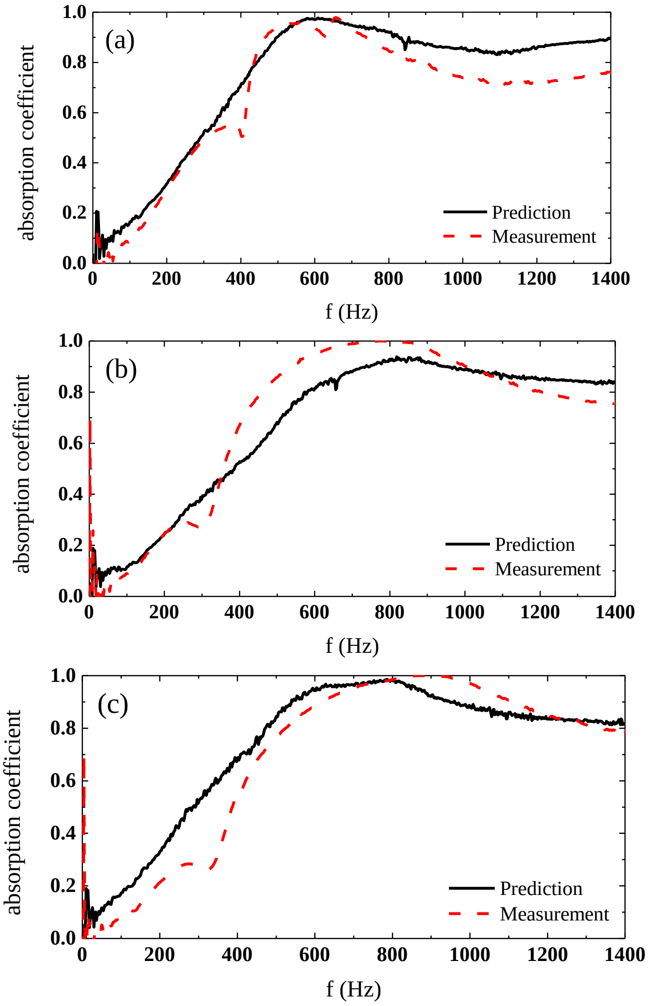

Figure 4: Comparison of the calculated results and the measured results,

(a) sample a of MPP; (b) sample b of MPP; (c) sample c of MPP.

5. Conclusions

In the present work, the acoustic impedance of the porous material/MPP compound structure is built. The acoustic resistance and the acoustic reactance of the compound structure are represented by the acoustic resistance and the acoustic reactance of the porous material and the MPP absorber respectively. Conclusions are gained through the analysis of the general trend of the value of the acoustic resistance and the acoustic reactance of the porous material and the MPP absorber. And the conclusions were verified by experimental results.

Based on the theoretical and experimental research on the porous material/MPP compound structure, a model is proposed for predicting the absorption coefficient of the compound structure in low frequency range. According to the model, the absorption coefficient of the compound structure would be predicted easily by the absorption coefficients of the porous material and the MPP absorber. And there are many researches on the porous materials and the MPP absorbers, so it is very easy to get the absorption coefficient of the porous materials and the MPP absorbers if their parameters were known. Compared with the calculation of the absorption coefficient of the compound structure directly, this method is easier to implement. What is more, the method is effective, the prediction results and the measured results have a good agreement. And it would also be useful in the design of the MPP absorber and the porous material, in the compound structure.

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