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# Calculating Sound Absorption Coefficients of Sound-Absorbing Materials Using Flow Resistivity

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**Abstract:** To minimize the calculation errors in the sound absorption coefficient resulting from inaccurate measurements of flow resistivity, a simple method for determining the sound absorption coefficient of sound-absorbing materials is proposed. Firstly, the sound absorption coefficients of a fibrous sound-absorbing material are measured at two different frequencies using the impedance tube method. Secondly, utilizing the empirical formulas for the wavenumber and acoustic impedance in the fibrous material, the flow resistivity and porosity of the sound-absorbing materials are calculated using the MATLAB cycle program. Thirdly, based on the values obtained through reverse calculations, the sound absorption coefficient, the real and the imaginary parts of the acoustic impedance of the sound-absorbing material at different frequencies are theoretically computed. Finally, the accuracy of these theoretical calculations is verified through experiments. The experimental results indicate that the calculated values are basically consistent with the measured values, demonstrating the feasibility and reliability of this method.

**Keywords:** sound-absorbing material; sound absorption coefficient; flow resistivity; acoustic impedance

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## 0 Introduction

Porous materials contain a large number of interconnected pores inside and play a crucial role in sound absorption. As sound waves propagate through the material, the viscosity of the air and the thermal conductivity of the material contribute to a gradual loss of sound energy. Research indicates a strong correlation between porosity and sound absorption performance<sup>[1-3]</sup>. If the porosity is too low, the material becomes dense, hindering sound waves from penetrating its interior, and resulting in poor sound absorption. Conversely, if the porosity is excessively high, the material becomes too

loose, allowing sound waves to pass through the pores without sufficient friction, which diminishes sound absorption performance. Additionally, the size of the pore reflects the magnitude of the resistivity encountered by air as the sound wave moves through the material, i. e. the flow resistivity<sup>[4-5]</sup>. Therefore, we can assess the acoustic performance of porous sound-absorbing materials by measuring their flow resistivity and conducting acoustic calculations and analyses.

Wang<sup>[6]</sup> proposed a method for measuring the flow resistivity of materials in an impedance tube that could measure the sound absorption coefficient of materials using the existing transfer function method. He analyzed the accuracy of measuring the flow resistivity using this method and verified its feasibility through experiments. Li<sup>[7]</sup> measured the flow resistivity of porous materials using the direct current method, as well as their sound absorption coefficients using the transfer function method. He found that there was an optimal flow resistivity that enabled the porous sound-absorbing material to achieve its maximum sound absorption coefficient. Wang<sup>[8]</sup> designed a device to measure the flow resistivity of different porous materials and employed impedance tubes to measure their sound absorption coefficients. Ma<sup>[9]</sup> measured the sound absorption coefficients and flow resistivity of four types of sound-absorbing materials and subsequently performed inverse operations on other parameters of the materials through a differential evolution algorithm. The reliability of the inverse operation results was also verified by experiments. Xiong<sup>[10]</sup> added a sealing ring, applied petroleum jelly, and polished the surface of sound-absorbing material samples during flow resistivity measurements, successfully reducing significant errors in the measurements.

The flow resistivity of porous sound-absorbing materials is generally measured by experiments, but due to the interference of the sample preparation effect and environmental factors, the actual measurement results are

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often inaccurate<sup>[11]</sup>. To avoid calculation errors in sound absorption coefficients resulting from inaccurate experimental measurements of flow resistivity, this study bypasses the experimental measurement process and instead employs theoretical inversion for calculations. The overview of the approach is as follows. Firstly, the sound absorption coefficients of a fibrous sound-absorbing material are measured at two frequencies using the impedance tube method. Secondly, a MATLAB program based on empirical formulas is employed to reverse-calculate the material's flow resistivity and porosity. Thirdly, these parameters are utilized to theoretically predict the sound absorption coefficient and acoustic impedance at other frequencies. Finally, the accuracy of these theoretical predictions is experimentally validated to assess the feasibility of the method.

## 1 Establishment of Mathematical Model for Calculating Sound Absorption Coefficient

Figure 1 shows the acoustic impedance layout of the sound-absorbing material, in which  $l$  is the thickness of the sound-absorbing material;  $x$  is the sound path length.

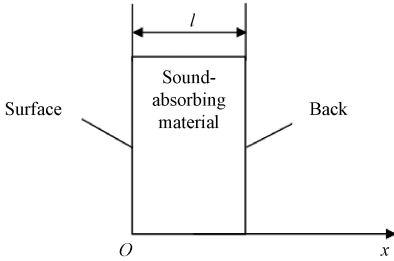


Fig. 1 Acoustic impedance layout of sound-absorbing material

The acoustic impedance at the surface of the sound-absorbing material  $Z_s$  at  $x=0$  is expressed as<sup>[12]</sup>

$$Z_s = \rho c \frac{Z_b \cosh(\gamma l) + \rho c \sinh(\gamma l)}{Z_b \sinh(\gamma l) + \rho c \cosh(\gamma l)}, \quad (1)$$

where  $Z_b$  is the acoustic impedance at the back of the sound-absorbing material;  $\rho$  is the density of the sound-absorbing material;  $c$  is the sound speed in the sound-absorbing material;  $\gamma$  is the wavenumber of the sound.

$$\begin{cases} \rho_1(\omega) = 1.2 + [-0.0364(\rho_0 f_1/\sigma)^{-2} - j0.1144(\rho_0 f_1/\sigma)^{-1}]^{\frac{1}{2}}, \\ K_1(\omega) = 101320 \times \frac{j29.64 + [2.82(\rho_0 f_1/\sigma)^{-2} + j24.9(\rho_0 f_1/\sigma)^{-1}]^{\frac{1}{2}}}{j21.17 + [2.82(\rho_0 f_1/\sigma)^{-2} + j24.9(\rho_0 f_1/\sigma)^{-1}]^{\frac{1}{2}}}, \end{cases} \quad (8)$$

$$\begin{cases} \rho_2(\omega) = 1.2 + [-0.0364(\rho_0 f_2/\sigma)^{-2} - j0.1144(\rho_0 f_2/\sigma)^{-1}]^{\frac{1}{2}}, \\ K_2(\omega) = 101320 \times \frac{j29.64 + [2.82(\rho_0 f_2/\sigma)^{-2} + j24.9(\rho_0 f_2/\sigma)^{-1}]^{\frac{1}{2}}}{j21.17 + [2.82(\rho_0 f_2/\sigma)^{-2} + j24.9(\rho_0 f_2/\sigma)^{-1}]^{\frac{1}{2}}}, \end{cases} \quad (9)$$

When the sound-absorbing material is backed by a rigid wall, i. e. ,  $Z_b=0$ , then the acoustic impedance  $Z_s$  at  $x=0$  is

$$Z_s = Z_0 \coth(\gamma l), \quad (2)$$

where  $Z_0$  is the acoustic impedance of the sound-absorbing material, and  $Z_0 = \rho c$ .

In this paper, the glass fiber is used as the sound-absorbing material, whose bulk elastic modulus  $K(\omega)$  and density  $\rho(\omega)$  can be expressed as<sup>[13]</sup>

$$K(\omega) = 101320 \times \frac{j29.64 + [2.82(\rho_0 f/\sigma)^{-2} + j24.9(\rho_0 f/\sigma)^{-1}]^{\frac{1}{2}}}{j21.17 + [2.82(\rho_0 f/\sigma)^{-2} + j24.9(\rho_0 f/\sigma)^{-1}]^{\frac{1}{2}}}, \quad (3)$$

$$\rho(\omega) = 1.2 + [-0.0364(\rho_0 f/\sigma)^{-2} - j0.1144(\rho_0 f/\sigma)^{-1}]^{\frac{1}{2}}, \quad (4)$$

where  $\rho_0$  is the air density,  $\text{kg/m}^3$ ;  $f$  is the acoustic frequency,  $\text{Hz}$ ;  $\sigma$  is the flow resistivity,  $\text{N}\cdot\text{s/m}^4$ ;  $\omega$  is the angular frequency.

The wavenumber  $\gamma(\omega)$  and acoustic impedance  $Z_0(\omega)$  of the sound wave propagating in sound-absorbing materials are<sup>[14]</sup>

$$\gamma(\omega) = \omega \left[ \frac{\rho(\omega)}{K(\omega)} \right]^{\frac{1}{2}}, \quad (5)$$

$$Z_0(\omega) = \frac{1}{\phi} [\rho(\omega)K(\omega)]^{\frac{1}{2}}, \quad (6)$$

$$\alpha = 1 - \left( \frac{Z_s - \rho_0 c_0}{Z_s + \rho_0 c_0} \right)^2, \quad (7)$$

where  $\phi$  is the porosity;  $\alpha$  is the sound absorption coefficient;  $c_0$  is the sound speed in air.

## 2 MATLAB Cycle Program Calculation Method

The sound absorption coefficient was measured at two different frequencies. The sound absorption coefficient at frequency  $f_1$  is  $\alpha_1$ ; the sound absorption coefficient at frequency  $f_2$  is  $\alpha_2$ . Therefore, according to Eqs. (3) and (4), the density and bulk elastic modulus of the sound-absorbing material at two frequencies are as follows:

where  $\rho_i(\omega)$  ( $i=1, 2$ ) and  $K_{0i}(\omega)$  ( $i=1, 2$ ) represent the density and the bulk elastic modulus at two frequencies, respectively.

By substituting Eqs. (8) and (9) into Eqs. (5)

and (6), respectively, the wavenumbers and acoustic impedance of sound waves propagating in the sound-absorbing material at two frequencies were obtained:

$$\left\{ \begin{array}{l} \gamma_1(\omega) = \omega \left[ \frac{\rho_1(\omega)}{K_1(\omega)} \right]^{\frac{1}{2}} = \omega \left\{ \frac{1.2 + [-0.0364(\rho_0 f_1/\sigma)^{-2} - j0.1144(\rho_0 f_1/\sigma)^{-1}]^{\frac{1}{2}}}{101320 \times \frac{j29.64 + [2.82(\rho_0 f_1/\sigma)^{-2} + j24.9(\rho_0 f_1/\sigma)^{-1}]^{\frac{1}{2}}}{j21.17 + [2.82(\rho_0 f_1/\sigma)^{-2} + j24.9(\rho_0 f_1/\sigma)^{-1}]^{\frac{1}{2}}}} \right\}^{\frac{1}{2}}, \\ Z_{01}(\omega) = \frac{1}{\phi} [\rho_1(\omega) K_1(\omega)]^{\frac{1}{2}} = \frac{1}{\phi} \left\{ 1.2 + [-0.0364(\rho_0 f_1/\sigma)^{-2} - j0.1144(\rho_0 f_1/\sigma)^{-1}]^{\frac{1}{2}} \right\}^{\frac{1}{2}} \times \\ \left\{ 101320 \times \frac{j29.64 + [2.82(\rho_0 f_1/\sigma)^{-2} + j24.9(\rho_0 f_1/\sigma)^{-1}]^{\frac{1}{2}}}{j21.17 + [2.82(\rho_0 f_1/\sigma)^{-2} + j24.9(\rho_0 f_1/\sigma)^{-1}]^{\frac{1}{2}}} \right\}^{\frac{1}{2}}, \end{array} \right. \quad (10)$$

$$\left\{ \begin{array}{l} \gamma_2(\omega) = \omega \left[ \frac{\rho_2(\omega)}{K_2(\omega)} \right]^{\frac{1}{2}} = \omega \left\{ \frac{1.2 + [-0.0364(\rho_0 f_2/\sigma)^{-2} - j0.1144(\rho_0 f_2/\sigma)^{-1}]^{\frac{1}{2}}}{101320 \times \frac{j29.64 + [2.82(\rho_0 f_2/\sigma)^{-2} + j24.9(\rho_0 f_2/\sigma)^{-1}]^{\frac{1}{2}}}{j21.17 + [2.82(\rho_0 f_2/\sigma)^{-2} + j24.9(\rho_0 f_2/\sigma)^{-1}]^{\frac{1}{2}}}} \right\}^{\frac{1}{2}}, \\ Z_{02}(\omega) = \frac{1}{\phi} [\rho_2(\omega) K_2(\omega)]^{\frac{1}{2}} = \frac{1}{\phi} \left\{ 1.2 + [-0.0364(\rho_0 f_2/\sigma)^{-2} - j0.1144(\rho_0 f_2/\sigma)^{-1}]^{\frac{1}{2}} \right\}^{\frac{1}{2}} \times \\ \left\{ 101320 \times \frac{j29.64 + [2.82(\rho_0 f_2/\sigma)^{-2} + j24.9(\rho_0 f_2/\sigma)^{-1}]^{\frac{1}{2}}}{j21.17 + [2.82(\rho_0 f_2/\sigma)^{-2} + j24.9(\rho_0 f_2/\sigma)^{-1}]^{\frac{1}{2}}} \right\}^{\frac{1}{2}}, \end{array} \right. \quad (11)$$

where  $\gamma_i(\omega)$  ( $i=1, 2$ ) and  $Z_{0i}(\omega)$  ( $i=1, 2$ ) represent the wavenumbers and acoustic impedance at two frequencies, respectively.

If the back of the sound-absorbing material is a rigid wall, the surface acoustic impedance of the sound-absorbing material at two frequencies respectively are

$$\begin{aligned} Z_{s1} &= Z_{01} \coth(\gamma_1 l) = \frac{1}{\phi} \left\{ 1.2 + [-0.0364(\rho_0 f_1/\sigma)^{-2} - j0.1144(\rho_0 f_1/\sigma)^{-1}]^{\frac{1}{2}} \right\}^{\frac{1}{2}} \times \\ &\left\{ 101320 \times \frac{j29.64 + [2.82(\rho_0 f_1/\sigma)^{-2} + j24.9(\rho_0 f_1/\sigma)^{-1}]^{\frac{1}{2}}}{j21.17 + [2.82(\rho_0 f_1/\sigma)^{-2} + j24.9(\rho_0 f_1/\sigma)^{-1}]^{\frac{1}{2}}} \right\}^{\frac{1}{2}} \times \\ &\coth \left( \omega \left\{ \frac{1.2 + [-0.0364(\rho_0 f_1/\sigma)^{-2} - j0.1144(\rho_0 f_1/\sigma)^{-1}]^{\frac{1}{2}}}{101320 \times \frac{j29.64 + [2.82(\rho_0 f_1/\sigma)^{-2} + j24.9(\rho_0 f_1/\sigma)^{-1}]^{\frac{1}{2}}}{j21.17 + [2.82(\rho_0 f_1/\sigma)^{-2} + j24.9(\rho_0 f_1/\sigma)^{-1}]^{\frac{1}{2}}}} \right\}^{\frac{1}{2}} l \right), \end{aligned} \quad (12)$$

$$\begin{aligned} Z_{s2} &= Z_{02} \coth(\gamma_2 l) = \frac{1}{\phi} \left\{ 1.2 + [-0.0364(\rho_0 f_2/\sigma)^{-2} - j0.1144(\rho_0 f_2/\sigma)^{-1}]^{\frac{1}{2}} \right\}^{\frac{1}{2}} \times \\ &\left\{ 101320 \times \frac{j29.64 + [2.82(\rho_0 f_2/\sigma)^{-2} + j24.9(\rho_0 f_2/\sigma)^{-1}]^{\frac{1}{2}}}{j21.17 + [2.82(\rho_0 f_2/\sigma)^{-2} + j24.9(\rho_0 f_2/\sigma)^{-1}]^{\frac{1}{2}}} \right\}^{\frac{1}{2}} \times \\ &\coth \left( \omega \left\{ \frac{1.2 + [-0.0364(\rho_0 f_2/\sigma)^{-2} - j0.1144(\rho_0 f_2/\sigma)^{-1}]^{\frac{1}{2}}}{101320 \times \frac{j29.64 + [2.82(\rho_0 f_2/\sigma)^{-2} + j24.9(\rho_0 f_2/\sigma)^{-1}]^{\frac{1}{2}}}{j21.17 + [2.82(\rho_0 f_2/\sigma)^{-2} + j24.9(\rho_0 f_2/\sigma)^{-1}]^{\frac{1}{2}}}} \right\}^{\frac{1}{2}} l \right). \end{aligned} \quad (13)$$

The sound absorption coefficients at two frequencies are

$$\alpha_1 = 1 - \left( \frac{Z_1 - \rho_0 c_0}{Z_1 + \rho_0 c_0} \right)^2, \quad (14)$$

$$\alpha_2 = 1 - \left( \frac{Z_2 - \rho_0 c_0}{Z_2 + \rho_0 c_0} \right)^2. \quad (15)$$

From Eqs. (12)–(15), it can be seen that the flow resistivity  $\sigma$  and porosity  $\phi$  are unknown. Solving these two unknowns using general methods is relatively difficult, so it is necessary to use a MATLAB cyclic program to solve this problem.

### 3 Theoretical Calculation and Experimental Verification

#### 3.1 Experimental measurement of sound absorption coefficient

The impedance tube method, also known as the standing wave ratio method, is a method to measure the absorption coefficient of sound-absorbing materials utilizing an impedance tube<sup>[15–16]</sup>. Figure 2 presents a schematic diagram of the impedance tube method.

The testing steps are outlined below.

1) Place the tested material sample at the end of the impedance tube and ensure that it is sealed tightly.

2) Use a speaker to emit a single-frequency sound signal that propagates through the pipeline and creates standing waves.

3) Use sensors to measure the sound pressures at different positions within the pipeline, and obtain the locations and amplitudes of the maximum and minimum sound pressure values.

4) Calculate the standing wave ratio using the measured sound pressures, and subsequently determine

the sound absorption coefficient at that frequency.

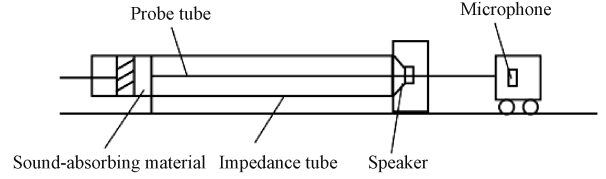


Fig. 2 Schematic diagram of impedance tube method

It is assumed that the sound wave in the impedance tube is positive along the negative direction of  $x$ ; the incident sound pressure, the reflected sound pressure and the reflection coefficient are denoted as  $P_i$ ,  $P_r$  and  $r$ , respectively.

When  $P_i$  and  $P_r$  are in phase, the maximum measured pressure  $P_{\max}$  is described by

$$|P_{\max}| = |P_0| \times (1 + |r|), \quad (16)$$

where  $P_0$  is the pressure of the air.

When  $P_i$  and  $P_r$  are in reverse phase, the minimum measured pressure  $P_{\min}$  is described by

$$|P_{\min}| = |P_0| \times (1 - |r|). \quad (17)$$

The standing wave ratio  $G$  is expressed as

$$G = \frac{|P_{\max}|}{|P_{\min}|} = \frac{1 + |r|}{1 - |r|}. \quad (18)$$

The absorption coefficient  $\alpha$  is expressed as

$$\alpha = 1 - |r|^2 = \frac{4G}{(G + 1)^2}. \quad (19)$$

The flowchart illustrating the measurement of the sound absorption coefficient is presented in Fig. 3. The corresponding experimental setup is identical to that used in our previous work<sup>[17]</sup>.

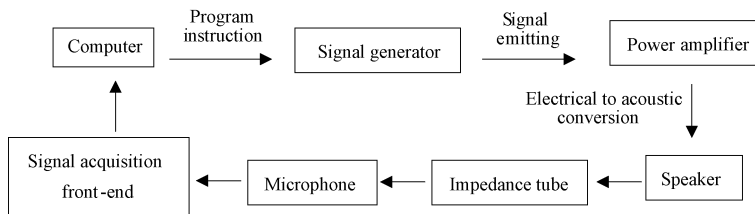


Fig. 3 Flowchart for measuring sound absorption coefficient

#### 3.2 Theoretical calculation and verification

The sound absorption coefficients of the sound-absorbing materials with different thicknesses at 500 Hz and 1 000 Hz were measured, respectively. Then, the flow resistivity and porosity at different thicknesses were derived using the MATLAB cycle program. The experimentally measured and the theoretically calculated acoustic properties of the sound-absorbing materials are presented in Table 1.

Table 1 illustrates that the porosity of the sound-

absorbing material remains constant, even as the thickness increases. This consistency is attributed to the porosity being inherently defined by the material's structural characteristics. However, the flow resistivity increases with increasing the thickness. This increase is due to the greater number of pores and the longer pathways that air must travel through within the thicker material, leading to the heightened flow resistivity. This behavior is consistent with the sound-absorbing properties of the material.

**Table 1** Experimentally measured and theoretically calculated acoustic properties of sound-absorbing materials

Thickness/mm (measured)	Absorption coefficient (measured)		Porosity/% (calculated)	Flow resistivity/(N·s/m <sup>4</sup> ) (calculated)
	500 Hz	1 000 Hz		
50	0.91	0.87	2	15 905
100	0.90	0.85	2	20 688
150	0.93	0.87	2	24 048
200	0.94	0.89	2	26 829
250	0.95	0.91	2	28 912
300	0.96	0.93	2	30 830

After calculating the flow resistivity using the MATLAB cycle program, the sound absorption coefficient, as well as the real and imaginary parts of the acoustic impedance, was measured at frequencies of 200, 500, 1 000, 1 500, 2 000, 2 500, 3 000, 3 500 and 4 000 Hz. The experimentally measured values were then compared with the theoretically calculated values for the corresponding frequencies (Figs. 4–6). These comparisons were conducted using sound-absorbing materials with different thicknesses, each with a porosity of 2% and a rigid back wall.

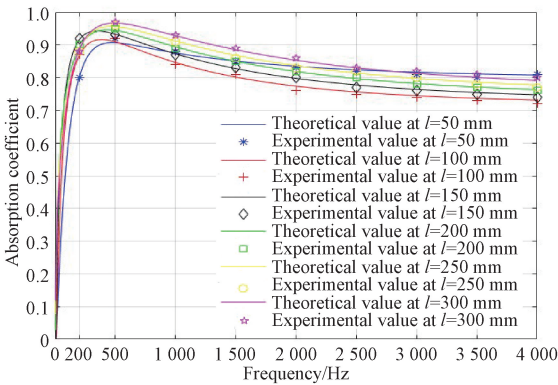


Fig. 4 Comparison of theoretical and experimental sound absorption coefficients versus frequency for sound-absorbing materials at different thicknesses

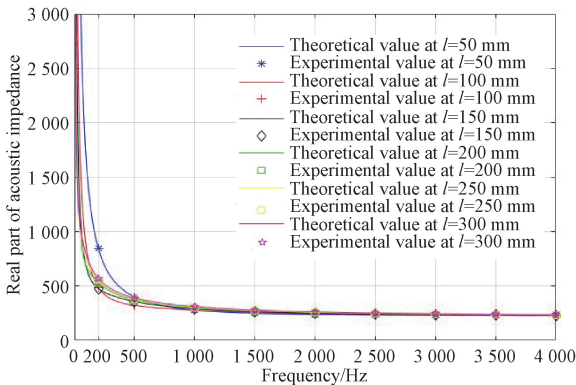


Fig. 5 Comparison of theoretical and experimental real part of acoustic impedance versus frequency for sound-absorbing materials at different thicknesses

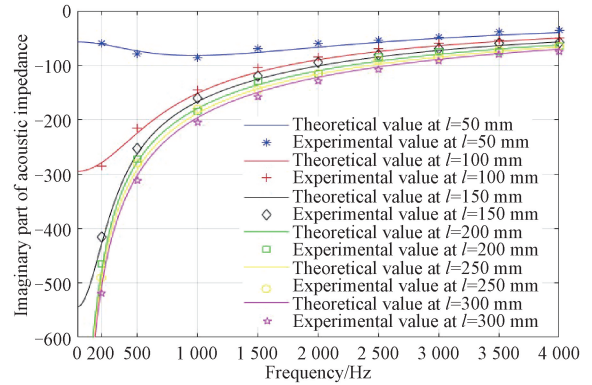


Fig. 6 Comparison of theoretical and experimental imaginary part of acoustic impedance versus frequency for sound-absorbing materials at different thicknesses

From Figs. 4–6, it is evident that the theoretically calculated values are basically consistent with the experimentally measured values.

### 4 Conclusions

In this study, a simple method for calculating the sound absorption coefficient of the sound-absorbing material theoretically was provided. Firstly, the sound absorption coefficient of the sound-absorbing material at two frequencies was measured in the sound-absorbing material by the impedance tube method. Then, according to the empirical formulas of wavenumber and acoustic impedance in the fibrous material, the flow resistivity of the sound-absorbing material was calculated by using the MATLAB cycle program. Secondly, by changing the thickness of the sound-absorbing material and using the flow resistivity obtained by the reverse operation, the absorption coefficient, the real part of the acoustic impedance and the imaginary part of the acoustic impedance of the sound-absorbing material at different frequencies were calculated, and the relationship between the frequency and them was investigated. Finally, the calculated sound absorption coefficient, as well as the real and imaginary parts of the acoustic impedance was compared with the measured values. The results show that the theoretically calculated values are basically

consistent with the experimentally measured values, which verifies the feasibility and reliability of calculating the sound absorption coefficient by using the flow resistivity obtained by the reverse operation.

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# 用流阻率计算吸声材料吸声系数

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**摘要:** 为了降低由于流阻率测量不准确而引起的吸声系数计算误差, 提出了一种计算吸声材料吸声系数的简便方法。首先, 通过阻抗管法测量出吸声材料的两个频率的吸声系数, 根据纤维材料的波数和声阻抗的经验公式, 利用 MATLAB 循环程序逆算出吸声材料的流阻率。其次, 计算出不同频率下吸声材料的理论吸声系数、阻抗实部和阻抗虚部。最后, 通过试验验证理论计算值的正确性。多组试验结果表明, 理论计算值与试验测量值基本一致, 验证了此方法的可行性和可靠性。

**关键词:** 吸声材料; 吸声系数; 流阻率; 声阻抗