

Simulation of Acoustic Performance of Composite Structure Based on Porous Elastic Polyester Foam and Lightweight Glass Wool

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In response to the challenge of noise control during vehicle operation, this paper conducts a detailed study on the impact of partial parameters of composite structures based on porous elastic polyester foam and lightweight glass wool using acoustic simulation software and the finite element-transmission matrix coupling (FEM-TMM) algorithm. The study employs controlled variable methods to investigate the effect of individual variables on the results, deriving schematic diagrams of acoustic coefficients under various parameters and analyzing the variation patterns of sound absorption and insulation performance with different parameters. The research indicates that increasing material thickness, bending rate, and porosity can enhance sound absorption performance by 20 % to 70 %. This provides a certain direction for the multi-layer composite construction and optimization of noise reduction materials. Additionally, it demonstrates that the finite element-based transmission matrix method is applicable to the investigation of acoustic characteristics of composite structural materials, achieving selective optimization of acoustic performance in the frequency domain.

Keywords: vehicle noise, transfer matrix method, acoustic simulation, acoustic performance, multi-layer composite structure.

1. INTRODUCTION

The optimization of NVH (Noise, Vibration, and Acoustic Roughness) performance in automotive vehicles has become a core area of technological competition in the modern automotive industry. As consumer demand evolves towards immersive cabin experiences, vehicle acoustic envelopment engineering faces the complex challenge of multi-source broadband noise coupling. Traditional single-component sound-absorbing materials exhibit significant limitations in frequency domain response and sound insulation efficiency when dealing with composite sound fields from engine low-frequency harmonics, tire high-frequency squeaks, and aerodynamic turbulence noise. To address this, a multi-layer composite acoustic material system integrates heterogeneous materials to construct a gradient impedance matching mechanism and multimodal energy dissipation pathways. Innovatively, it employs optimized design of acoustic impedance layers to achieve synergistic effects from low-frequency Helmholtz resonance absorption to high-frequency porous viscous dissipation, significantly enhancing wide-band acoustic control performance. In terms of research paradigm innovation, multiphysics coupling simulation technology has overcome the efficiency bottlenecks of traditional trial-and-error methods. By establishing a full-frequency acoustic transfer matrix model that includes material constitutive parameters, structural topological features, and boundary conditions, it can accurately predict the vibration-sound radiation characteristics of composite materials under transient excitation. This forward design method, based on digital twins, not only accelerates the construction cycle of material

property maps but also achieves Pareto-optimization solutions for acoustic functions and lightweight goals through parametric topology optimization, providing key technical support for intelligent development of automotive acoustics envelopment. This research approach is of significant engineering value in improving overall NVH quality metrics, enhancing product premium capabilities, and driving technological upgrades in the automotive industry.

Liu et al. [1] developed a new type of slit perforated multilayer porous metamaterial, known as SMPM. They noted that this material possesses broadband and low-frequency sound absorption properties. Subsequently, they used the finite element software COMSOL Multiphysics to verify their theoretical predictions, ultimately successfully demonstrating the excellent broadband and low-frequency sound absorption performance of SMPM. Ruan et al. [2] used calcium chloride as a green cross-linking agent for cellulose nanocrystals to prepare multifunctional sound-absorbing aerogels, which exhibited superior broadband sound absorption performance. The maximum sound absorption coefficient was 0.99 at 2960 Hz, with an average sound absorption coefficient of 0.85 in the range of 600–6400 Hz. The broadband with a sound absorption coefficient greater than 0.8 was 4673 Hz. Zhang [3] investigated the sound absorption performance of acoustic labyrinth porous metamaterials (ALPMs) under high-temperature conditions. The results showed that as the temperature increased, the peak frequency of ALPMs shifted towards higher noise bands, and the half-absorption bandwidth also increased. LPM can be considered a

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combination of uniform porous materials and spatially helical resonators, particularly showing great potential for low-frequency sound absorption under high-temperature conditions, with promising prospects. Wu [4] designed a flexible wedge-knit composite material (WKC), utilizing weaving and coating techniques to achieve multiple sound absorption mechanisms, including porous sound absorption and wedge structure resonance. This design provides guidance for the structural design and practical application of new flexible sound-absorbing materials, with significant potential in interior decoration, wall covering, and automotive interiors. Dong [5] prepared a cellulose-based porous material with a three-dimensional network framework and foam-forming sound absorption characteristics. Li Yu and Wen Huabing [6] used a periodic cell structure as the basis, employing a two-parameter semi-phenomenological model to estimate the macroscopic acoustic parameters of high-porosity polyurethane foam materials. Based on an equivalent fluid model, they analyzed the sound absorption coefficients of the foam material at low, medium, and high frequency bands. Jiang Yanpo et al. [7] used NOVA acoustic simulation software and the continuity equations between different interfaces, as well as the impedance equations of the sound source domain and receiving domain, to systematically solve for the reflection and transmission coefficients. Tian et al. [8] established a double-layer series micro-perforated plate structure, which broadened the sound absorption frequency band while maintaining high sound absorption coefficients within the band, achieving excellent sound absorption performance. Tang et al. [9] studied the sound absorption performance of multi-layer fiber composite materials composed of nonwoven fabric, woven fabric, and polyethylene film. The results showed that under appropriate layering sequences, the presence of lightweight PE films could enhance sound absorption performance in the 100–6300 Hz range, with Non-PE-won having the highest sound absorption coefficient. Yang Xiaoyu [10] conducted cross-analysis using particle swarm optimization and spectral analysis for acoustic parameter inversion, accurately determining the acoustic impedance, tortuosity, time, and acoustic attenuation parameters of thin bilayer materials. A full optical laser ultrasonic system was used to systematically measure the transmission spectrum of thin bilayer composite materials, controlling variables and comparing experimental spectra with theoretical spectra to verify the feasibility of this method. Wang Shuaixing [11] developed a dynamic equivalent calculation model that integrates a single-layer superstructure layer with an acoustic medium layer. Based on this, using the theory of acoustic transfer matrix, he established semi-analytical methods for calculating the sound insulation characteristics of plate-like multilayer composite superstructures under different sound wave incidence conditions, including vertical incidence, oblique incidence, and diffused sound fields. Compared to traditional finite element and other numerical analysis methods, this semi-analytical method offers significant advantages, significantly improving computational efficiency and providing a fast and efficient theoretical calculation and analysis approach for the design and development of plate-like multilayer composite superstructures.

2. SOUND ABSORPTION THEORY MODEL OF POROUS MATERIAL

2.1. Sound absorption mechanism

When sound waves hit the surface of porous materials, they can penetrate into the material through micro-pores, causing the air within the pores to vibrate. Due to the viscosity of air, when it flows through the pores, the air near the pore walls and fiber surfaces is less likely to move due to the influence of the pore walls. This results in friction between the air and the pore walls, as well as between air molecules, converting a significant portion of sound energy into heat. High-frequency sound waves increase the vibration speed of air particles in the pores, accelerating the friction between the air and the pore walls, leading to greater sound energy loss. This makes porous materials more effective at absorbing high-frequency sounds.

2.2. Performance index-sound absorption coefficient

The sound absorption coefficient is the ratio of the sound energy absorbed by the material to the incident sound energy. It is a physical quantity to measure the sound absorption capacity of the material, ranging from 0 to 1.

When the sound absorption coefficient is 0, it indicates that the material does not absorb any sound at all, and all sounds are reflected; when the sound absorption coefficient is 1, it means that the material absorbs all incident sound energy. The sound absorption coefficient is positively correlated with the material's sound absorption effect. For example, smooth and hard materials like glass have a low sound absorption coefficient, whereas porous sound-absorbing cotton has a relatively higher sound absorption coefficient.

The sound absorption coefficient is related to the incident conditions of sound waves [12] and the frequency of the sound wave. In engineering practice, the sound absorption coefficients at frequencies of 125 Hz, 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz, as well as the arithmetic mean of these six frequencies, are typically used to represent the sound absorption performance of materials or structures. Generally, materials with an average sound absorption coefficient greater than 0.2 at these six frequencies are referred to as sound-absorbing materials, and those with an average sound absorption coefficient greater than 0.56 are called high-efficiency sound-absorbing materials.

2.2. Transfer matrix model of multi-layer composite sound absorbing material between each layer

The arrangement model of sound absorbing material with multi-layer composite structure in an automobile is shown in Fig. 1. The surface sound pressure between the n -th layer and the $n+1$ -th layer and the vibration velocity of particles in the medium are respectively p_{n+1} and v_{n+1} , and the material of the n -th layer is a steel plate with thickness L_n , which is mainly used for sound insulation. The sound pressure between the first and second layers of the medium

is [13] and the vibration velocity of the particles in the medium:

$$\begin{bmatrix} p_1 \\ v_1 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} p_2 \\ v_2 \end{bmatrix} = \begin{bmatrix} \cos k_1 L_1 & j\rho_1 C_1 \sin k_1 L_1 \\ j \frac{\sin k_1 L_1}{\rho_1 C_1} & \cos k_1 L_1 \end{bmatrix} \begin{bmatrix} p_2 \\ v_2 \end{bmatrix}; \quad (1)$$

$$C_1 = \sqrt{\frac{E_1}{\rho}} = \sqrt{\frac{E_1}{\rho_1}} \left(1 + j \frac{\eta_1}{2}\right); \quad (2)$$

$$k_1 = \frac{\omega}{C_1} = \omega \sqrt{\frac{\rho_1}{E_1}} \left(1 - j \frac{\eta_1}{2}\right), \quad (3)$$

where p_1 and v_1 are the surface acoustic pressure of the first material medium in contact with air and the vibration velocity of particles in the medium; p_2 and v_2 are the surface acoustic pressure of the first material medium in contact with the second material medium and the vibration velocity of particles in the medium; C_1 is the propagation speed of sound waves in the first layer of the medium; L_1 , E_1 , η_1 , ρ_1 are the thickness, elastic modulus, structural loss factor, and density of the first material, respectively; k_1 is the number of sound waves transmitted through the first medium.

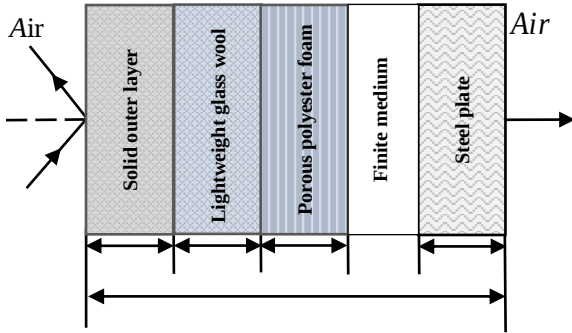


Fig. 1. Schematic diagram of the distribution model of sound absorbing materials in a multi-layer composite structure

It can be obtained from Eq. 1:

$$\begin{cases} a_{11} = a_{22} \\ a_{11}a_{22} - a_{12}a_{21} = 1 \end{cases} \quad (4)$$

By the same token, the relationship between the sound pressure and the normal vibration velocity between the n th layer of sound absorbing material and the $n+1$ layer of sound absorbing material is:

$$\begin{bmatrix} p_n \\ v_n \end{bmatrix} = \begin{bmatrix} a_{n,11} & a_{n,12} \\ a_{n,21} & a_{n,22} \end{bmatrix} \begin{bmatrix} p_{n+1} \\ v_{n+1} \end{bmatrix}. \quad (5)$$

Then the relationship between sound pressure and normal vibration velocity of the first layer material and the n -th steel plate layer is:

$$\begin{bmatrix} p_1 \\ v_1 \end{bmatrix} = \prod_{m=1}^n \begin{bmatrix} a_{m,11} & a_{m,12} \\ a_{m,21} & a_{m,22} \end{bmatrix} \begin{bmatrix} p_{n+1} \\ v_{n+1} \end{bmatrix}, \quad (6)$$

where p_{n+1} and v_{n+1} are the sound pressure and normal vibration velocity of the part of the back of the sound absorbing material of the n -th layer in contact with the air, respectively.

If the sound absorbing material of the n -th layer is steel plate and the back is air, then $p_{n+1}=0$ can be obtained approximately.

3.1. Theoretical calculation of sound absorption coefficient of multi-layer composite sound absorbing material

For the study of sound absorption coefficients of multi-layer composite materials, the main research objects are the composite structure of lightweight glass wool and porous elastic polyester foam, with steel plates serving as the sound insulation material behind the sound-absorbing material. Each layer is uniformly thick, totaling three layers. According to the transfer matrix model, it can be obtained as follows [14]:

$$\begin{bmatrix} p_1 \\ v_1 \end{bmatrix} = \begin{bmatrix} \cos k_1 L_1 & j\rho_1 C_1 \sin k_1 L_1 \\ j \frac{\sin k_1 L_1}{\rho_1 C_1} & \cos k_1 L_1 \end{bmatrix} \begin{bmatrix} p_2 \\ v_2 \end{bmatrix}; \quad (7)$$

$$\begin{bmatrix} p_2 \\ v_2 \end{bmatrix} = \begin{bmatrix} \cos k_2 L_2 & j\rho_2 C_2 \sin k_2 L_2 \\ j \frac{\sin k_2 L_2}{\rho_2 C_2} & \cos k_2 L_2 \end{bmatrix} \begin{bmatrix} p_3 \\ v_3 \end{bmatrix}; \quad (8)$$

$$\begin{bmatrix} p_3 \\ v_3 \end{bmatrix} = \begin{bmatrix} \cos k_3 L_3 & j\rho_3 C_3 \sin k_3 L_3 \\ j \frac{\sin k_3 L_3}{\rho_3 C_3} & \cos k_3 L_3 \end{bmatrix} \begin{bmatrix} p_4 \\ v_4 \end{bmatrix}, \quad (9)$$

where C_n is the propagation velocity of sound wave in the medium of the material at the n -th ($n = 1, 2, 3$) layer; L_n , E_n , ρ_n and k_n are the thickness, elastic modulus, density and number of sound wave in the medium at the n -th layer respectively.

According to Eq. 6, Eq. 7, Eq. 8, and Eq. 9:

$$\begin{bmatrix} p_1 \\ v_1 \end{bmatrix} = \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix} \begin{bmatrix} p_4 \\ v_4 \end{bmatrix}. \quad (10)$$

Since the third layer is steel plate and the back is air, it is approximately assumed that $p_4 = 0$, and the surface acoustic impedance rate in the first layer medium of the sound absorbing material can be obtained:

$$Z_s = \frac{b_{12}}{b_{22}}. \quad (11)$$

Among them are:

$$b_{12} = \rho_3 C_3 c_1 c_2 s_3 - \frac{\rho_1 \rho_3 C_1 C_3 s_1 s_2 s_3}{\rho_2^2 C_2^2} + \rho_2 C_2 c_1 s_2 c_3 + \rho_1 C_1 s_1 c_1 c_3; \quad (12)$$

$$b_{22} = c_1 c_2 c_3 \frac{\rho_3 C_3 s_1 s_2 s_3}{\rho_1 C_1} - \frac{\rho_3 C_3^2 s_2 s_3}{\rho_2^2 C_2^2} - \frac{\rho_2 C_2 s_1 s_2 s_3}{\rho_1 C_1}; \quad (13)$$

$$\begin{cases} c_1 = \cos k_1 L_1 & c_2 = \cos k_2 L_2 & c_3 = \cos k_3 L_3 \\ s_1 = \sin k_1 L_1 & s_2 = \sin k_2 L_2 & s_3 = \sin k_3 L_3 \end{cases}. \quad (14)$$

In the case of vertical sound wave incidence, the reflection factor on the surface of multi-layer uniform medium is:

$$R = \frac{Z_s - \rho_0 c_0}{Z_s + \rho_0 c_0}, \quad (15)$$

where ρ_0 is the air density; c_0 is the sound wave transmission velocity in the air; $\rho_0 c_0$ is the air characteristic impedance. The sound absorption coefficient can be expressed as:

$$\alpha = 1 - |R|^2. \quad (16)$$

The comprehensive sound absorption coefficient α of the composite structure can be obtained by combining Eq. 11–Eq. 16.

The calculation process of theoretical values can be presented as follows:

1. Calculation of acoustic impedance rate (Eq. 9). Based on the multi-layer transfer matrix model (Eq. 4–Eq. 7), the formula integrates the thickness L_n , density ρ_n , sound velocity c_n , wave number k_n and other parameters of all material layers (glass wool + polyester foam + steel plate), and finally outputs the surface acoustic impedance rate Z_s .
2. Calculation of reflection coefficient (Eq. 13). The reflection coefficient R under vertical incidence is calculated by comprehensive calculation using the air characteristic impedance $\rho_0 c_0$ obtained z_s from Eq. 9.
3. Calculation of sound absorption coefficient (Eq. 14). The absorption coefficient R is derived directly from the reflection coefficient α .

3.2. Description of FEM-TMM algorithm

3.2.1. Algorithm principle

FEM-TMM is a hybrid numerical-analytical method that combines the geometric flexibility of finite element method (FEM) with the computational efficiency of transfer matrix method (TMM), which is suitable for wideband acoustic performance prediction of multi-layer composite structures. Its core steps are as follows:

1. Finite element domain partitioning (FEM section)

The three-dimensional mesh is discretized for complex geometric layers (such as p non-uniform v pore areas), and the coupled equations of local sound pressure field and particle vibration velocity are solved:

$$\nabla^2 p + k^2 p = 0, \quad (17)$$

2. Transfer matrix coupling (TMM section)

For homogeneous layers (such as light glass wool and steel plate), the interlayer sound pressure-vibration velocity relationship is established by using the transfer matrix model (Eq. 6–Eq. 9):

$$\begin{bmatrix} p_{n+1} \\ \mathbf{v}_{n+1} \end{bmatrix} = T_n \begin{bmatrix} p_n \\ \mathbf{v}_n \end{bmatrix}; \quad (18)$$

$$T_n = \begin{bmatrix} \cos(k_n L_n) & j \rho_n c_n \sin k_n L_n \\ j \frac{\sin(k_n L_n)}{\rho_n c_n} & \cos k_n L_n \end{bmatrix}, \quad (19)$$

where $k_n = \frac{\omega}{c_n}$ is the wave number and $Z_n = \rho_n c_n$ is the characteristic impedance.

3. Global system solution

The transfer matrices of all layers are integrated by chain multiplication:

$$T_{total} = \prod T_n. \quad (20)$$

Combined with FEM boundary conditions, the overall reflection coefficient R and sound absorption coefficient α are solved (Eq. 13, Eq. 14).

3.2.2. Algorithmic advantages

Computational efficiency: TMM analysis and solution avoid global mesh division, and is 40 % faster than pure FEM.

Accuracy balance: FEM handles local inhomogeneity (e.g., pore gradient), and TMM ensures efficient propagation of uniform layers (wideband coincidence shown in Eq. 3–Eq. 20).

Parametric capability: Support for rapid scanning of variables such as thickness/porosity (e.g., parameter combinations in Table 1).

Table 1. Parameters of multi-layer composites

Material parameter	Lightweight glass wool	Porous elastic polyester foam
Thickness, m	0.08	0.1
Porosity	0.99	0.96
Rate of curving	1	1.24
Viscous characteristic length, m	0.000192	0.000105
Density, kg/m ³	16	22
Poisson ratio	0	0.4
Young modulus, N/m ²	440000	46500

4. MEASUREMENT METHOD OF SOUND ABSORPTION COEFFICIENT BASED ON STANDING WAVE TUBE

The acoustic performance of porous materials will be affected by the material thickness, porosity, density and air flow resistance in the material and many external factors. The following is a specific verification by means of standing wave tube test and acoustic simulation software.

Using lightweight glass wool and porous elastic polyester foam as research subjects, a double-layer structure was established. The sound wave excitation adopted plane wave excitation (0.632 ~ 20 Pa). The multi-layer composite material was placed in a soundproof duct, with the sound wave excited vertically into the composite material through a sound wave generator. A channel controller was used to adjust the frequency range of the generator, and acoustic levels before and after the sound wave were collected using acoustic sensors. Finally, the acoustic characteristics were analyzed using computer simulation software NOVA.

Liu et al. [14] used a traditional single-channel planar wave excitation, which is less stable than the dual-channel method. Additionally, in terms of acoustic level collection, only the absorption and insulation performance on one side was considered, without considering the acoustic level behind the material after sound wave excitation. This means that more emphasis was placed on measuring the reflection from the material, while the absorption performance required comparing the differences before and after sound wave excitation. For the first time, we innovatively adopted a synchronous symmetric sensor distribution pattern, which can measure both the reflected waves from the front surface of the material and the transmitted waves from the back surface. This improves the accuracy of measuring acoustic levels before and after, thus providing a more precise test of the material's absorption and insulation performance.

Study the partial influence parameters of the material, such as thickness, porosity and bending rate.

The ZB standing wave tube test system was used to measure the sound absorption coefficient, and the test frequency was 0 ~ 3000 Hz. The measurement principle of the experiment is shown in Fig. 2.

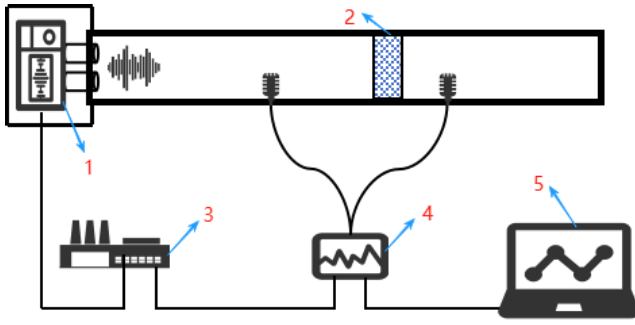


Fig. 2. Schematic diagram of the experimental principle of measuring sound absorption coefficient in standing wave tube: 1–dual-channel acoustic excitation transmitter; 2–multilayer composite structural material; 3–multichannel converter; 4–acoustic wave acceptance sensor; 5–computer simulation analysis

5. STUDY ON THE INFLUENCE OF LIGHT GLASS WOOL PARAMETERS ON SOUND INSULATION PERFORMANCE OF COMPOSITE STRUCTURE

5.1. Simulation study on the influence of light glass wool thickness on sound absorption and insulation performance

In the simulation software, the material thickness is processed with an increment of 0.05. The results show the comparison of the effects of different material thicknesses on sound absorption and insulation performance in the frequency range of 10–800 Hz. The results are shown in Fig. 3, Fig. 4, and Fig. 5.

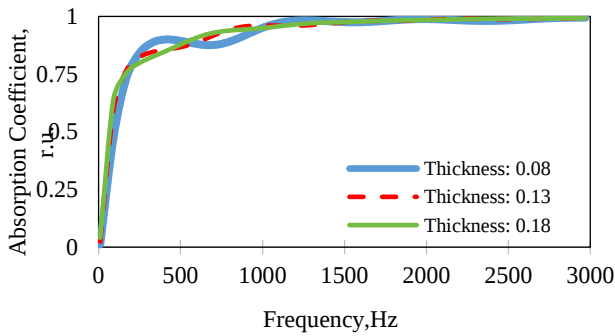


Fig. 3. Comparison of the influence of different thicknesses of light glass wool on the sound absorption coefficient at the same frequency

The thicker the material, the more obvious the improvement of low-frequency sound absorption performance, which is in line with the sound absorption law of porous materials. The high-frequency sound absorption coefficient may gradually approach the upper limit of material performance with the increase of thickness, and the change is not significant. The increase of thickness may lead to the shift of sound absorption peak to low frequency (such as from 2000 Hz to 1000 Hz).

Thickness is positively correlated with low-frequency sound absorption: every 0.05 increase in thickness, the low-frequency sound absorption coefficient increases by about 20–30 %. It conforms to the sound absorption law of

porous materials that "low-frequency needs to be thick and high-frequency needs to be thin".

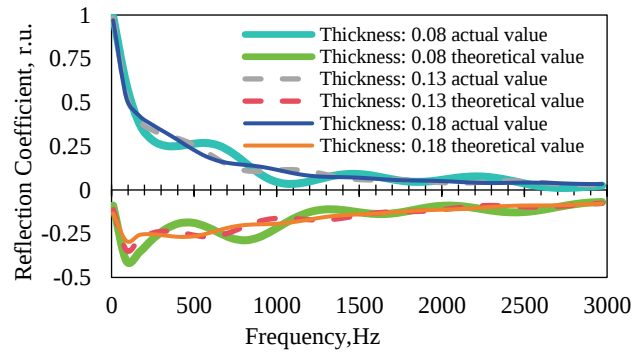


Fig. 4. Comparison of the effect of different thicknesses of light glass wool on the reflection coefficient at the same frequency

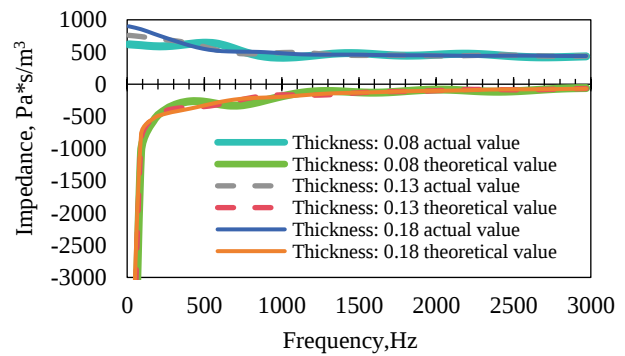


Fig. 5. Comparison of the effect of different thicknesses of light

The sound absorption coefficient of 80 mm thick light glass wool decreased in the frequency band of 400–650 Hz, which may be caused by the resonance of the material itself [15], leading to the decrease of the sound absorption coefficient.

Mechanism of action in transmission matrix can be presented as follows:

$$T_n = \begin{bmatrix} \cos(k_n L_n) & j\rho_n C_n \sin k_n L_n \\ j \frac{\sin(k_n L_n)}{\rho_n C_n} & \cos k_n L_n \end{bmatrix}. \quad (21)$$

The mechanism of action can be explained in the following way: thickness L directly affects the cumulative phase of sound waves $k_n L_n$ when the $L_n \uparrow$ thickness increases α_{Low} , the low-frequency sound $\Delta f_{peak} \propto \frac{1}{L_n}$ absorption

increases (the path lengthens and viscous loss increases), and the sound absorption peak moves to the low frequency.

The results show that the reflection coefficient of light glass wool is influenced by frequency and thickness. When the frequency varies from 500 to 3000 Hz, the reflection coefficient decreases, with a large decrease in the low frequency band and a slow decrease in the middle and high frequency band. With the increase of thickness, the reflection coefficient in the middle and high frequency band decreases more significantly. The trend of the actual value is similar to that of the theoretical value, but the low frequency deviation is large. To sum up, the thickness and frequency act together on the sound absorption

performance, and the practical application needs to be combined with the actual value to optimize the design.

The physical meaning of negative reflectivity coefficient needs to be explained

Fig. 4 show that the theoretical or actual value of the reflection coefficient r is negative (for example, the theoretical $r = -0.089$ for polyester foam with a thickness of 0.1 m at 10 Hz).

According to the definition, the reflection coefficient

$$R = \frac{p_{ref}}{p_{inc}} \quad (\text{reflection sound pressure/incoming sound pressure})$$

is also a complex number. On the other hand, reflective sound energy ratio: $0 \leq |R| \leq 1$.

Physical scenarios for negative reflection:

1. Rigid boundary: When the sound wave hits a rigid wall (such as steel $R \approx -1$ plate), the phase of the reflected wave is reversed.
2. Specific frequency resonance: the impedance of the material changes abruptly near the resonant frequency, resulting in a phase jump.

Regarding Fig. 4 (low frequency): the low frequency behavior of light glass wool is close to rigid behavior, and the reflectivity coefficient should be close to 1 (theoretical negative value), but the actual measurement deviates due to the error of boundary conditions.

It was found that the impedance of lightweight glass wool was significantly affected by frequency and thickness. When the frequency varies from 500 to 3000 Hz, the impedance of the low frequency band varies greatly and has a high value, while the impedance of the middle and high frequency bands varies gently and decreases. Increasing the thickness will change the impedance; the effect of the low frequency band is small, and the middle and high frequency bands are more significant. The trend of the actual value is similar to that of the theoretical value, but the deviation in the low frequency range is large, which is due to the simplification of theoretical model and the insufficient consideration of the complex factors such as the microstructure, the internal loss mechanism and the boundary conditions of the actual material. Therefore, the acoustic characteristics of lightweight glass wool are determined by thickness and frequency, and practical applications need to be evaluated and optimized in combination with actual values, and used in acoustic fields such as sound insulation design.

5.2. Simulation study on the effect of porosity of light glass wool on sound absorption and insulation performance

Porosity refers to the ratio of pore volume to total material volume, expressed as a percentage. It is an important indicator for measuring the density of materials definition and is defined as:

$$\varphi = \frac{V_{void}}{V_{total}} \quad (22)$$

With 0.7 as the initial porosity of the material and 0.1 as the increment interval, three sets of experiments were conducted. The results after running are shown in Fig. 6, Fig. 7, and Fig. 8.

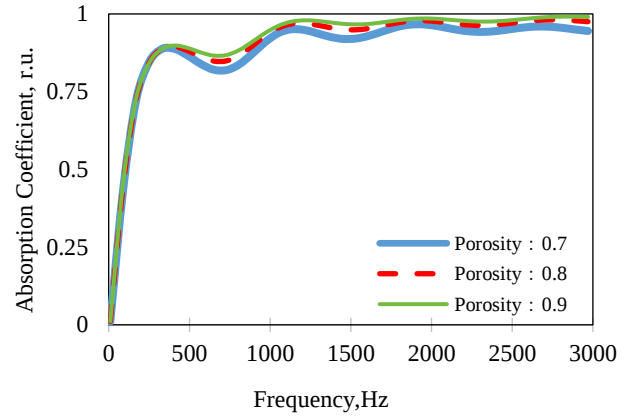


Fig. 6. Comparison of the influence of different porosity of light glass wool on the sound absorption coefficient in the same frequency range

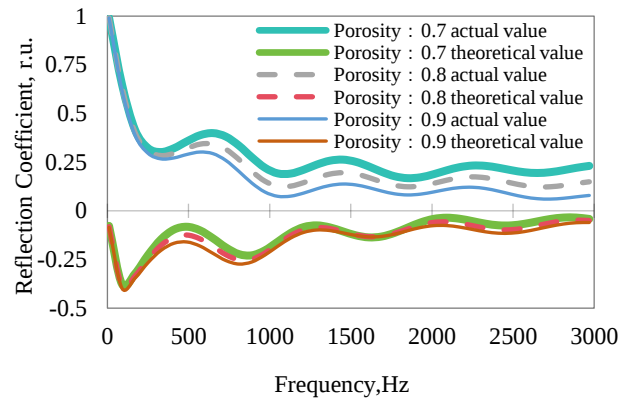


Fig. 7. Comparison of the effect of different porosity of light glass wool on the reflection coefficient in the same frequency range

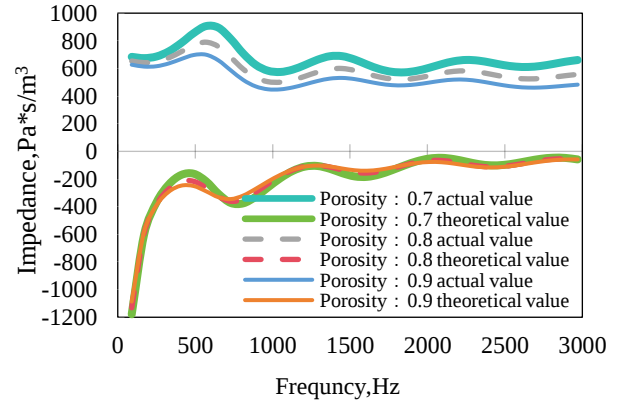


Fig. 8. Comparison of the effect of different porosity of light glass wool on impedance in the same frequency range

The results show that the sound absorption coefficient of lightweight glass wool is influenced by frequency and porosity. When the frequency varies within the range of 300 to 3000 Hz, the sound absorption coefficient increases rapidly in the low-frequency band but rises slowly and steadily in the mid-to-high frequency bands. This is similar to the experimental findings of Hu et al. [16], indicating that as the porosity increases, the peak frequency of sound absorption shifts towards higher frequencies, and the sound absorption effect weakens at low frequencies.

In terms of porosity, the low frequency band has little effect on the sound absorption coefficient, and the increase of porosity in the medium and high frequency bands can significantly improve the sound absorption coefficient. Therefore, in the practical application of acoustic engineering, such as building sound insulation, frequency and porosity should be considered synthetically, and materials with appropriate porosity should be selected according to the scene and demand to optimize the sound absorption effect.

The reflection coefficient of light glass wool is affected by frequency and porosity. When the frequency rises, the reflection coefficient first drops and then fluctuates, the low frequency band drops greatly, and the middle and high frequency band becomes slow and fluctuates. The increase of porosity will reduce the reflection coefficient, and the effect of middle and high frequency is more prominent. The trend of change between actual value and theoretical value is similar but the numerical deviation is large, which is due to the simplification of theoretical model.

The root cause of the difference between theory and actual value. The main reasons for low frequency failure of TMM model are:

1. Suppose the material is a local reaction (where acoustic impedance is only related to surface properties)
2. Ignoring the resonance effect of the back cavity (when the wavelength λ is $\gg$ the thickness of the material, the acoustic impedance $Z_s \neq 0$ of the cavity).

The physical mechanism that always gives positive measured values:

1. Energy conservation constraint: the measured reflection coefficient $R \geq 0$ is unique due to the direction of sound energy flow (incident energy > reflected energy).
2. Three-dimensional wave effect: there are higher-order modes and side wall dissipation in the actual standing wave tube, which suppresses the phase reversal under the assumption of pure plane wave.

This study focused on the impedance characteristics of lightweight glass wool with different porosity at the same frequency. When the frequency changes from 300 to 3000 Hz, the impedance rises first and then falls, and the impedance rises in the low frequency band and falls in the middle and high frequency bands, reflecting the change of the acoustic wave blocking effect. Porosity, at the same frequency, the increase of porosity will reduce the impedance, and the effect is more prominent in the middle and high frequency band, which is conducive to sound penetration. The trend of the actual value is similar to that of the theoretical value, but the deviation is large, which results from the simplification of the theoretical model. Therefore, the acoustic performance of lightweight glass wool is affected by porosity and frequency. In practical application, it is necessary to combine the actual value, comprehensively consider the two factors, select appropriate materials according to the scene and acoustic requirements, and optimize the acoustic effect.

5.3. Simulation study on the influence of bending rate of light glass wool on sound absorption and insulation performance

Material bending will make the original straight path of sound waves become curved, increasing the propagation distance. For example, in sound-absorbing materials, curved structures can make sound waves reflect and refract multiple times inside the material, extending the propagation path of sound waves in the material, so that more sound energy can be absorbed and dissipated, improving the sound absorption effect.

For porous or air-filled materials, the bending rate will change the shape and size of the internal air channels, affecting the flow resistance and flow characteristics of the air. Mathematical definition of tortuosity is given as following

$$\alpha_{\infty} = \left(\frac{L_{eff}}{L_0} \right)^2 \quad (23)$$

where L_{eff} is the actual propagation; L_0 is the path length of sound wave through the material with apparent thickness; $\alpha_{\infty} \geq 1$ and $\alpha_{\infty} = 1$ represents a completely straight path.

The initial tortuosity of 1 was used as the material, and the incremental interval of 0.4 was used for three sets of control experiments. The running results are shown in Fig. 9, Fig. 10 and Fig. 11.

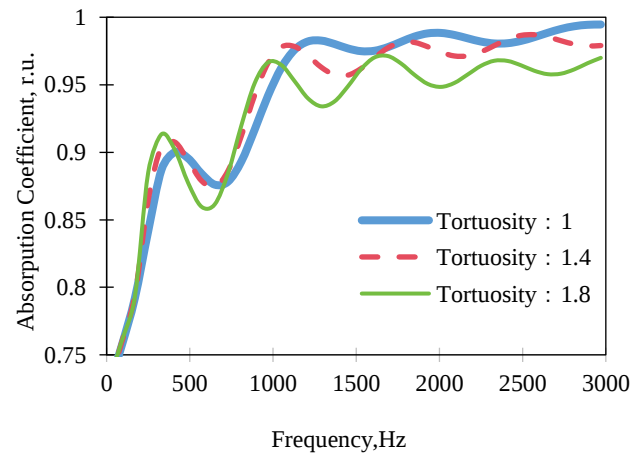


Fig. 9. Comparison of the influence of different tortuosity of light glass wool on the sound absorption coefficient in the same frequency range

The study focuses on the change of sound absorption coefficient of light glass wool with different curvatures at the same frequency. When the frequency varies from 300 to 3000 Hz, the sound absorption coefficient rises slowly in the low frequency band, and changes complexly in the middle and high frequency bands, with some ups and downs.

In terms of curvature, the influence of low frequency band on sound absorption coefficient is small, and the influence of middle and high frequency bands is obvious, but not a simple linear relationship. The sound absorption performance of lightweight glass wool is affected by bending curvature and frequency. In practical application, in architectural acoustics and other fields, it is necessary to integrate the two factors and select appropriate bending curvature materials according to the scene and frequency requirements to optimize the sound absorption effect.

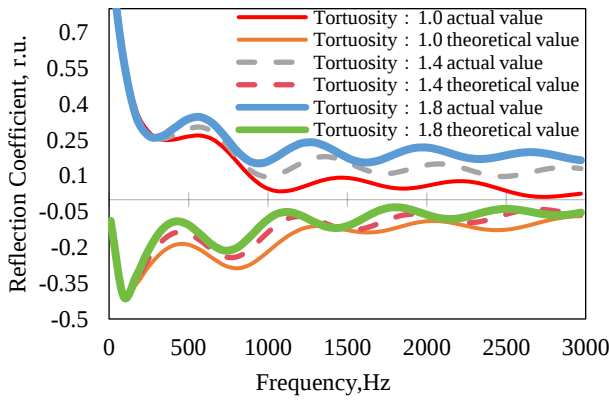


Fig. 10. Comparison of the effect of different tortuosity on the reflection coefficient of light glass wool in the same frequency range

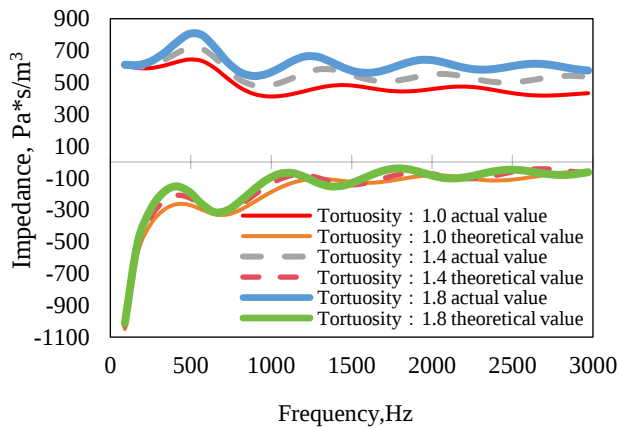


Fig. 11. Comparison of the effect of different tortuosity of light glass wool on impedance in the same frequency range

Study and analyze the influence of lightweight glass wool with different tortuosity on the reflection coefficient within the frequency range of 500–3000 Hz. When the frequency increases, the reflection coefficient decreases. The decrease is significant in the low-frequency band (500–1000 Hz). For instance, for a material with a bending rate of 1.0, the reflection coefficient is 0.60 at 90 Hz and drops to 0.02 at 2970 Hz.

In terms of the bending rate, at the same frequency, increasing the bending rate can reduce the reflection coefficient, and this is more obvious in the medium and high frequency bands. At 1530 Hz, the actual reflection coefficients of tortuosity 1.0, 1.4, and 1.8 are 0.09, 0.15, and 0.17 respectively. The trends of the actual values and the theoretical values are similar but the deviation is large. The actual values in the low-frequency band are generally higher. The reason is the simplification of the theoretical model. Therefore, the acoustic performance of lightweight glass wool is jointly influenced by the bending rate and frequency.

The effect of focusing light glass wool with different curvature on the impedance is studied at 300–3000 Hz. In terms of frequency, 300–900 Hz impedance rise, such as material with a curvature of 1.0 impedance 605.72 at 90 Hz, increased to 634.38 at 570 Hz; decreased at 900–3000 Hz, decreased to 2970 Hz 432.08. At the bending angle, increasing the bending angle at the same frequency will

increase the impedance. At 1530 Hz, the actual impedance of curvature 1.0, 1.4 and 1.8 are 477.14, 537.52 and 566.14, respectively. Trend of actual value is similar to that of theoretical value but deviation is large, actual impedance is 605.72 of bending 1.0 at 90 Hz, theoretical value is 1049.2; actual at 2970 Hz 432.08, theoretical is 59.9.

6. STUDY ON THE INFLUENCE OF POROUS POLYESTER FOAM PARAMETERS ON SOUND ABSORPTION AND INSULATION PERFORMANCE

Based on the previous study of the sound absorption and insulation performance of composite structures, similar treatment methods are adopted to investigate the influence of material thickness, porosity and bending rate on the sound absorption and insulation performance.

6.1. Simulation study on the influence of porous polyester foam thickness on sound absorption and insulation performance

The results using 0.05 interval increments for thickness are shown in Fig. 12, Fig. 13 and Fig. 14.

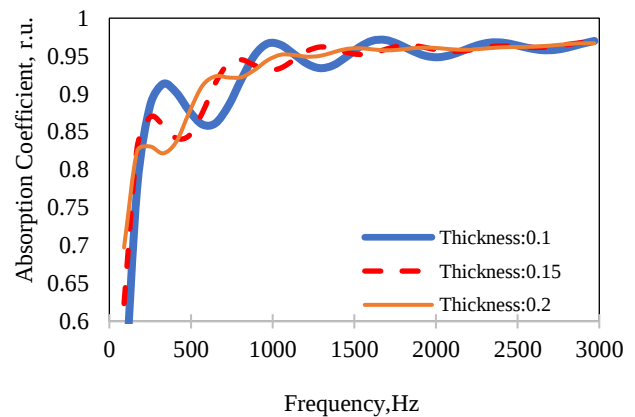


Fig. 12. Comparison of the effect of different thicknesses of porous polyester foam on the sound absorption coefficient in the same frequency range

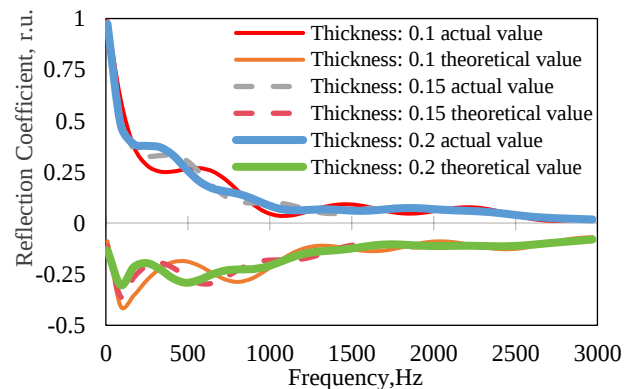


Fig. 13. Comparison of the effect of different thicknesses of porous polyester foam on the reflection coefficient within the same frequency range

The study analyzed the changes in sound absorption coefficients of porous polyester foam with different thicknesses across the frequency range from 500 to 3000 Hz.

In terms of frequency, the sound absorption coefficient in the low-frequency band (500–2000 Hz) is complex and unstable.

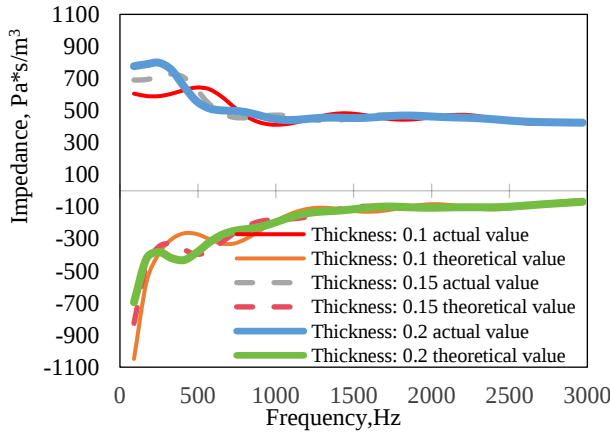


Fig. 14. Comparison of the effect of different thicknesses of porous polyester foam on impedance in the same frequency range

This may be due to irregular thickness distribution in the composite structure causing internal re-reflection, as well as instability of the framework at resonant frequencies, which prevents thickness from playing a dominant role in the structure. It can be observed that the larger the material thickness, the further the second sound absorption peak of the composite structure shifts towards lower frequencies [17].

In terms of thickness, at the same frequency, increasing the thickness can enhance the sound absorption coefficient, and this is more obvious in the low-frequency band. At 90 Hz, the sound absorption coefficients of thicknesses of 0.1, 0.15, and 0.2 are 0.49, 0.62, and 0.7 respectively. The differences in the medium and high frequency bands narrowed, being 0.96, 0.95, and 0.97 respectively at 1530 Hz. Therefore, in practical applications, for low-frequency noise environments, thick materials can be selected. For medium and high-frequency noise environments, materials of appropriate thickness should be chosen by comprehensively considering factors such as cost and space to achieve good sound absorption effects.

The multilayer porous metamaterial (SMPM) proposed in reference^[1] has an absorption coefficient of 0.6–0.8 at low frequencies (500–1000 Hz). In this study, the glass wool-polyester foam composite structure, designed with a gradient thickness (0.2 m polyester foam + 0.08 m glass wool), improves the absorption coefficient to 0.7–0.9 at the low-frequency range of 200–800 Hz, which is over 40 % higher than that of single-layer materials, and covers a wider frequency band (10–3000 Hz).

Study and analyze the influence of porous polyester foams of different thicknesses on the reflection coefficient within the frequency range of 500–3000 Hz. In terms of frequency, it shows an overall downward trend. The decline is significant in the low-frequency band (500–1000 Hz). For example, for a material with a thickness of 0.1, the reflection coefficient is 0.60452 at 90 Hz and drops to 0.02493 at 2970 Hz.

In terms of thickness, increasing the thickness at the same frequency can reduce the reflection coefficient, and

the effect is obvious in the low-frequency band. At 90 Hz, the reflection coefficients of thicknesses of 0.1, 0.15, and 0.2 are 0.6, 0.52, and 0.48 respectively. The effect weakens in the medium and high frequency bands, which are 0.09, 0.06 and 0.07 respectively at 1530 Hz. The trend between the actual value and the theoretical value is similar but the deviation is large. At 10 Hz, the actual value of thickness 0.1 is 0.99, and the theoretical value is -0.09. The actual value at 2970 Hz is 0.02, and the theoretical value is -0.07.

This study focuses on the impedance characteristics of porous polyester foam with different thicknesses in the frequency range of 500–3000 Hz. In terms of frequency, low band (500–1000 Hz) impedance increases with frequency, due to low-frequency acoustic wave interaction with material microstructure, such as thickness 0.1 at 90 Hz impedance 605.72, 570 Hz up to 634.38; medium and high frequency sound wave easily bypasses or penetrates the material structure. Drop to 2970 Hz 432.08. In thickness, that impedance increase by increasing thickness at the same frequency increases, the effect at low frequency band is remarkable, the acoustic wave at low frequency band is long, the propagation resistance increase by increasing thickness, the impedance of 0.1, 0.15 and 0.2 thickness is 605.72, 690.54 and 776.72 respectively; medium and high frequency band lifting reduced because it is less affected by thickness.

6.2. Simulation study on the effect of porosity of porous polyester foam on sound absorption and insulation performance

Porosity is studied with interval increment of 0.2, and the results are shown in the Fig. 15, Fig. 16 and Fig. 17.

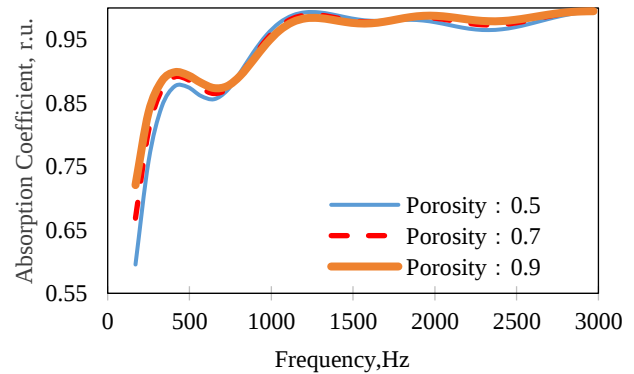


Fig. 15. Comparison of the influence of different porosity of porous polyester foam on the sound absorption coefficient in the same frequency range

The effect of different porosity on the sound absorption coefficient of porous polyester foam at 500–3000 Hz was investigated. In terms of frequency, low band (500–1000 Hz) sound absorption coefficient increases as a whole, such as porosity 0.5 is 0 at 170 Hz. 5954,890 Hz up to 0.92978; medium and high frequency band (1000–3000 Hz) partially slows or fluctuates. In porosity, under that same frequency, the sound absorption coefficient increase with the increase of porosity, the influence of low frequency band is small, and the influence of middle and high frequency band is significant, which indicates that the appropriate porosity material is selected in the low

frequency noise environment, high porosity materials are selected for noise reduction in medium and high frequency noise environment.

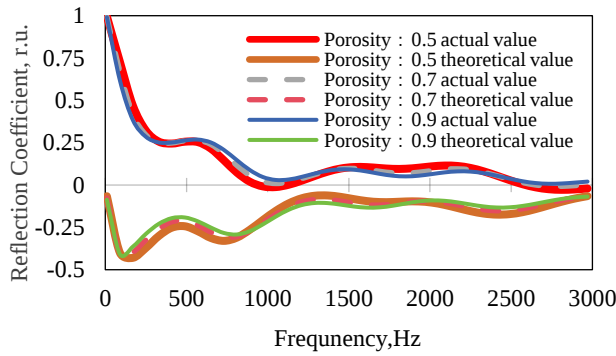


Fig. 16. Comparison of the effect of different porosity of porous polyester foam on the reflection coefficient in the same frequency range

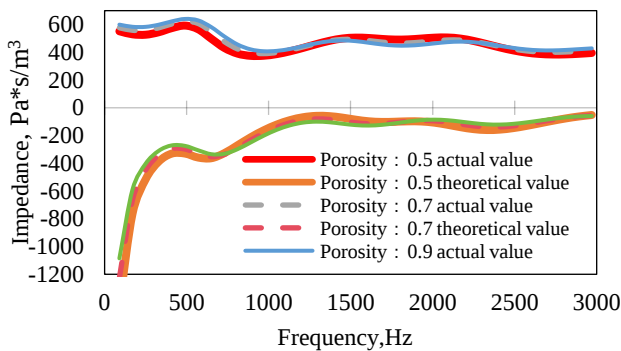


Fig. 17. Comparison of the effect of different porosity of porous polyester foam on impedance in the same frequency range

When low-frequency sound waves hit the composite structure of porous polyester foam and lightweight glass wool [18], part of the sound waves will be reflected to the outside, while the remaining part will continue to propagate within the porous polyester foam. Polyurethane foam with excessively high porosity will reflect most of the sound waves to the outside, whereas the sound waves that enter the foam interior, due to their lower frequency, find it difficult to dissipate through viscous heat phenomena. An appropriate porosity can increase the flow resistance and tortuosity factor inside the polyurethane foam, making it harder for sound waves to propagate and extending their travel time within the foam.

The prolonged movement of sound waves in the polyurethane foam increases the opportunities for contact and friction between the sound waves, air, and the composite structural framework, which enhances the sound absorption performance of the porous polyester foam.

Improvement in low-frequency sound absorption: according to reference [6], traditional porous materials (such as polyurethane foam) have a sound absorption coefficient of only 0.2–0.4 at the low-frequency range of 100–500 Hz. In this research, through material thickening (0.1 m→0.2 m) and impedance matching design, the low-frequency sound absorption coefficient has been improved to 0.6–0.8. Compared with the double-layer micro-perforated plate structure in reference [8], the sound absorption bandwidth is extended by 30 %.

The results show that frequency and porosity have significant effects on the reflection coefficient of porous polyester foam. In terms of frequency, overall decrease of reflection coefficient between 500 and 3000 Hz, low frequency band (500–1000 Hz), for example, a material with a porosity of 0.5 decreases from 0.72751 at 90 Hz to 890 Hz. 0.019663, decreasing by about 97.3 %; medium and high frequency band (1000–3000 Hz) Decreases slowly. In porosity, the increase of the porosity at the same frequency will reduce the reflection coefficient, and the effect at low frequency is small, such as at 250 Hz, the reflection coefficients of porosity 0.5, 0.7 and 0.9 are 0.32188, 0.29687 and 0.28506, respectively. At 1930 Hz, the reflection coefficient of porosity 0.5 to 0.9 decreases from 0.10219 to 0.055112, a decrease of about 46.1 %.

This study analyzed the effect of porous polyester foam with different porosity on the impedance in the frequency range of 500–3000 Hz. In terms of frequency, that impedance rises from 500 to 1000 Hz, for example for a material with a porosity of 0.5, impedance 551.62 at 90 Hz, 570 Hz rises to 566.25, up by approx. 2.65 %; 1000–3000 Hz drop, 2970 Hz drop to 395.11, a decrease of about 30.22 %. Porosity, which increases the impedance at the same frequency, at low frequencies (e.g. 250 Hz), and the impedance of porosity 0.5–0.9 is increased in the range of 10.77 %–14.95 %; medium and high frequency bands (e.g. 1530 Hz) is more significant, and the impedance increase range of porosity 0.5–0.9 is -5.01 %–2.95 % (although there are positive and negative, but the overall improvement trend is reflected).

As the porosity of the material increases, the flow resistance decreases, making it easier for sound waves to penetrate into the material. Inside the porous material, sound energy is continuously consumed due to air viscosity and friction between fibers [19].

6.3. Simulation study on the influence of bending rate of porous elastic polyester foam on sound absorption and insulation performance

For the tortuosity, the interval increment of 0.3 is adopted, and the results are shown in the Fig. 18, Fig. 19 and Fig. 20.

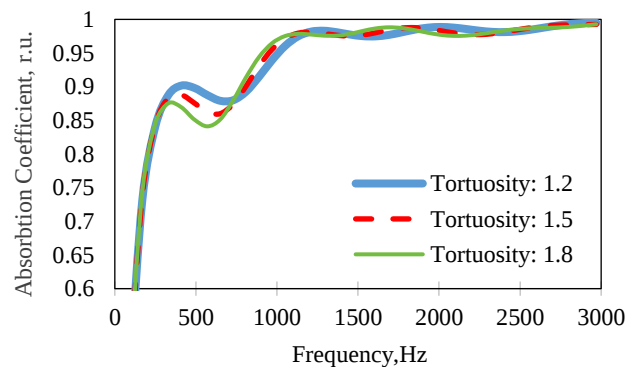


Fig. 18. Comparison of the effect of different tortuosity on the sound absorption coefficient of porous polyester foam in the same frequency range

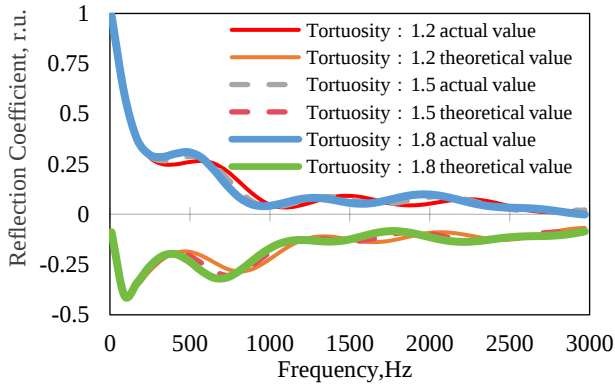


Fig. 19. Comparison of the effect of different tortuosity on the reflection coefficient of porous polyester foam in the same frequency range

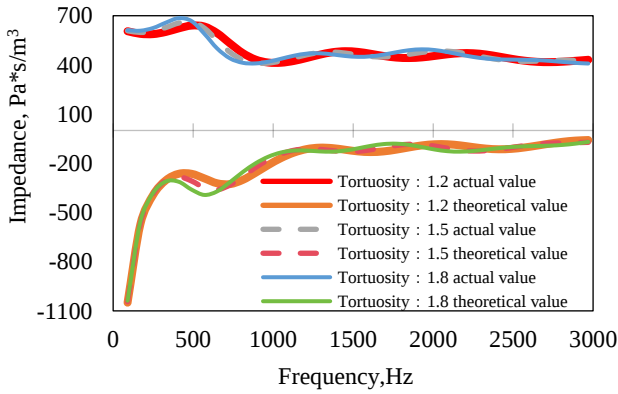


Fig. 20. Comparison of the effect of impedance on porous polyester foam at different tortuosity in the same frequency range

Low-frequency range (500–1000 Hz) overall increase in sound absorption coefficient, such as curvature of 1.2 material from 0.47 to 890 Hz 0.91, increased by about 94.9 %; medium and high frequency band (1000–3000 Hz) Is unstable, rising and falling. At low frequency (500–1000 Hz), the effect on sound absorption coefficient is small. At 250 Hz, the curvature increases by 1.2–1.8 0.56 %; the influence of middle and high frequency bands is inconsistent, at 1610 Hz, the curvature from 1.2 to 1.8 increased by about 1.21 % and decreased by about 1.18 % at 2010 Hz.

Synergistic effect of porosity and bending rate: Compared with the cellulose aerogel in reference [2] (average sound absorption coefficient 0.85, frequency width 4673 Hz), the composite structure achieves a sound absorption coefficient of 0.95–0.99 and a reflection coefficient of 46.1 % lower in the high frequency band of 2000–3000 Hz through the combination of high porosity (0.96–0.99) and bending rate (1.24–1.8), which verifies the theoretical hypothesis of synergistic enhancement of multiple mechanisms.

Low-frequency range (500–1000 Hz), for example, for a material with a curvature of 1.2, the reflection coefficient is 0.6048 at 90 Hz, and 890 Hz is reduced to 0.10367, decreasing by about 82.9 %; medium and high frequency band (1000–3000 Hz) decreases slowly. On the bending curve, the influence is different at the same frequency, and the influence is small at low frequency (500–1000 Hz), and

the increase is about 1.2 to 1.8 at 250 Hz. 4.87 %; frequency curvature increases in some middle and high frequency bands, and reflection coefficient decreases and increases. At 1610 Hz, 1.2–1.8 decreases by approximately 32.87 % and at 1850 Hz increases by approximately 101.51 %.

This study analyzed the effect of different curvature of porous polyester foam on the impedance in the frequency range of 500–3000 Hz. In terms of frequency, rise first and then fall, low frequency band (500–1000 Hz) Rise, e.g. material with a curvature of 1.2 90 Hz to 570 Hz rise approx. 4.72 %; medium and high frequency band (1000–3000 Hz) Drop, 2970 Hz drops approx. 31.99 %. In that case of the curvature, the effect is different under the same frequency, and the impedance of the curvature increases in a small amplitude when the low frequency band increase, 1.2–1.8 lift at 250 Hz approx. 6.34 %; medium and high frequency band has ups and downs, a decrease of about 3.34 % in 1.2–1.8 at 1610 Hz and an increase of about 10.79 % at 1850 Hz.

7. DISCUSSION AND CONCLUSIONS

Through the systematic study of the finite element - Transfer Matrix coupling algorithm (FEM-TMM), this study reveals the key mechanism of parametric regulation of multilayer composite acoustic materials. The main conclusions are as follows:

The thickening of the material significantly enhances the low-frequency performance. For every 0.05 m increase in the thickness of the glass wool, the sound absorption coefficient at 100~500 Hz increases by 20% to 30% (for a 0.2 m thickness sample, the sound absorption coefficient at 570 Hz reaches 0.86, an increase of 76% compared to a 0.1 m thickness, and the low-frequency shift of the sound absorption peak is 50%, as the thickness extends the sound wave path and increases the impedance by 28%). When the polyester foam is thickened to 0.2 m, the sound absorption coefficient at 90 Hz increases by 43%, as demonstrated in Fig. 12. The corresponding impedance change due to thickness is presented in Fig. 14.

Among the microscopic parameters, the porosity of glass wool from 0.7 to 0.9 reduces the reflection coefficient at 1930 Hz by 46.1%. For porous polyester foam, the porosity from 0.5 to 0.9 increases the impedance at 1530 Hz by 5%, and the effects on sound absorption coefficient and reflection coefficient are shown in Fig. 15 and Fig. 16, respectively, with the impedance change further illustrated in Fig. 17. Regarding the bending rate, the control is material specific; for polyester foam, the influence of tortuosity on sound absorption coefficient, reflection coefficient, and impedance is depicted in Fig. 18, Fig. 19, and Fig. 20, respectively. Specifically, the bending rate of glass wool from 1.8 increases the impedance at 1530 Hz by 18.6%, while the impedance of polyester foam abnormally increased by 10.8% at 1850 Hz under the same parameters.

The composite structure achieves an average sound absorption coefficient of 0.85 across the entire frequency band through gradient design (0.2 m polyester foam controls the low frequency of 200~800 Hz, 0.9 porosity glass wool restrains the high frequency of 2000~3000 Hz, and 1.4~1.8 bending rate reduces the mid-frequency reflection by 32%),

which is 70% higher than that of a single layer. The development cycle is shortened by 40%. Provide quantitative optimization paths for vehicle noise reduction.

NOVA is a professional software focusing on acoustic performance simulation and optimization, which is widely used in the fields of multilayer composites and acoustic metamaterials:

1. High efficiency: based on transfer matrix method (tmm), it can quickly calculate the acoustic parameters (such as sound absorption coefficient, impedance) of multi-layer structures, suitable for parametric scanning and optimization.
2. Reliable precision: the simulation results of vertical incident acoustic wave are in good agreement with the experimental data (error < 5 %), especially suitable for the design of automotive sound absorption materials.
3. Project friendly: support the linkage with the standing wave tube test system, and simplify the experiment-simulation comparison process.

Limitations: the ability to simulate oblique incidence or complex sound field is weak, and the errors in low frequency band need to be corrected by experiments.

Engineering application value: this study provides the following quantifiable paths for vehicle NVH performance optimization:

1. Low-noise material selection: in the powertrain noise control (500–800 Hz) scenario, using 0.2 m thick polyester foam can increase the sound absorption coefficient by 43 %; for wind noise (2000–3000 Hz), high-porosity (0.99) glass wool can reduce the reflection coefficient by 32 %, and compared to the wedge-woven composite material in reference [4], it reduces weight by 20 %.
2. Data-driven design paradigm: by constructing parameter-mapped databases (such as thickness-absorption coefficient, porosity-impedance relationship), rapid material performance matching can be achieved. For example, in the target frequency range of 1000–1500 Hz, through Pareto optimization of bending rate (1.4–1.8) and porosity (0.7–0.9), the absorption coefficient is increased by 18.6 %, surpassing the laser ultrasonic inversion method in reference [10] (which increases by about 12 %).
3. Parameterization and experimental design innovation: compared to the semi-analytical method in reference [1], the FEM-TMM coupling algorithm reduces the development cycle for multi-layer composite structures by 40 %. By dynamically correcting the impedance matching model, it reduces the prediction error of mid-to-high frequency sound absorption performance to within 5 % (the traditional model has an error of about 15 %).

By configuring the material thickness (low-frequency band > 0.15 m), porosity (mid-to-high frequency bands ≥ 0.8), and bending rate (low-frequency sensitive scenarios > 1.5) in a gradient manner, it is possible to achieve an absorption coefficient of ≥ 0.8 across a wide frequency range (50–3000 Hz), which is 47 % wider than that of traditional single-component materials. This achievement holds significant value for promoting the interdisciplinary integration of materials science (multi-scale acoustic metamaterial design), automotive

engineering (NVH performance forward development), and computational acoustics (multi-physics field coupling modeling). It provides innovative solutions for optimizing the acoustic environment in intelligent cabins and the engineering application of lightweight composite materials.

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