Research on sound insulation of multiple-layer structure with porous material and air-layer

Guofeng Bai[1]; Pei Zhan; Fusheng Sui; Jun Yang

Key Laboratory of Noise and Vibration Research, Institute of Acoustics, Chinese Academy of Sciences, China

ABSTRACT

Sound insulation performance of multiple-layer structure is investigated which consists of elastic solid, fluid and porous material. The Biot theory of sound propagation in elastic porous medium and the method of transfer matrix are used to derive the transmission loss of typical layered-structure. The influence of air-layer and porous material on sound insulation performance of multiple-layer structure had been discussed by numerical calculation and experimental testing. The result indicates that the air-layer and porous material can improve sound insulation performance of multiple-layer structure and their distribution also has great influence on the sound insulation performance.

Keywords: sound transmission loss; transfer matrix; porous material

I-INCE Classification of Subjects Number(s): 51.4

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1. INTRODUCTION

Sound insulation performance of single plate depends on not only its stiffness, internal loss and mass, but also the incident wave frequency and incident angle etc. Acoustic characteristic curve of thin plate is divided into four regions: the stiffness control, damping control, mass control and coincident effect area. Because most of acoustical transmission loss curve is mass control area, mass law is the most important influence on sound insulation properties. Although in recent years the single plate has changed into bilayer or multilayer insulation structure in order to attenuate noise energy as much as possible, it is difficult to increase sound insulation performance and reduce surface density at the same time for mass law. Therefore a compromise must be made when choosing the sound insulation materials. There is a pressing need to overcome the shortcoming of acoustical materials in order to reduce the transport noise, especially the high-speed train. The transfer matrix method(TMM) was first proposed to analyze multilayer medium by Thomson[1]. Brekovskikh once described plane wave propagation in elastic solid by the transfer matrix, which greatly develops TMM of the fluid and solid[2]. Biot theory is a very classical method to analyze wave propagation in porous materials[3]. According to Biot theory, there are three kinds of wave propagation in porous media: two dilatation waves and one shear wave. All kinds of wave propagation in porous material, the fluid, and elastic layer can be represented by the transfer matrix, which are composed of the final matrix system to acquire acoustical insulation performance. Because too many parameters of Biot theory make it very complex, Allard, Brouard and Atalla developed TMM to describe to normal or oblique plane wave propagating in various media[4-6]. In this paper we introduce air layer to design light composite materials for sound insulation. TMM and acoustic measurement are used to research on sound insulation performance of composite materials containing air layer.

2. THE TRANSFER MATRIX OF LAYERED COMPOSITE MATERIALS

Figure 1 is single layer with h thickness when plane wave is incident. The two point M and M' on the medium surface are defined. Figure 2 is multi-layer composite medium when plane wave is incident. The two point A and B on the incident and transmission surface are defined.

[1] bgf@mail.ioa.ac.cn

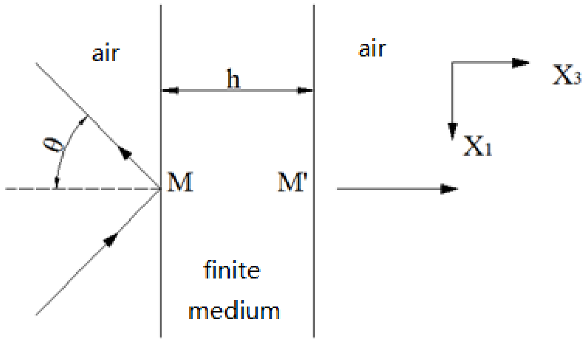


Figure 1 – Plane wave incidence of single layer medium with h thickness

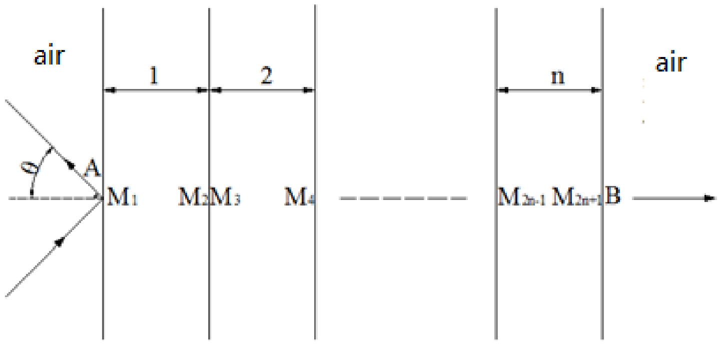


Figure 2 – Plane wave incidence of multi-layer composite medium

2.1 The Air Layer

When the air layer is included in composite media, The M point in sound field is determined by

$$V^f(M) = [p(M), v_3{}^f(M)]^T \tag{1}$$

where p and v are pressure and particle velocity, the lower index is coordinate direction, k is complex wave number , and ρ is density. Based on $V^f(M) = T^f V^f(M')$, for fluid medium the sound pressure and particle velocity can be represented by the 2×2 transmission matrix.

$$T^f = \begin{pmatrix} \cos(k_3 h) & \dfrac{j\omega\rho}{k_3}\sin(k_3 h) \\ \dfrac{jk_3}{\omega\rho}\sin(k_3 h) & \cos(k_3 h) \end{pmatrix} \tag{2}$$

2.2 The elastic solid

As finite medium is elastic solid layer in Figure 1, $v_1^s(M), v_2^s(M), \sigma_{33}^s(M), \sigma_{13}^s(M)$ are described the sound propagation in an elastic solid and can be written as follows

$$V^s(M) = [v_1^s(M), v_2^s(M), \sigma_{33}^s(M), \sigma_{13}^s(M)]^T \tag{3}$$

where $v_1{}^s(\mathrm{M})$ and $v_3{}^s(\mathrm{M})$ are the velocity components of point M in x_1 and x_3 directions, $\sigma_{33}{}^s(\mathrm{M})$ and $\sigma_{13}{}^s(\mathrm{M})$ are respectively the normal and tangential stress of point M .

Let $A=[A_1+A_2, A_1-A_2, A_3+A_4, A_3-A_4]^T$, $V^s(M)=\Gamma(x_3)A$, Combining with equation (3) it can be obtained as follows

$$\Gamma=\begin{pmatrix} \omega k_1 c_{13} & -j\omega k_1 s_{13} & j\omega k_{33} s_{33} & -\omega k_{33} c_{33} \\ -j\omega k_{13} s_{13} & \omega k_{13} c_{13} & \omega k_1 c_{33} & -j\omega k_1 s_{33} \\ -D_1 c_{13} & jD_1 s_{13} & jD_2 k_{33} s_{33} & -D_2 k_{33} c_{33} \\ jD_2 k_{13} s_{13} & -D_2 k_{13} c_{13} & D_1 c_{33} & -jD_1 s_{33} \end{pmatrix} \tag{4}$$

where $D_1=\lambda(k_1{}^2+k_{13}{}^2)+2\mu k_{13}{}^2=\mu(k_{13}{}^2-k_1{}^2)$, $D_2=2\mu k_1$ $c_{13}=\cos(k_{13}x_3)$, $s_{13}=\sin(k_{13}x_3)$, $c_{33}=\cos(k_{33}x_3)$, $s_{33}=\sin(k_{33}x_3)$. The transfer matrix of elastic solid can be obtained when x_3 are equal to $-h$ and 0 in equation (4) respectively.

$$[T^s]=[\Gamma(-h)][\Gamma(0)]^{-1} \tag{5}$$

2.3 The porous materials

According to Biot's theory, $v_1{}^s$ and $v_3{}^s$ the definition of the two velocity and component framework in a porous material, $v_3{}^f$ is component velocity of the fluid, $\sigma_{33}{}^s$ and $\sigma_{13}{}^s$ are the two stress components and framework, $\sigma_{33}{}^f$ is stress component of fluid, the sound field in the point of porous material layer can be expressed as

$$V^p(M)=[v_1^s, v_3^s, v_3^f, \sigma_{33}^s, \sigma_{13}^s, \sigma_{33}^f]^T \tag{6}$$

Let $A=[A_1+A_1', A_1-A_1', A_2+A_2', A_2-A_2', A_3+A_3', A_3-A_3']^T$ and $V^p(M)=[\Gamma(x_3)]A$, then

$$[\Gamma(x_3)]=\begin{pmatrix} \omega k_t c_{13} & -j\omega k_t s_{13} & \omega k_t c_{23} & -j\omega k_t s_{23} & j\omega k_{33} s_{33} & -\omega k_{33} c_{33} \\ -j\omega k_{13} s_{13} & \omega k_{13} c_{13} & -j\omega k_{23} s_{23} & \omega k_{23} c_{23} & \omega k_t c_{33} & -j\omega k_t s_{33} \\ -j\omega k_{13}\mu_1 s_{13} & \omega\mu_1 k_{13} c_{13} & -j\omega k_{23}\mu_2 s_{23} & \omega\mu_2 k_{23} c_{23} & \omega k_t \mu_3 c_{33} & -j\omega k_t \mu_3 s_{33} \\ -D_1 c_{13} & jD_1 s_{13} & -D_2 c_{23} & jD_2 s_{23} & 2jNk_{33}k_t s_{33} & -2Nk_{33}k_t c_{33} \\ 2jNk_t k_{13} s_{13} & -2Nk_t k_{13} c_{13} & 2jNk_t k_{23} s_{23} & -2Nk_t k_{23} c_{23} & N(k_{33}{}^2-k_t{}^2)c_{33} & -jN(k_{33}{}^2-k_t{}^2)s_{33} \\ -E_1 c_{13} & jE_1 s_{13} & -E_2 c_{23} & jE_2 s_{23} & 0 & 0 \end{pmatrix},$$

where $c_{23}=\cos(k_{23}x_3)$, $s_{23}=\sin(k_{23}x_3)$.

Let x_3 in the equation (7) be respectively $-h$ and 0, we can get the transfer matrix for porous materials

$$[T^p]=[\Gamma(-h)][\Gamma(0)]^{-1} \tag{7}$$

2.4 Transmission loss of composite materials

When it is a semi-infinite air medium at the end of multiple-layer structure, we can derive the transmission loss of typical composite materials by using transfer matrix. The impedance at B point of Figure 2 can be expressed as

$$Z_B/\cos\theta = p(B)/v_3^f \quad (\tag{8}$$

There is a relationship between the transmission coefficient t and reflection coefficient r

$$\frac{p(A)}{1+r}=\frac{p(B)}{t} \tag{9}$$

Combined with transfer matrix of multiple-layer structure, we can obtain transmission loss with incident angle θ for plane wave.

$$TL=-10\log\tau(\theta) \tag{10}$$

where $\tau(\theta)=\left|t^{2}(\theta)\right|$

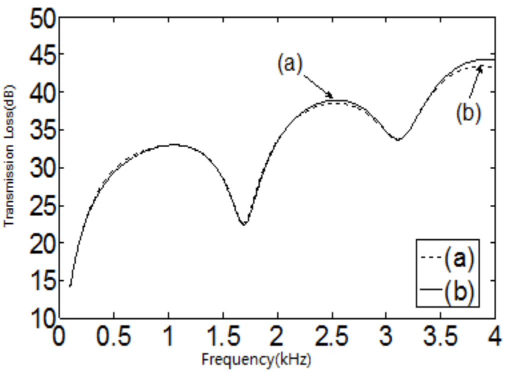
3. RESULTS AND DISCUSSIONS

3.1 Simulation Verification

Sound insulation for aluminum and glass wool composite materials in Figure 3 are compared between experimental results in the Ref. [4] and the simulation results. The legend of G is glass cotton, AL stands for aluminum plate. The two curves in Fig.3 are agreement, which shows that the model is suitable for the prediction of composite materials.

3.2 Computational results

Figure 4 is transmission loss (TL) curves of different thickness of porous materials between double aluminum panels, which panel thickness is 1mm. TL of aluminum panel with 2mm thickness is compared with melamine foam with 30mm, 50mm and 70mm thickness respectively. The legend P represents the melamine foam. It can be seen that porous materials between double aluminum panels play a good role in increasing TL and the thickness of porous materials are positively correlated. Porous materials have a great influence on composite structures and are mainly concentrated in the high frequency. In general, the influence of porous materials is limited in low frequency.



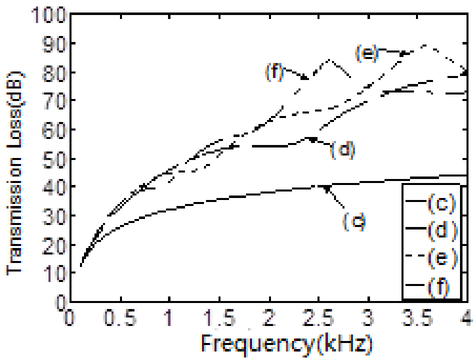
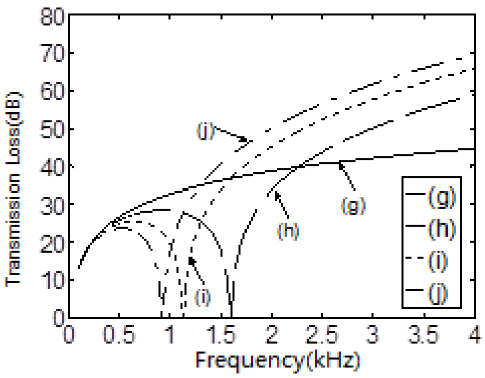


Figure 3 –Simulation Verification Figure 4 –TL of different thickness of porous material

(a)70mmG+1mmAL(simulation result) (b)70mmG+1mmAL(experimental result in Ref. [4])

(c)1mmAL+1mmAL (d)1mmAL+30mmP+1mmAL (e)1mmAL+50mmP+1mmAL (f) 1mmAL+70mmP+1mmAL



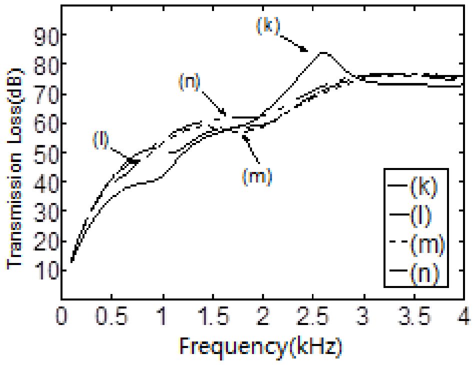


Figure 5 –TL of different thickness of air layer Figure 6 –TL of different multiple-layer structure

(g) 1mmAL+1mmAL (h) 1mmAL+1mmAir+1mmAL (i) 1mmAL+2mmAir+1mmAL (j) 1mmAL+3mmAir+1mmAL

(k)1mmAL+70mmP+1mmAL (l)1mmAL+30mmP+10mmAir+30mmP+1mmAL (m)1mmAL+20mmP+10mmAir+ 40mmP+ 1mmAL (n) 1mmAL+10mmP+10mmAir+50mmP+1mmAL

Figure 5 is transmission loss curves of different thickness of air-layer between double aluminum panels, which panel thickness is 1mm. TL of aluminum panel with 2mm thickness is compared with air-layer with 1mm, 2mm and 3mm thickness respectively. From the simulation results we can see that the air-layer of these structures has a good role in high frequency, but in the specific frequency generate acoustic valley for the cavity resonance. It can be seen that with increasing the air-layer thickness, TL is increasing in high frequency and acoustic valley is moving to low frequency at the same time. In general, the presence of air layer improves sound insulation performance for this kind of structure because of the air viscous dissipation effects. At the same time, the presence of air-layer makes the impedance mismatch strengthened between panel and air.

Figure 6 is transmission loss curves of different multiple between double aluminum panels, which panel thickness is 1mm. The composite structure contains air-layer and porous materials, whose thickness is 70mm. By comparing several curves in Figure 6 we can get the following conclusions: (1) TL can be significantly improved in low frequency while reducing a portion of porous materials and increasing air-layer appropriately, which lead to smaller the overall weight and surface density of composite materials. (2) When the total thickness of composite material is constant, the different distribution means for porous materials and air-layer has great influence on the sound insulation performance. Good optimization combination can increase impedance mismatch and improve the sound insulation performance obviously, especially restrain resonant sound valley in low frequency.

3.3 The experimental testing

Figure 7 is the transmission loss curves of experimental testing in reverberation room for different materials between aluminium extrusion and ceiling panel, which are used in the high-speed trains. The transmission loss of composite material containing air layer is increased greatly than the other material in low frequencies, and the weighted transmission loss is improved 3.5dB. It shows that the air-layer can improve the sound insulation performance and reduce quality of composite materials at the same time.

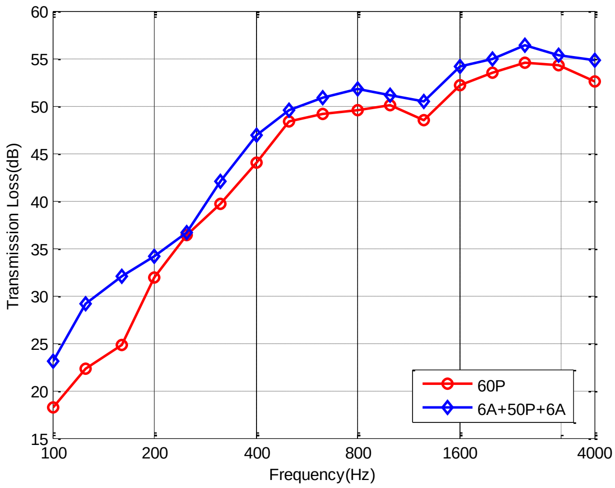


Figure7. Transmission loss curves of experimental testing in reverberation room for different materials

4. CONCLUSIONS

This paper discusses the theory of sound propagation in layered composite materials, and sound insulation performance of composite materials is calculated based on the transfer matrix method of the porous material, elastic solid and fluid layer. The simulation and experimental results show that sound insulation performance is greatly improved after the air-layer is used appropriately for composite materials, which provides a new way for designing light acoustical insulation materials. The air-layer in the composite structure make impedance mismatch between the different medium, while sound absorption of porous materials make acoustical energy further attenuation. The distribution method for porous material and the air-layer also affects sound insulation performance and noise reduction. We should select different structural parameters and the optimization combination for specific frequency bands.

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