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AN INVESTIGATION ON THE OPTIMIZATION OF AIR LAYERS AND POROUS ELASTIC MATERIALS FOR SOUND INSULATION OF COMPOSITE STRUCTURE

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Based on the Biot theory of sound propagation in multi-layer materials, the method of transfer matrix were used to derive the transmission loss of typical layered-structure consists of elastic solid, fluid and porous material. The influence of air layer and porous material on sound insulation performance of multi-layer structure have been discussed by numerical calculation. The sound insulation performance of the composite structure has been optimized in the specific frequency band by using genetic algorithm and transfer matrix. The results indicate that the air layer and porous materials can improve the sound insulation performance of the composite structure. The distribution of the air layer and porous materials also has great influence on the sound insulation performance.

Keywords: sound transmission loss, air layers, porous material, parameter optimization

1. Introduction

As we know, 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 environment noise. The transfer matrix method(TMM) was used 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. The composite structure and sound insulation performance of the specified frequency band is optimized by using the transfer matrix and genetic algorithm.[7-9] In order to improve sound insulation performance and reduce materials thickness at the same time, the combination means and distribution thickness for the layered structure including air layer, porous material layer and other materials are debated and analyzed in-depth. The composite structure with air layer has an advantage on the reduction of mass and it achieves the goal of low energy consumption and lightening design. The research results can provide a theoretical means for optimization design of layered composite structure.

2. General physical model

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.

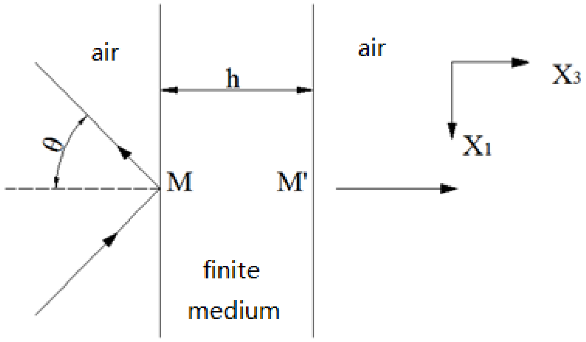

Figure 1: Plane wave incidence of single layer medium with h thickness

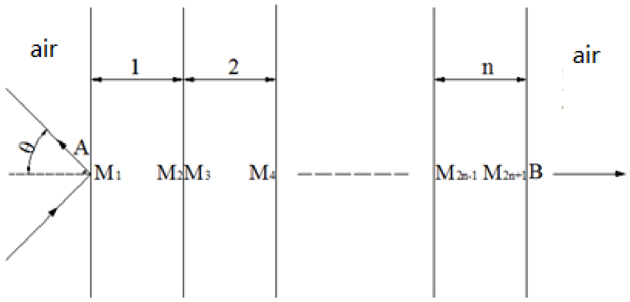

Figure 2: Plane wave incidence of multi-layer composite medium

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 transfer matrix of layered composite materials for the air layer, the elastic solid and the porous materials are described in Ref.10.

The impedance at B point of Figure 2 can be expressed as

$$Z_B/\cos\theta = p(B)/v_3^f(B) \tag{1}$$

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

$$\frac{p(A)}{1+r} = \frac{p(B)}{t} \tag{2}$$

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

$$TL = -10\log\tau(\theta) \tag{3}$$

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

3. The genetic algorithm of the optimization model

According to two typical composite structure: "Aluminum panel+ Porous material+ Air layer+ Porous material + Aluminum panel" and "Aluminum panel + Air layer + Porous material + Air layer+ Aluminum panel", we can get the following optimization model by using genetic algorithm and according to the relationship between sound insulation of the composite structure and material thickness of each layer.

Design variables: $H = h_i \quad i = 1,\cdots,N$ (4)

Objective function: $\mathrm{MAX}\{TL(H)\}$, (5) Constraint condition: $a_i \le h_i \le b_i$

$$h_1 + ... + h_i + ... + h_N = \text{const} \quad (6)$$

In equation (6), h_i is the i layer thickness of the composite structure, a_i, b_i is the lower and upper limit value of the i layer thickness, the total thickness of the air layer or the porous material layer in the composite structure is kept constant.

The number of population in genetic algorithm is 100, the iterated algebra is 200, the crossover probability is 0.95, the mutation probability is 0.08, and the optimal solution is obtained after the independent operation of 10 times. The parameters of genetic algorithm are same as the following paper.

The materials parameters are used in the calculation. The aluminum density is 2800kg/m^3, Young's modulus is 7e10N/m^2, Poisson's ratio is 0.3, the damping factor is 0.007, porous materials are melamine foam, its parameters and glass cotton are shown in table 1.

Table 1: The main parameters of numerical simulation

Parameters	Thickness (m)	Prosity	Flow resistance (N S M^4)	Tortuoty	Viscous characteristic length (m)	Thermal Characteristic length (m)	Skeleton density (kg/m^3)	Young's modulus (N/m^2)	Poisson's ratio	Damping factor
Glass cotton	0.07	0.94	40000	1.06	56e-6	110e-6	130	4.4e6	0	0.10
Melamine	Change	0.99	1.09e4	1.02	Indirect calculation	Indirect calculation	8.80	8e4	0.40	0.17

4 Optimization results

4.1 Optimization of sound insulation of composite structures at specific frequency

The composite structure of "AL+P1+A+P2+AL" (AL is aluminium panel, P is porous material, A is air layer, with the symbol definition is same as the following paper) are kept the left aluminium panel 6mm, the right aluminium panel 3mm, and the air layer thickness 10mm in structure middle. While we maintain that thickness sum of two porous material layers is 76mm on both sides of the air layer, one of thickness of porous material layer is assume as the design variables, which optimized range from 0mm to 76mm in order to get the best insulation at the specific frequency. The parameters and optimized results are shown in table 2. The design frequency is taken from 100Hz to 4000Hz, corresponding to the frequency point of 1/3 octave.

Table 2: Results of the optimization of the thickness of the porous material at the specific frequency

Frequency /Hz	P1 thickness of left porous material /mm	P2 thickness of right porous material /mm	TL /dB
100	63.9	12.1	32.18
125	57.9	18.1	36.41
160	51.6	24.4	41.53
200	46.8	29.2	46.48
50	75.2	32.7	51.65
315	43.3	35.1	57.14
400	40.9	36.6	62.82
500	39.4	37.4	67.88
630	38.6	37.7	72.14
800	38.3	75.9	75.18
1000	0.1	0.8	79.77
1250	15	61	83.07

1600	0.1	75.9	85.37
2000	75.9	0.1	93.45
2500	75.9	0.1	100.46
3150	75.9	0.1	101.73
4000	6	70	109.41

It can be seen from table 2 that the optimization results of the thickness of porous material on both sides of the air layer are different from frequency. From the data in table 2 it is not difficult to find that when the sound insulation of composite structure are achieved the optimal thickness of porous materials in the frequency range of 630Hz to 100Hz, the left thickness of porous material is higher than that of the right side, and with the increase of frequency, both thickness of porous material for the optimized sound insulation are tended to be same. From 800Hz to 4000Hz, it is more favorable that porous material are placed to one side of the air layer in order to increase sound insulation performance of composite structure. Which side to choose the incident or transmission wave for the porous material depend on the situation noise for different frequency.

From 100Hz to 630Hz, the porous material distribution on both sides of the air layer, are formed a kind of composite structure such as "AL+P1+A+P2+AL". On the one hand, the porous material viscosity and heat dissipation make the acoustic energy attenuation, on the other hand, this composite structure make mismatch impedance. Acoustic waves are reflected many times between porous material layer and air layer, which increase the sound travel times in the air layer. We can make full use of sound attenuation effect of the air layer in low-frequency. From 800Hz to 4000Hz, sound energy attenuation mainly depend on sound absorption of porous material itself, so porous materials should be placed centrally in high frequency.

The composite structure of "AL+A1+P+A2+AL", are kept the left aluminum panel 6mm and the right aluminum panel 3mm, and porous material thickness is 76mm. While we maintain the air layer thickness 10mm on both porous material sides, we can get the best sound insulation by optimizing both sides of the air layer thickness, which regarded as the design variables and its range from 0mm to 10mm.

Table 3: Optimization Results of the air layer thickness at the specific frequency

Frequency /Hz	A1 thickness of left air layer /mm	A2 thickness of right air layer /mm	TL /dB
100	10	0	13.85
125	10	0	26.94
160	10	0	36.14
200	10	0	43.06
50	10	0	49.39
315	10	0	55.60
400	10	0	61.74
500	10	0	67.25
630	10	0	72.62
800	10	0	77.59
1000	4.9	5.1	81.83
1250	4.9	5.1	85.14
1600	5	5	88.36
2000	5	5	94.97
2500	5	5	101.28
3150	5	5	102.34
4000	5	5	110.15

It can be seen from table 3 that the optimization results of the air layer thickness on both sides of the porous material at the specific frequency point. From the data in table 3 it showed that in the frequency range from 100Hz to 800Hz, it is more favorable for increasing sound insulation performance of composite structure while the air layer is placed centrally to the porous material side. From 1000Hz to 4000Hz, the sound characteristics will change obviously and uniform distribution for air layer on both sides of the porous material get the optimal results for sound insulation performance of composite structure. For 100Hz to 800Hz, we can make full use of sound attenuation effect in low frequency by centrally placing the air layer. From 1000Hz to 4000Hz, the air layer is uniformly distributed on both sides of porous material in order to improve the sound insulation by increasing impedance mismatch of composite structure.

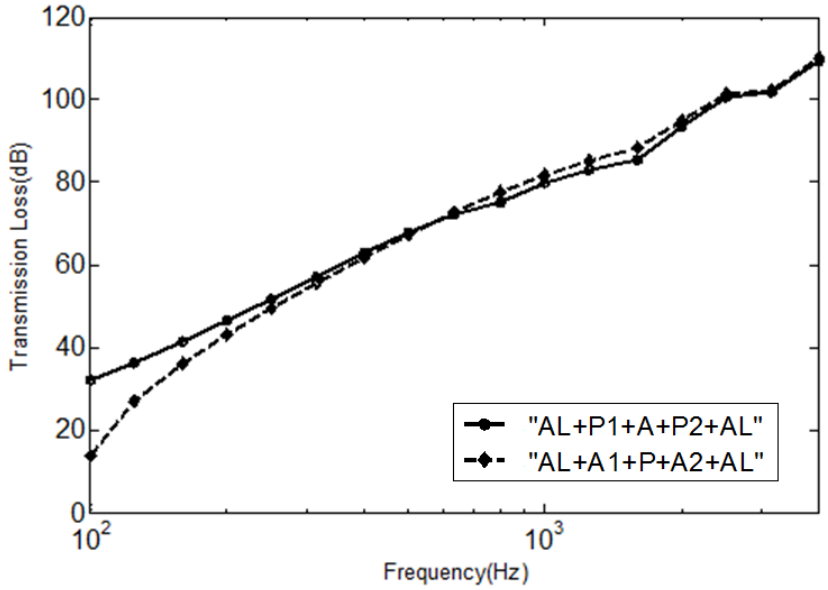

Figure 1: TL curves of two kinds of optimized composite structures

Transmission Loss(TL) of the two kinds of composite structures are optimized and compared from figure 1. Their total thickness of composite structures are 95mm. It can be seen that from 100Hz to 500Hz after optimization TL of "AL+P1+A+P2+AL" is relatively large with some advantages of the porous materials, which are distributed on both sides of the air layer as table 1 showing. From 630Hz to 4000Hz after optimization, TL of the composite structure "AL+A1+P+A2+AL" is relatively large with some advantages of the air layer, which are distributed on both sides of the porous materials as table 2 showing. To sum up, for the above two kinds of typical composite structure TL have different features in various specific different frequencies. If aiming at reducing concerned noise frequency, it should be emphasized to choose the corresponding composite structure and optimization structure parameters.

4.2 Optimization analysis

The optimization effect can be compared the optimal value of the objective function with the original scheme. The optimal values of design variables are also regarded as an important indicator whether the optimization design scheme is feasible, and we can get the optimization direction by comparing original design variables and the optimal value constantly. Our original design structure form a similar composite structure such as "AL+P+AL". We assume that two thickness of aluminum panels are 6mm, 3mm, and the thickness of porous materials is 86mm.

In consideration of noise spectrum characteristics in one environment, the optimization of the composite structure for "AL+P1+A+P2+AL" and "AL+A1+P+A2+AL" from 100Hz to 1000Hz were analyzed in order to increase sound insulation performance. The sound insulation curve, material thickness and weight of composite structure are discussed. According to the transfer matrix theory, we calculate that TL of the original design of "6mm AL +86mm P+3mm AL" is 82.55dB in the band of 100Hz-1000Hz. According to optimization results of table 2 and 3, "AL+P1+A+P2+AL" and " AL+A1+P+A2+AL" in the frequency range of 100Hz-1000Hz are 92.18dB and 94.87dB respectively after optimization, which has greatly improved relative to the original design scheme. TL curves of the optimization scheme and original design are showed in figure 2. It can be seen from figure 2 that sound insulation performance of the optimized composite structures have improved in the frequency range of 100Hz-1000Hz relative to the original design scheme. But these optimization results from 100Hz to 200Hz is not as good as the original design.

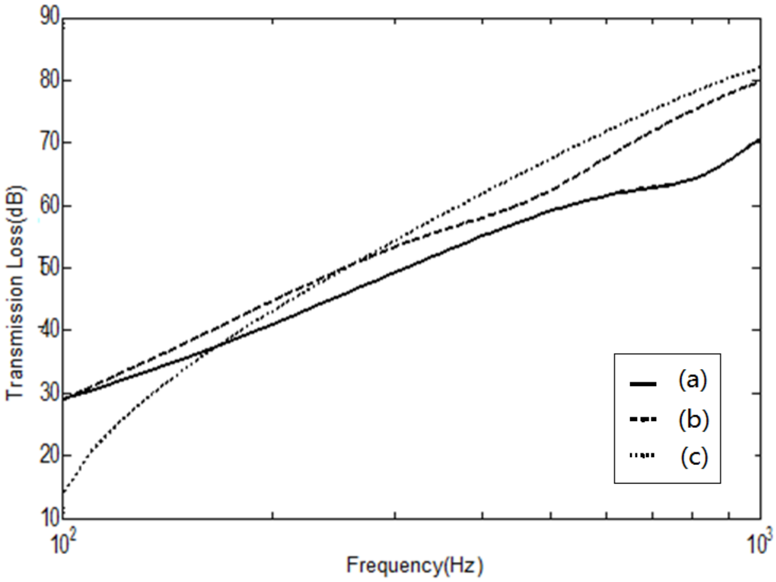

Figure 2: TL of different thickness of porous material
(a)Solid Line: 6mmAL+86mmP+3mmAL (b) Dashed Line: 6mmAL+10mmA+76mmP+3mmAL
(c) Dotted Line: 6mmAL+10mmA+66mmAL+10mmA+3mmAL

Before and after optimization results of each layer thickness for composite structure and the total TL are shown in table 4. It can be seen that the conversion from a part of the porous material in the original design scheme into the air layer will improve the sound insulation performance of composite structures. At the same time it can reduce the amount of porous materials, which will play an important role in reducing the production cost. It obviously has good economic effect.

Table4: TL before and after optimization of composite structure for each layer thickness

	Composite structure form	Thickness of each layer between two aluminum panels/mm			TL from 100 to 1000Hz /dB
Before optimization	AL+P+AL	P			
		86			82.55
After optimization	AL+P+A+P+AL	P	A	P	
		0	10	76	92.18
	AL+A+P+A+AL	A	P	A	
		10	66	10	94.87

From the analysis of the weight, the surface density of composite structure between two aluminum panels is used as an index of porous material. The porous materials is melamine foam and its density is 8.8kg/m^3. We can calculate the surface density of various composite structures as shown in table 5. It can be seen from table 5 that the weight of the optimized composite structure is lower than that of the original design.

Table 5: Surface density of composite structure before and after optimization

	Original scheme	Optimized scheme	
	86mmP	10mmA+76mmP	10mmA+66mmP+10mmA
surface density （kg/m^2）	0.7568	0.6688	0.5808
Relative original scheme	100%	88.37%	76.74%

5. CONCLUSIONS

In this paper the acoustic model of porous material was established by using Biot theory. The sound insulation properties of layered structure are studied for by transfer matrix method. We use genetic algorithm to optimize the designation of two kinds of typical composite containing air layer and porous material layer. The influence of the air layer and the thickness of the porous material and their combination means on the sound insulation performance are mainly discussed. Through the above research we can know that the optimization of composite structure can increase the sound insulation performance. For a similar layered structure such as "aluminum panel+porous materials +aluminum panel", the conversation from a part of porous material into the air layer can significantly improve sound insulation performance in low frequency, but also reduce the overall weight and surface density of composite structure, which achieve low energy consumption, low noise and lightweight design requirements at the same time.

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