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Research on the sound performance of double-layer plate coupled membrane-type acoustic metamaterial

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Abstract: A double-layer plate with a built-in membrane-type acoustic metamaterial is proposed for the effective control of low-frequency noise.The structure is composed of cavity double-layer plate, membrane and mass block. Through theoretical analysis and numerical simulation, the results show that the structure can make up for the defect of double-layer plate in low frequency. Through the design of the distance between the two plates, thickness of plate, the size of the mass block and the thickness of the membrane, the peak frequency of the sound insulation of the membrane-type acoustic metamaterial corresponds to the valley frequency of the double-layer plate, achieving the coupling resonance effect of membrane -mass block and double-layer plate, so as to make up for the defect of the sound insulation of the double-layer plate and improve the sound insulation performance of the double-layer plate partly.
Keywords: membrane-type acoustic metamaterial,double-layer plate,sound insulation performance, low frequency

I. INTRODUCTION

With the continuous development of social economy, noise pollution has increasingly affected the life of residents and the normal work of instruments and equipment. Especially that the control of medium and low frequency noise has been one of the difficulties in the field of noise control. Generally speaking, increasing the thickness and density of the single-layer plate can improve the sound insulation according to the law of mass. However, this method is not economical and can not meet the needs of the actual environment under certain conditions. Although the double-layer plate has a good sound insulation effect in the high-frequency section, it has its inherent sound insulation defect in the low-frequency section, appearing a valley value, which affects its engineering application. Although there are a lot of studies on the sound insulation performance of double-layer board at home and abroad[2-8], how to effectively improve the sound insulation performance of double-layer plate still needs further study.

In recent years, the development of acoustic metamaterials has provided new solutions for the control of medium and low frequency noise, and has been applied to various fields [9-10]. At the beginning of the 21st century, Liu et al firstly proposed the local resonance type acoustic metamaterials in science, which realized that small size controls large wavelength.The effective control of low frequency noise is realized by using millimeter level materials, which breaks the law of mass[11].In 2011, Naify et al used simulation calculation and experiment methods to study the transmission loss of membrane-type acoustic metamaterials,which is composed of membrane and additional mass block[13]. The acoustic metamaterials studied by Mei Jun and Yang et al had achieved good results in low-frequency noise control [14-15]. However, it has not been found that the membrane-type acoustic metamaterials coupled with the double-layer plate structure can improve the sound insulation effect in low frequency. In this paper, we design a double-layer plate structure with a built-in membrane-type acoustic metamaterial and study its acoustic performance, which provides a new idea for the design of sound insulation structure.

II. STRUCTURAL DESIGN AND THEORETICAL ANALYSIS

2.1 Structural model design

The whole structure model is composed of membrane-type acoustic metamaterial and double-layer plates. The silicon rubber membrane is fixed by aluminum frame and a mass block is pasted in the center of the membrane, making the membrane-type acoustic metamaterial. Then, placing it in the cavity of the double-layer plate and fixing the aluminum frame makes the whole structure.The double-layer plates are connected with a rigid sleeve. As shown in Figure 1, **A** is a double-layer plate with radius R_1 of 15mm and thickness d of 2mm; **B** is a membrane with radius R_3 of 13mm and thickness H of 0.4mm. The tension around the membrane fixed on the aluminum frame is 0.5MPa on the **XY** plane; **C** is an aluminum frame with outer radius R_2 of 15mm and inner radius R_3 of 13mm and height of 4mm. The inner diameter is fixed with the outer boundary of the membrane; **D** is a cylinder mass block with height *h* of 2mm and radius of 3mm. The material of membrane is silicon rubber. The material of frame is aluminum. The material of double-layer plate material is steel.The material of mass block material is lead. The involved material parameters are shown in Table 1.

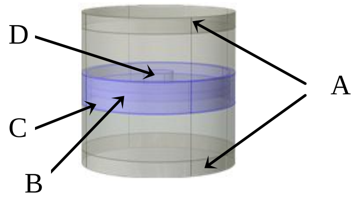

Fig. 1 Structure Model of double-layer plate with membrane-type acoustic metamaterial

Table 1

Material	Density(kg/m^3)	Young modulus（Pa）	Poisson's ratio
Lead	11340	$7*10^9$	0.42
Steel	7890	$2*10^{11}$	0.3
Aluminum	2700	$7*10^{10}$	0.346
Silicon rubber	980	$6*10^6$	0.49

2.2 loss of transmission

When the radiated sound field is infinite, the ratio of the average sound power of the incident sound field to the average sound power of the radiated sound field is expressed in dB, which is defined as sound transmission loss (STL). Assuming that the average sound power of the incident sound field is W_{in} and the average sound power of the radiated sound field is W_{out}, the transmission loss [1] is expressed as:

$$STL = 10\log_{10}\frac{W_{in}}{W_{out}}$$

2.3 Sound insulation performance of double-layer plate

According to the vibration law of the double-layer plate, for the medium frequency, the sound insulation quantity of the double-layer plate is:

$$STL = 10\lg\left|1 - \frac{\omega MD}{R} + j\left[\frac{\omega M}{R} + D - \frac{1}{2}D\left(\frac{\omega M}{R}\right)^2\right]\right|^2$$

Where, *D* is the distance between the two plates; *M* is the mass of the plate per unit area; *R* is the characteristic impedance of the plate [1]. It can be seen from the above formula that when the imaginary number term is zero, that is:

$$\omega = R\sqrt{\frac{2}{M\rho_1 D}} \tag{1}$$

That is to say, the air between the two plates resonates as a spring with the plate, making the sound insulation performance appear a valley[1].

2.4 Nature frequency of membrane-mass structure

For the circular membrane structure with an additional mass at the fixed boundary, the inertial force generated by the additional mass is added to the vibration equation of the membrane as the external excitation force, and the free vibration equation of membrane with additional mass structure can be obtained:

$$\rho_s\frac{\partial^2 w}{\partial t^2} + \rho_m h(r, r_1, r_2)\frac{\partial^2 w}{\partial t^2} - T\nabla^2 w = 0 \tag{2}$$

Where $h\ (r, r_1, r_2)$ is a step function.

According to the modal superposition theory, the displacement expression of the membrane structure transverse vibration can be obtained from equation (2) . By integrating the displacement expression into equation (2) in the membrane plane and using the orthogonality of the modal function, the following results can be obtained:

$$\{\omega^2 [\boldsymbol{M} + \boldsymbol{Q}] - \boldsymbol{K}\}[\tilde{q}] = 0 \tag{3}$$

Where ***M*** is the matrix affected by the surface density of the film, ***Q*** is the matrix affected by the additional mass, and ***K*** is the matrix affected by the tension of the film.

From formula (3), the natural frequency *f* of circular film with additional mass block can be obtained:

$$f = \frac{1}{2\pi}\sqrt{\frac{\boldsymbol{K}}{\boldsymbol{M} + \boldsymbol{Q}}} \tag{4}$$

In this paper, we design a double-layer plate structure with membrane-type acoustic metamaterial. The membrane-mass structure is coupled with the double-layer plate. The peak value of sound insulation of the membrane-type acoustic metamaterial is used to make up the sound insulation valley value of the double-layer plate, so as to improve the sound insulation performance of the double-layer plate.

III. ACOUSTIC PERFORMANCE ANALYSIS

This paper analyzes the acoustic characteristics of the membrane-type acoustic metamaterial, the common cavity double-layer plate and the double-layer plate with built-in the membrane-type acoustic metamaterial. According to the established structure model, acoustic solid coupling module of the finite element software COMSOL multiphysics 5.4 is used for numerical simulation analysis. The specific structural dimensions and material parameters of the model have been given above. Figure. 2 shows the comparison curve of sound insulation performance of membrane-type acoustic metamaterial, cavity double-layer plate and double-layer plate with built-in membrane-type acoustic metamaterial.

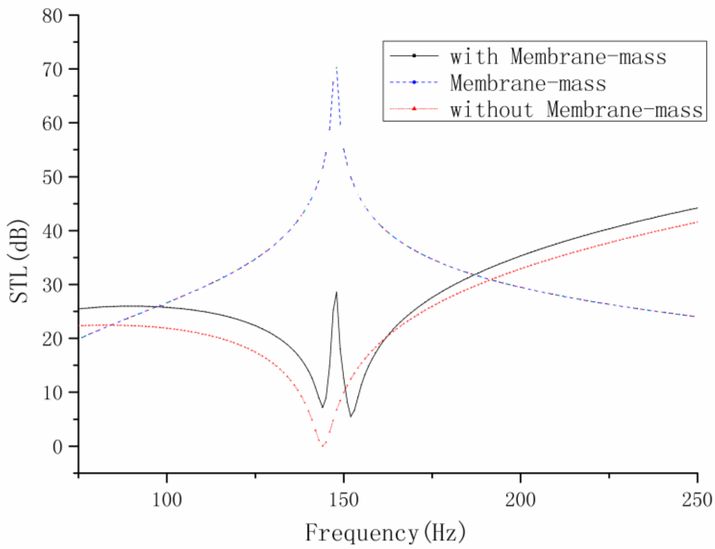

Fig.2 Comparison of sound insulation performance of membrane-type acoustic metamaterial, cavity double-layer plate and double-layer plate with membrane-type acoustic metamaterial

It can be seen from Figure 2 that under the boundary condition of simple support, due to the resonance between the air and the plate, the sound insulation curve of double-layer plate has a valley value when the frequency is *f*=144Hz. While the sound insulation curve of membrane-type acoustic metamaterial based on the local resonance mechanism has a peak value of 70dB when the frequency is *f* = 148Hz. Owing that the membrane-type acoustic metamaterial and the double-layer plate are coupled with each other, the sound insulation curve of the double-layer plate coupled membrane-type acoustic metamaterial has a good effect. During the valley range of the double-layer plate, there is a sound insulation peak value at *f* = 148Hz, which can reach 28dB, The results show that the double-layer plate structure with built-in membrane-type acoustic metamaterial can make up the sound insulation valley of double-layer plate and improve its sound insulation performance effectively.

Furthermore, the membrane-type acoustic metamaterial can be applied to the common cavity three-layer plate, and the sound insulation curve is shown in Figure. 3. The common cavity three-layer plate has two sound insulation valley values at f = 107hz and f = 185Hz; Adjusting relevant parameters make the membrane-type acoustic metamaterial have a sound insulation peak value of 70dB at f = 105Hz. Due to the coupling effect of membrane-type acoustic metamaterial and three-layer plate, there is a peak value at f = 105Hz during the valley range, which can reach 55dB, corresponding to the valley value of the three-layer plate and the peak value of the membrane-type acoustic metamaterial. That is to say, the membrane-type acoustic metamaterial can improve the sound insulation valley value of the three-layer plate and can enhance the sound insulation performance of the three-layer plate.

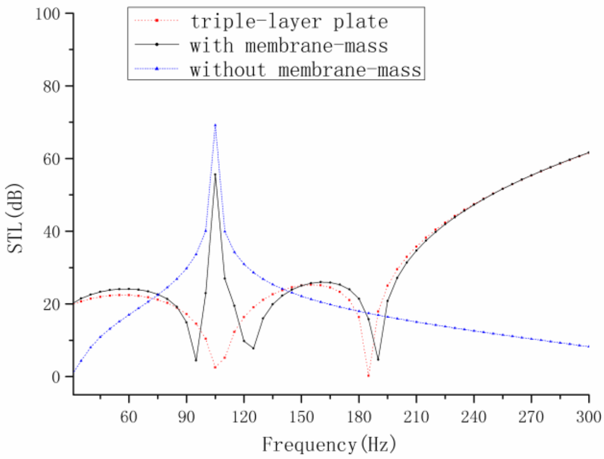

Fig. 3 Comparison of sound insulation performance of membrane type acoustic metamaterial, cavity triple-layer plate and triple-layer plate with membrane type acoustic metamaterial

IV. STUDY ON MODEL STRUCTURAL PAARMETERS

4.1 Thickness of silicone rubber membrane

The outer radius R_2 of the aluminum frame is 15mm and the inner radius R_3 is 14mm. The radius of the silicon rubber membrane is 14mm. The radius R_3 of the mass block pasted on the center of the membrane is 4mm, and its height h is 2mm. Change the thickness of the silicone rubber film. Take the thickness h of the film as 0.2mm, 0.4mm, 0.6mm, 0.8mm, 1mm respectively. The sound insulation curve of the membrane-type acoustic metamaterial is shown in Figure 4. With the increase of film thickness, the bandwidth of sound insulation becomes wider and the peak frequency of sound insulation moves towards high frequency. Specifically, as shown in Figure 5, with the increase of film thickness, the peak frequency of the structure moves to high frequency. It can be seen that when the height of the mass block is 2mm, the peak frequency moves from 71Hz to 374Hz, changing 303Hz totally. Judging from figure 4, we take the STL over 30dB as the bandwidth and calculate the relationship between the sound insulation bandwidth and the thickness of the membrane. As shown in Figure 6, with the increase of the film thickness, the sound insulation bandwidth widens gradually. It can be seen that when the height of the mass is 2mm, the sound insulation bandwidth increases from 16Hz to 408hz. Increasing the thickness of the film is equivalent to increasing the tension of the membrane, which means that the stiffness matrix $\boldsymbol{K}$ becomes larger as well. From formula (4), it can be seen that the natural frequency of the membrane-mass structure moves to the high frequency when the stiffness matrix $\boldsymbol{K}$ becomes larger. In addition, it can be seen from Figure. 5 and Figure. 6 that as the film thickness increases, the movement of peak frequency and bandwidth also increase.

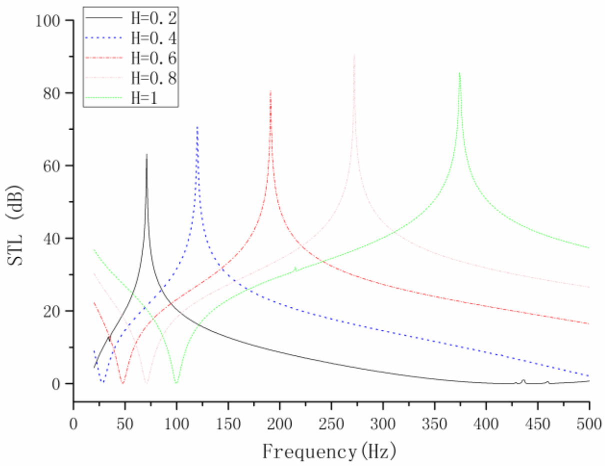

Fig. 4 Sound insulation performance of membrane type acoustic metamaterial with different membrane thickness

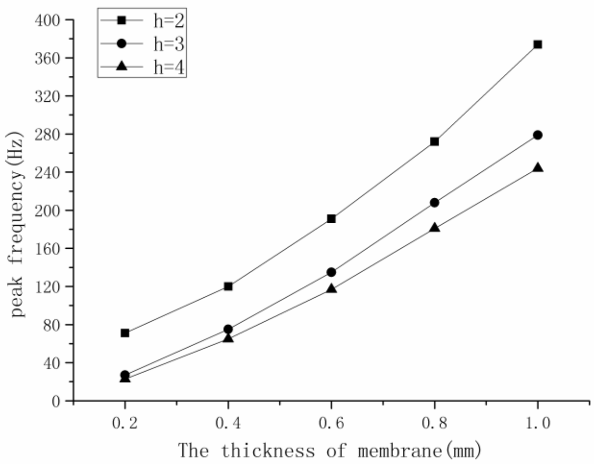

Fig. 5 The curve of peak frequency with different membrane thickness

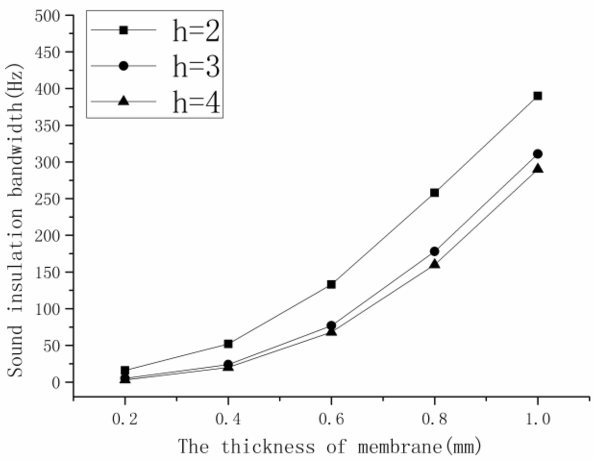

Fig. 6 The curve of sound insulation bandwidth with different membrane thickness

3.2 Quality of mass block

From formula (4), the quality of the mass block pasted in the center of the membrane will also affect the sound insulation performance of the structure. Set the film thickness *h* as 0.6mm, and vary the height of mass block as 1.5mm, 2.5mm, 3.5mmm and 4.5mm. Figure 7 shows the sound insulation curve of the membrane-type acoustic metamaterials with different mass blocks. Increasing the height of the mass block is equal to increase the quality of mass blocks. It can be seen that the peak frequency of sound insulation of the membrane-type acoustic metamaterial is constantly moving to the low frequency. Specifically, as shown in Figure 8, when the thickness of the film *h* is 0.6mm, the peak frequency is reduced from 219hz to 129hz and the decreasing range is gradually small. According to formula (4), if the quality of the mass block is increased, which means that the influence degree of matrix ***Q*** is increased, the natural frequency of the membrane-type acoustic metamaterial will move to the low frequency.

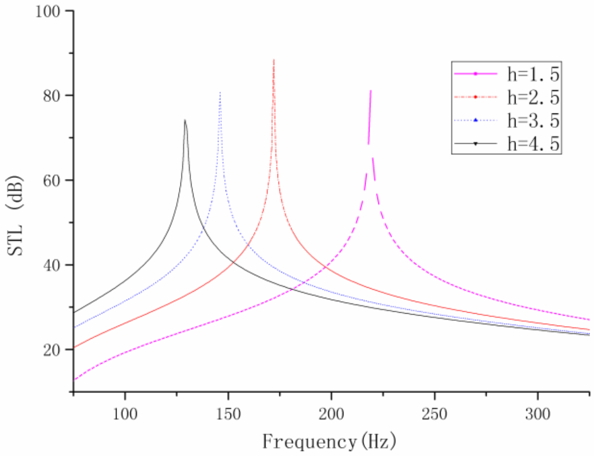

Fig. 7 Sound insulation performance of membrane type acoustic metamaterial with different mass blocks

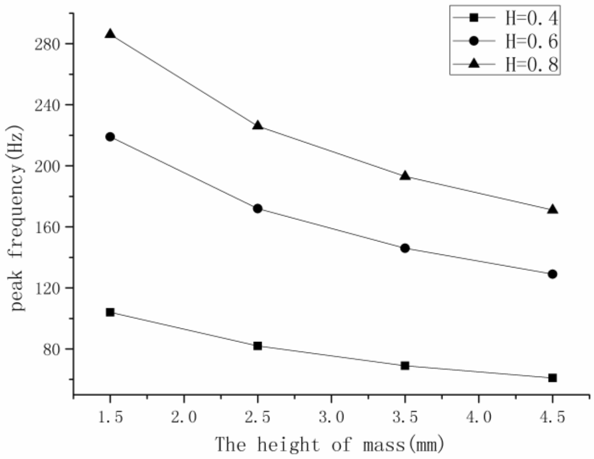

Fig. 8 The curve of peak frequency with different mass blocks

4.3 Thickness of plate

The distance between the two plates is set as 10 mm, and the thickness *d* of the plate is taken as 1 mm, 1.5 mm, 2 mm, 2.5 mm and 3 mm. The sound insulation curve of the cavity double-layer plate with different plate thickness varying with the frequency is shown in Figure 9. As the plate thickness increases, the valley value of the curve moves to the low frequency. According to Figure. 9, the change rule of valley frequency is calculated. It can be seen from Figure. 10 that with the increasing thickness of the plate, the valley value of the curve is constantly moving to the low frequency. Specifically, when the distance between the two boards is 10 mm, the valley value frequency is reduced from 302hz to 175hz, and the amount of movement is constantly reduced. According to formula (1), it can be analyzed that when the thickness of the board is continuously increasing, it is equivalent to increasing the quality of the board. Then the frequency of the valley value of the double-layer plate will be reduced. The numerical results are consistent with the theoretical results.

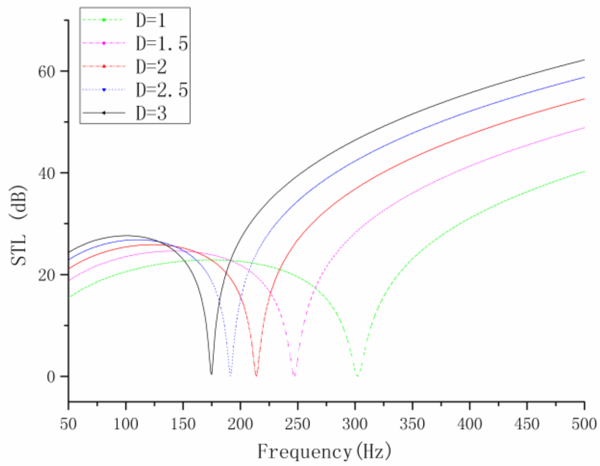

Fig. 9 Sound insulation performance of double-layer plate with different plate thickness

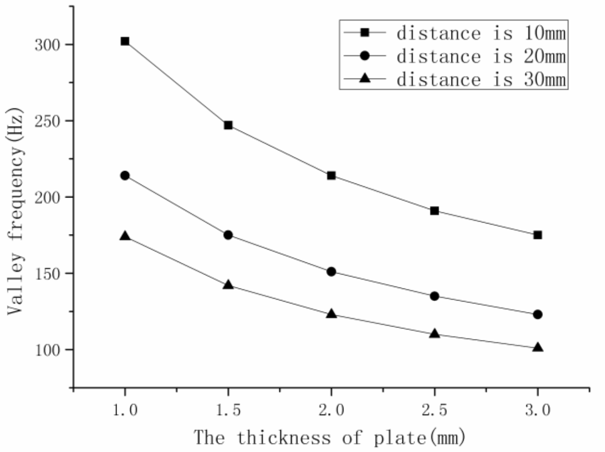

Fig. 10 The curve of valley frequency with different plate thickness

4.4 The distance between two plates

When the thickness of the two plates is 2mm, the distance *D* between the two plates is 10 mm, 15 mm, 20 mm, 25 mm and 30 mm. The sound insulation curve of double-layer plates is shown in Figure 11. As the plate spacing increases, the valley value of the curve moves to the low frequency. It can be seen more clearly from Figure 12 that when the plate thickness is 2 mm, with the increase of the distance between the two plates, the frequency of valley value decreases from 214hz to 123hz, and the amount of movement is decreasing. According to the corresponding formula (1), it can be analyzed that when the distance D increases, the valley frequency of the double-layer plate will decrease. The numerical results match the theoretical results.

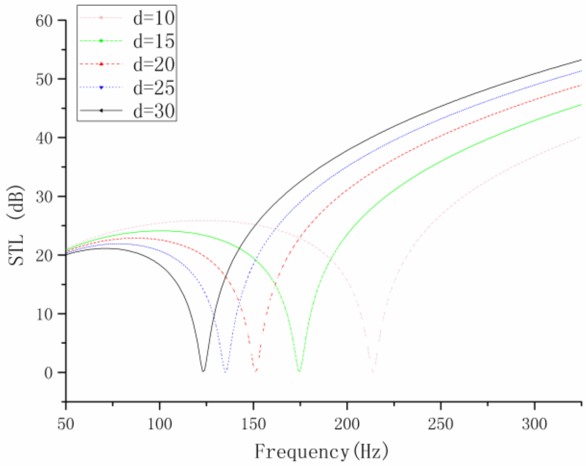

Fig. 11 Sound insulation performance of double-layer plate with different distances between two plates

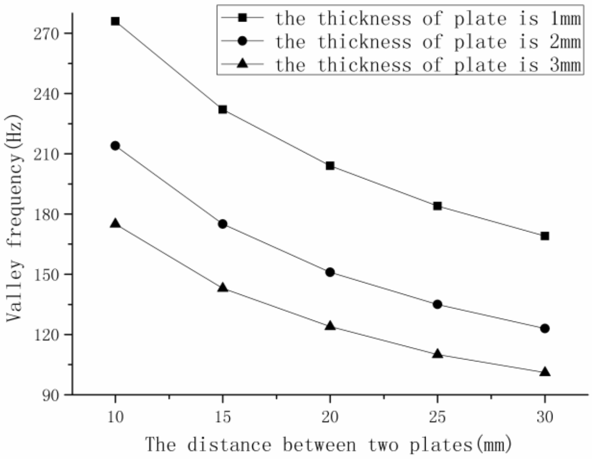

Fig. 12 The curve of valley frequency with different distances between two plates

V. CONCLUSION

In this paper, the sound insulation performance of the double-layer plate structure is improved by coupling the membrane-type acoustic metamaterial. The results show that the sound insulation performance of the double-layer plate with built-in membrane-type acoustic metamaterial is significantly higher than that of the ordinary double-layer plate. The valley value of the double-layer plate can be increased, and a peak value appears at the valley value.

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