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Research on the performance of frequency-tunable membrane-type active acoustic metamaterial

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Abstract: Aiming at the problem of slow attenuation of low-frequency noise and difficult control, an active acoustic metamaterial based on carbonyl iron powder and silicone membrane was designed, which was composed of a double-layer silicone membrane, carbonyl iron powder between membranes, additional lead, aluminum frame and electromagnetics field loading devices. Through theoretical analysis and numerical simulation, the research shows that the acoustic metamaterial can achieve good sound insulation effects in the low frequency, and changing the intensity of the input current can achieve the directional adjustment of the natural frequency of the structure. Compared with passive acoustic metamaterials, it can effectively realize the non-contact active control of the sound insulation performance of acoustic metamaterials. On this basis, the influence of thickness and Young's modulus of the carbonyl iron powder and silicone membrane on the sound insulation performance of the structure was further studied.

Keywords: acoustic metamaterials; low-frequency sound insulation; membrane type; active adjustmen

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I. INTRODUCTION

The world is experiencing a new round of technological revolution and industrial change, and the application of industrial products has brought the problem of noise pollution. Low-frequency noise has long wavelength, long transmission distance, strong penetration ability and slow attenuation, the control of low-frequency noise has become one of the challenges in today's acoustic research.[1] Traditional acoustic materials are difficult to meet the needs of social development.

In recent years, the study of acoustic metamaterials has attracted more attention with the development of industry. Acoustic metamaterials are artificial sub-wavelength composites. Through the design of their geometry and shape and structure, acoustic metamaterials can achieve unique material properties, such as negative mass density and negative equivalent bulk modulus.[2-3] Liu et al.[4]first proposed the concept of phononic crystals based on the local resonance mechanism, and successfully realised the ‘small size controlling large wavelength’ by placing silicone rubber-coated lead spheres in an epoxy resin matrix. Mei J. et al.[5-6]combined an elastic membrane with a rigid platelet, it produced negative dynamic mass density in the low frequency and absorbed all the incident sound waves. However, once such passive acoustic metamaterials are successfully designed and prepared, it is not easy to change their structural properties, thus making it difficult to adjust the acoustic properties of the structure. Therefore, study on the optimal design of acoustic metamaterials[7]and tunable dynamic acoustic properties (example bandgap and resonance frequency) become academic hotspot. A. M. Baz et al[8] proposed one-dimensional active acoustic metamaterials with adjustable effective mass density, using a thin piezoelectric diaphragm to separate an array of fluidic cavities, and the diaphragm stiffness was controlled by applying an external voltage and coupled to the fluidic domain, which realised the active control of acoustic metamaterials acoustic isolation properties. F. Landfeldt et al[9] proposed a membrane-type acoustic metamaterial with tunable sound transmission properties, where the adjustment of the intrinsic modulus of the structure and the sound transmission loss was achieved by injecting air between two elastic membranes and changing the air pressure. Li Y. et al[10] investigated a graphene-based membrane-type acoustic metamaterial, and the first anti-resonance frequency adjustment of the membrane was achieved by applying an external DC voltage. Numerous results have been achieved in the research on acoustic structural units for active control of acoustic isolation[11-12], but the existing acoustic units are complex in structure and require a high preparation process, so the non-contact active acoustic metamaterials with a simple structure and better modulation effect need to be further studied[13].

In this paper, a frequency-tunable double-layer membrane-type active acoustic metamaterials was designed. Carbonyl iron powder was added in the middle of the double-layer silicone rubber membrane, fix the boundary of membrane, and a cylindrical lead block was pasted in the centre of the double-layer membrane, placed the electromagnetic field loading device to form a frequency-tunable double-layer membrane-type active acoustic metamaterials. The electromagnetic field loading device was fed with current of different strengths, and under the action of the magnetic field, magnetic force was generated in the double-layer membrane, which realises the non-contact active tuning of the resonance frequency of acoustic metamaterials without changing the geometric dimensions and structural shapes, and effectively widens the acoustic isolation bandwidth of acoustic metamaterials.

II. STRUCTURAL DESIGN AND THEORETICAL ANALYSIS

2.1 Structural model design

As a kind of ferromagnetic particle, Carbonyl iron powder has magnetic characteristics such as high permeability and high magnetic saturation rate. According to the dipole theory, the displacement of carbonyl iron powder particles in the magnetic field is shown in Figure 1.

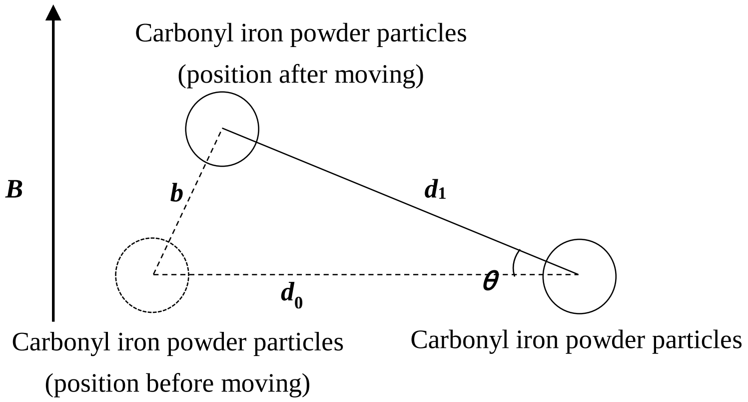

Figure 1: Microscopic schematic of particle displacement of carbonyl iron powder

Where $\boldsymbol{B}$ is the magnetic field strength, d_0 is the distance between two carbonyl iron powder particles before the magnetic field, d_1 is the distance between two carbonyl iron powder particles after the magnetic field was applied, b is the displacement of carbonyl iron powder particles when they are subjected to the magnetic field was applied, and θ is the angle of the displacement generated by the movement of carbonyl iron powder particles when the magnetic field is applied. Combined with the magnetic characteristics of carbonyl iron powder, this paper designed a double-layer silicone membrane containing carbonyl iron powder with different thicknesses, and placed micron-sized carbonyl iron powder particles uniformly in the middle of the double-layer silicone membrane through the filling and bonding methods. It was found that the prepared double-layer membrane had different properties from the ordinary membrane, not only had the advantages of large deformation, rapid magnetic response, but also had better controllable tuning characteristics than the magnetorheological membrane. The membrane can achieve rapid, significant and reversible deformation under the action of an applied magnetic field. Thus, the double-layer membrane has a wide range of applications in the field of actively controlled acoustic metamaterials.

The double-layer membrane-type acoustic metamaterial structural model was shown in Figure 2.

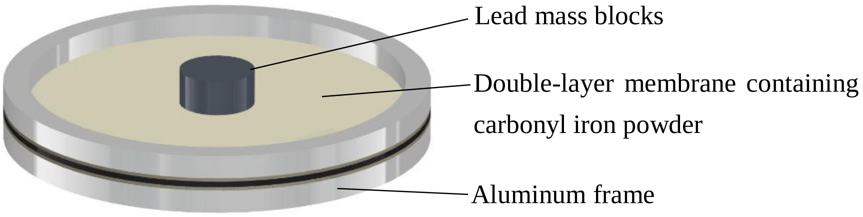

Figure 2: Structural model of double-layer membrance-type acoustic metamaterial

The model mainly consists of three parts: a cylindrical lead mass block, a double-layer membrane filled with carbonyl iron powder in the middle, and an aluminium fixing frame. The shape and thickness of the carbonyl iron powder layer can be designed according to the need of acoustic isolation, the lead mass block was pasted in the centre of the double-layer membrane, and the boundary of the bilayer membrane was fixed with an aluminium frame. The acoustic metamaterial was placed in the electromagnetic loading device, and the electromagnetic loading device was energised with direct current to produce an axial uniform magnetic field, and the magnetic field strength was adjusted by controlling the magnitude of the input current to realise the non-contact active tuning of the acoustic metamaterial.

2.2 Theoretical analysis

The acoustic metamaterial structures can creat localised resonances in the low frequency range, which can produce excellent sound insulation. From the thin membrane theory, the equation of motion of the thin membrane with the central additional mass block[14] is shown in equation (1)

$$\rho_{\mathrm{m}}\hbar\frac{\partial^2 w}{\partial t^2}+\rho_{\mathrm{s}}\frac{\partial^2 w}{\partial t^2}-\gamma\nabla^2 w=p_{\mathrm{i}}+p_{\mathrm{r}}+p_{\mathrm{t}} \tag{1}$$

Where h is the step function, $\boldsymbol{h}=[H(x-x_0)-H(x-x_0-l_x)]\cdot[H(y-y_0)-H(y-y_0-l_y)]$, ρ_{m} and ρ_{s} are the densities of the mass and the membrane, γ is the membrane tension; ∇ is the Laplace operator; p_{i}, p_{r}, and p_{t} are the incident, reflected, and transmitted sound pressures; $\boldsymbol{H}$ is the Heaviside function; and w is the transverse displacement of the point (x,y) on the membrane at time t. Integrating the model over the entire surface of the membrane structure and based on the orthogonality of the modal functions one can obtain equation (2)

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

Where ω is the circular frequency of the membrane; $\boldsymbol{M}$ is the matrix of film surface densities; $\boldsymbol{Q}$ is the matrix of additional masses; $\boldsymbol{K}$ is the matrix of membrane tensions; and $\boldsymbol{q}$ is the matrix of eigenvectors.

Combined with equation 2, the central additional mass vibrates with the membrane, and according to the equivalent concentration parameter method, the intrinsic frequency of the system is:

$$f=\frac{1}{2\pi}\sqrt{\frac{\boldsymbol{K}}{\boldsymbol{M}+\boldsymbol{Q}}} \tag{3}$$

Where $\boldsymbol{M}_{\mathrm{m}}$ is the mass of the mass block; $\boldsymbol{M}_{\mathrm{e1}}$ is the equivalent mass at the centre of the circle; $\boldsymbol{K}_{\mathrm{e1}}$ is the equivalent elasticity coefficient.

When the sound wave passes through the acoustic metamaterial structure, the mass block and the membrane produce a local resonance, which will achieve the sound insulation effect. From equation (3), it can be seen that compared with the membrane without the mass block, the intrinsic frequency of the acoustic metamaterial after attaching the mass block will be shifted to the low frequency. Considering the role of the mass block in the low-frequency range of sound isolation, the lead block with higher density is selected as the additional mass block of the acoustic metamaterial. When the electromagnetic field loading device is energised with a DC power supply, a uniform magnetic field is generated. Due to the magnetic force, the tension of the double-layer membrane containing carbonyl iron powder increases, and it can be seen from equation (3) that when the membrane tension matrix $\boldsymbol{K}$ increases, the acoustic metamaterial sound insulation peak moves to high frequency. Therefore, the magnetic field strength can be adjusted by changing the applied DC power supply, which in turn changes the tension of the double-layer membrane, and ultimately realises the electromagnetic tuning of acoustic metamaterial sound insulation.

III. NUMERICAL ANALYSIS

Based on the established acoustic metamaterial model, the acoustic properties of the acoustic metamaterial model were numerically analysed using COMSOL Multiphysics . The specific dimensions of the metacell structure are as follows: thickness of the bilayer membrane d = 1.1 mm, radius r = 15 mm; thickness of the aluminium frame h_1 = 4 mm, inner diameter r_1 = 15 mm, outer diameter r_2 = 17 mm; radius of the mass mass block r_3 = 4 mm, height h_2 = 4 mm. The frame of the cell is made of aluminium with density ρ = 2 700 kg/m^3, Poisson's ratio υ = 0.33, Young's modulus $\boldsymbol{E}$ = 71.0 GPa; the membrane is a double-layer silicone rubber membrane containing carbonyl iron powder, density ρ=1 800 kg/m^3, Young's modulus $\boldsymbol{E}$ =5.6 MPa, Poisson's ratio υ=0.47; the material of the mass block is lead, density ρ =11 680 kg/m^3, Young's modulus $\boldsymbol{E}$ =17.0 GPa, Poisson's ratio υ=0.42.

Figure 2 shows the acoustic transmission loss curves of the structure when the double-layer membrane is subjected to the force per unit area $\boldsymbol{F}$ = 0 N/m^2, 2 N/m^2, 4 N/m^2 and 6 N/m^2 .

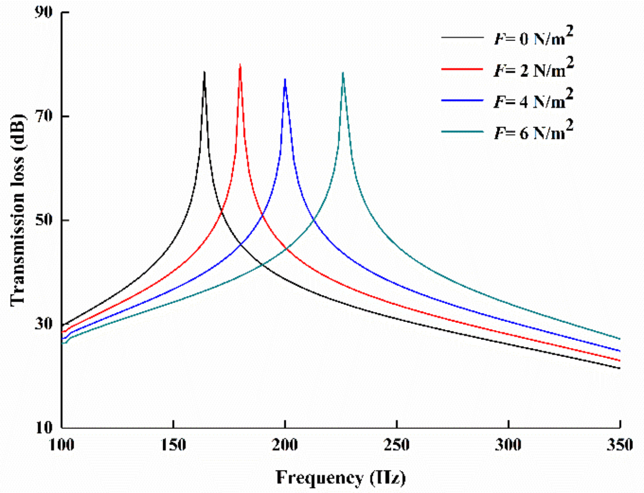

Figure 3: Frequency-transmission loss curves of structures subjected to different unit area force

As can be seen from Figure 3, with the increase of force per unit area, the sound transmission loss peak of acoustic metamaterials gradually moves to high frequency, and the width of the acoustic isolation bandgap also shows a trend of gradually becoming wider. Therefore, passing in different strengths of current, the electromagnetic loading device generates different strengths of magnetic field, and the action of the magnetic field makes the double-layer membrane tension change, so as to realise the controllable tuning of sound transmission loss peak in the low-frequency range, and broaden the sound insulation bandwidth of acoustic metamaterials.

IV. RESEARCH ON SOUND INSULATION PROPERTIES OF MATERIAL PARAMETERS

4.1 Thickness of double-layer membrane

The radius of the double-layer membrane is 15 mm; the height of the aluminium frame is 4 mm, the inner diameter is 15 mm, the outer diameter is 17 mm; the radius of the mass block is 4 mm, the height of the mass block is 4 mm, and the thicknesses of the double-layer membrane d are taken to be 0.9mm, 1.1mm, and 1.3 mm, respectively. The acoustic transmission loss of acoustic metamaterials were calculated of the double-layer membrane when subjected to different unit area force. The frequency- transmission loss curves of the structure for different membrane thicknesses were shown in Figure 4.

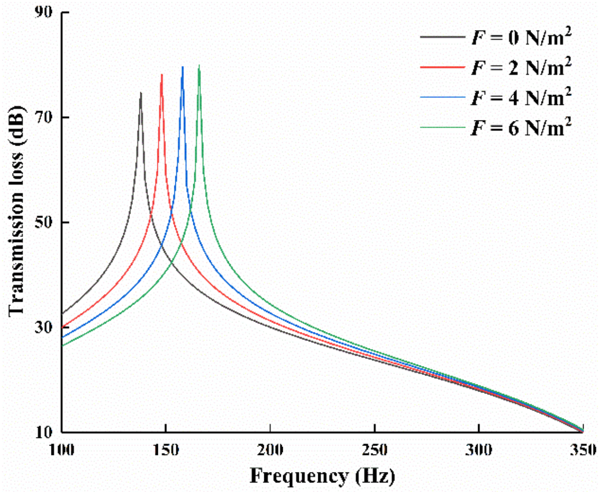

Figure 4(a): Frequency-transmission loss curves of structures with membrane thickness of 0.9 mm

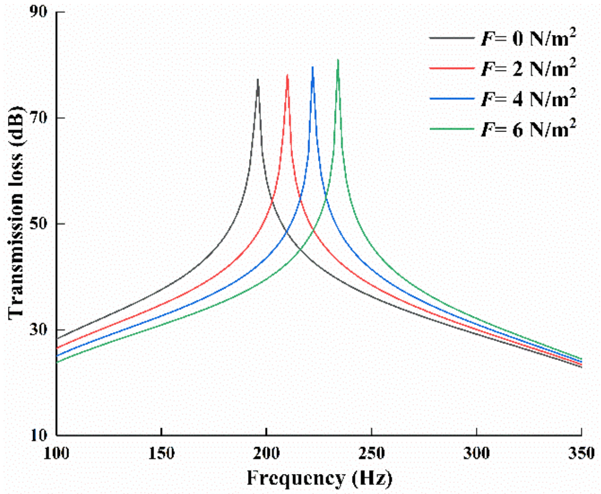

Figure 4(b): Frequency-transmission loss curves of structures with membrane thickness of 1.1 mm

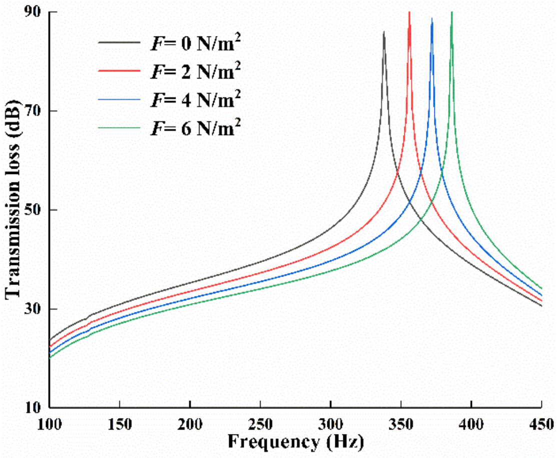

Figure 4(c): Frequency-transmission loss curves of structures with membrane thickness of 1.3 mm

From Figure 4, it can be seen that: for the double-layer membrane with thickness of 0.9 mm, with the increase of force per unit area, the acoustic metamaterials sound isolation curve gradually moves to the high frequency, and at the same time, the sound transmission loss curve gradually becomes broader, and the cumulative movement of the peak frequency of the sound transmission loss is 28 Hz; when the thickness of the double-layer membrane increased to 1.1 mm and 1.3 mm, the same trend is observed in the sound transmission loss curve, the maximum frequency of the peak frequency of sound transmission loss is increased to 40 Hz and 48 Hz, respectively.

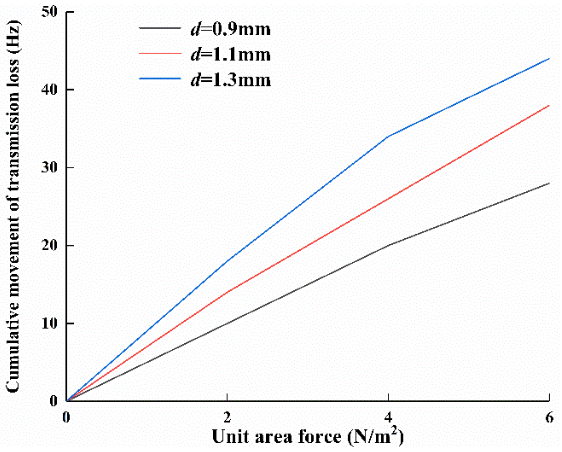

Figure 5: Unit area force-cumulative movement of transmission loss peak relationship curves of different membrane thicknesses

According to the theoretical analysis, it is known that as the thickness of the double-layer membrane increases, the membrane tension increases. According to equation (4), the stiffness matrix K affected by the membrane increases, the intrinsic frequency of the structure moves to high frequencies, while the amount of change in the peak value of the sound transmission loss will also increase. It can be seen that the sound insulation frequency of the double-layer membrane acoustic metamaterial has a good tunability.

4.2 Young's modulus of double-layer membrane

The sound transmission loss was calculated for a double-layer membrane with radius is 15 mm and thickness is 1.1 mm, and the other data parameters of the structure are the same as in **4.1**. The cumulative shifts of the sound transmission loss peak of the structure when the double-layer membrane is subjected to different unit area foece at Young's modulus ***E*** =1 MPa, 3 MPa and 5 MPa were calculated respectively, and the results were shown in Figure 6.

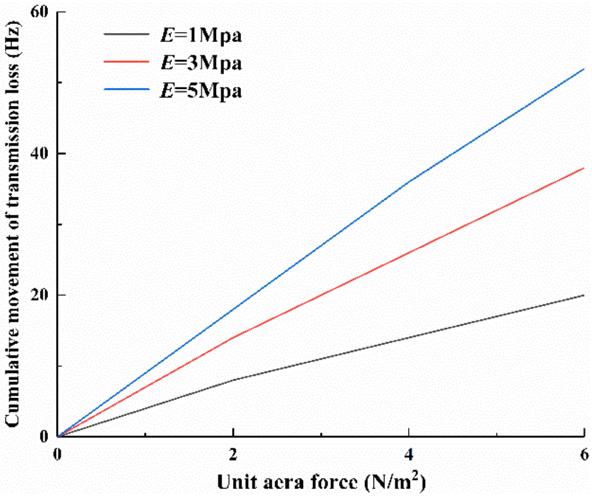

Figure 6: Unit area force-cumulative movement of transmission loss peak curves for different membrane Young's modulus

Figure 6 shows that: the Young's modulus of the double-layer membrane is 1 MPa, when the double-layer membrane is subjected to a force per unit area of 2 N/m^2, the structure of the cumulative movement of the sound transmission loss peak is 8 Hz, when the force per unit area is increased to 6 N/m^2, the cumulative movement of the sound transmission loss peak increased to 20 Hz; the Young's modulus of the double-layer membrane is 3 MPa, when the double-layer membrane is subjected to a force per unit area of 2 N/m^2, the cumulative movement of sound transmission loss peak is 14 Hz. When the force per unit area is increased to 6 N/m^2, the cumulative movement of sound transmission loss peak is 38 Hz; the Young's modulus of the double-layer membrane is 5 MPa, the double-layer membrane is subjected to a force per unit area of 2 N/m^2, the cumulative movement of sound transmission loss peak is 20 Hz, the force per unit area is increased to 6 N/m^2, the cumulative movement of sound transmission loss peak is 52 Hz; when the double-layer membrane is subjected to the same force per unit area, the Young's modulus is increased from 1 MPa to 5 MPa, the cumulative movement of sound transmission loss peak increases by 38 Hz. It can be seen that changing the Young's modulus of the double-layer membrane can effectively tune the acoustic insulation effect of acoustic metamaterials, and when the double-layer membrane with a larger Young's modulus is subjected to the same force per unit area in a magnetic field, the peak sound transmission loss has a greater amount of movement, which also has a greater tunable range, this is consistent with the theoretical analysis.

In conclusion, considering the sound insulation and tunability of acoustic metamaterials in the low-frequency range, the selection of double-layer membrane with thicker thickness and higher Young's modulus will have better sound insulation and active tunability in the low-frequency range.

V. CONCLUSION

In this paper, a frequency electromagnetically tunable active acoustic metamaterial with double-layer membrane was designed. Through theoretical analysis and simulation with finite element software, the sound insulation effect of the structure was analysed in detail. The results prove that the double-layer membrane with thicker thickness and higher Young's modulus will have better sound insulation and active tunability in the low-frequency range. The acoustic metamaterials designed in this paper provide an effective method for low-frequency sound isolation, which has potential applications in the direction of low-frequency vibration and noise reduction.

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