Research on Low Frequency Sound Insulation Properties of Membrane-Type Acoustic Metamaterials

Xiaokai Yin¹, Yongchao Xu² and Hongyu Cui¹,*

¹School of Naval Architecture and Ocean Engineering, Dalian University of Technology, Dalian, Liaoning 116024, China
²Marine Design and Research Institute of China, Shanghai 200011, China
*corresponding author’s e-mail: cuihongyu@dlut.edu.cn

Abstract. To solve the problem of low-frequency noise control in ship cabins, a new membrane-type acoustic metamaterial (MAM) with bulges on the surface of thin films is designed based on the characteristics of lightweight and low-frequency sound insulation of membrane-type acoustic metamaterials. The sound structure coupling module of COMSOL multiphysical field coupling software is used to analyse the sound insulation performance of MAMs. The sound insulation properties of the additional mass film and self-similar fractal convex structure are further discussed. The metamaterial structure studied in this paper has a better sound insulation effect than ordinary film, which provides strong technical support for ship cabin noise control.

1. Introduction

The radiated noise of a ship not only interferes with the work of the ship’s detection system and reduces the ship’s acoustic stealth performance, but also causes serious harm to the health of the people on board. Due to its long wavelength, slow attenuation, and longer propagation distance in the water, it is very important to achieve effective control of low-frequency ship noise.

Traditional sound insulation materials follow the law of mass action and often achieve better sound insulation effects by increasing material thickness and areal density. However, this method bears the cost of increasing the weight of the material, which is difficult to achieve for the noise protection design of a ship that requires a lightweight structure and a compact space. Because the structure of acoustic metamaterials breaks through the limitation of the law of mass action, special thin-film acoustic metamaterials have the advantages of light weight, small size and flexible layout, and exhibit good sound insulation performance in the low frequency range, which has become a hot research topic [1-2]. In 2008, at Hong Kong University of Science and Technology, Yang et al. proposed a lightweight MAM. Through theoretical research and experimental verification, it was found that this metamaterial has better low-frequency sound insulation band gap characteristics [3]. Subsequently, researchers studied the structure of thin-film metamaterials, designed various acoustic metamaterials with different structures, and discussed their sound insulation properties [4-6]. Because the MAM has excellent performance in the field of low-frequency sound insulation and vibration reduction, it provides a new way to solve the problem of low-frequency vibration and noise reduction of ship structures.

In this paper, based on ordinary MAMs, a new type of thin-film metamaterial structure is designed by adding convex structures on the surface of the membrane, and the change law of the sound transmission loss (STL) of the metamaterial under different structural parameters is discussed.
2. Samples and methods

2.1. Cell structure design
As shown in figure 1, the film is a square with a side length of $l$ and a thickness of $t_l$, to add a well-shaped bulge on the membrane with a side length of $a$ and a height of $h$.

Figure 1. Mode of cell structure. (a) Top view of the cell; (b) Side view of the cell.

2.2. Calculation method
According to the structural size and parameter characteristics of the MAM, the modal superposition method is used to calculate the sound insulation performance of the structural unit [7]. The equation of motion of the film structure with protrusions on the surface is

$$\rho_i \frac{\partial^2 \omega}{\partial t^2} + \rho_{\text{mass}} h(x,y,x_0,y_0,l_x,l_y) \frac{\partial^2 \omega}{\partial t^2} - TV^2 \omega = p_i + p_r + p_t$$

(1)

Where $\rho_i$, $\rho_{\text{mass}}$, $T$, $p_i$, $p_r$, $p_t$ represent the surface density of the film, the surface density of the convex mass, the film tension, the incident sound pressure, the reflected sound pressure, and the transmission sound pressure.

$$h(x,y,x_0,y_0,l_x,l_y) = \left[ H(x-x_0) - H(x-x_0-r) \right] \left[ H(y-y_0) - H(y-y_0-r) \right]$$

(2)

$$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}$$

(3)

where $H$ is the Heaviside function (step function), and $\omega(x,y,z)$ is the lateral displacement of a point $(x,y)$ on the film at time $t$ [8].

According to the modal superposition theory,

$$\omega(x,y,z) = \sum_{n=1}^{N} W_n(x,y) q_n(t) \quad q_n(t) = \tilde{q}_n e^{i\omega t}$$

(4)

where $W_n$ and $q_n$ are the mode shape and coordinates.

Integrating the entire membrane can obtain the vibration equation of the membrane under the action of acoustic waves, as shown in Equation (5).

$$-\omega^2 \left[ [M] + [Q] \right] \{\tilde{q}\} + j\omega [C][\tilde{q}] + [K]\{\tilde{q}\} = 2A\{H\}$$

(5)

Solving Equation (5) can obtain

$$\{\tilde{q}\} = \frac{2A}{-\omega^2 \left[ [M] + [Q] \right] + j\omega [C] + [K]} \{H\}$$

(6)
Substituting $L_x = L_y = l$ into the transmission coefficient $t_p$, it can be expressed as

$$t_p = \frac{j^{2\rho_0 c_0} \omega}{F^2} \left\{ \begin{array}{c} \frac{1}{\omega^2 ([M] + [Q]) + j\omega [C] + [K]} \end{array} \right\}^T$$

Then, the expression of the STL of the film-type acoustic metamaterial is

$$STL = 20 \log_{10} \left( \frac{1}{t_p} \right)$$

3. Result analysis

3.1. STL of MAMs

This study uses COMSOL Multiphysics 5.4 finite element software to numerically simulate the sound insulation of the metamaterial cell structure. The silicone rubber film ($l=30\text{mm}, t=0.2\text{mm}$) was applied at a $200\text{N/m}$ pre-pressure. The silicone rubber well-shaped bulge ($a=4\text{mm}, h=0.5\text{mm}$) was firmly attached to the membrane with a quality of $0.41\text{g}$. The frame was made of aluminium, and the corresponding material parameters of each material are shown in table 1. The finite element model is composed of MAM elements and air domains on both sides. Among them, the solid frame structure is surrounded by fixed constraints, and a displacement constraint is set between the membrane and the solid frame. One side of the air domain is set as the background pressure field, and the sound pressure amplitude is set to $1\text{ Pa}$, which is perpendicular to the surface of the film. The outermost part of the air domain is set as a perfect matching layer to eliminate the influence of sound wave reflection on the result. The remaining peripheral boundary conditions are uniformly set as hard sound field boundary conditions. The calculated sound insulation curve of the metamaterial structure in the range of $50$–$2000\text{Hz}$ is shown in figure 2.

| Parameters | Material     | Density($\text{kg} \cdot \text{m}^{-3}$) | Elastic Modulus(Pa) | Poisson’s ratio |
|------------|--------------|-----------------------------------------|---------------------|----------------|
| Film       | Silicone Rubber | 980                                    | $2 \times 10^5$     | 0.49           |
| Frame      | aluminum     | 2730                                    | $6.9 \times 10^{10}$| 0.33           |

Figure 2 shows that adding a convex structure on the surface of the ordinary film can improve the sound insulation effect of the structure in the low frequency range. The ordinary membrane structure has
3.2. The effects of the membrane properties and bulge configurations

Among the MAMs, the elastic membrane is an important part that affects the sound insulation effect of the material. Therefore, to study the change law of the sound insulation of the MAM, the membrane pre-pressure and the thickness of the membrane were changed to perform numerical calculations. The calculated sound insulation curve of the metamaterial structure is shown in figure 3.

![Figure 3](image)

**Figure 3.** Relationship of STL with film parameters. (a) STL curves of various membranes’ prestress; (b) STL curves of various membranes’ thickness.

Figure 3(a) calculates the STL curves of the film when the film prestress gradually increases from 200N/m to 500N/m. As shown in figure 3(a), with the gradual increase in the prestress of the film, the centre frequency corresponding to the STL peak of the material moves to high frequency, and the sound insulation capacity and the STL bandwidth gradually increase. Figure 3(b) explores the influence of the film thickness on the sound insulation performance of the film when the film thickness is gradually increased from 0.1mm to 0.4mm. With the gradual increase in the film thickness, the entire STL volume curve moves in the low frequency direction, and the STL volume gradually increases. Therefore, by increasing the film thickness, a better low-frequency sound insulation effect can be obtained, and in practical applications, the film weight is lighter, and increasing the film thickness does not significantly increase the quality of the metamaterial.

The convexity of the film surface designed in this paper is equivalent to adding mass to the surface of the film, so the quality and distribution of the convex structure also affects the sound insulation performance of the metamaterial. To further study the change law of the sound insulation of the MAM, the quality and distribution of the protrusions on the surface of the membrane were changed to perform numerical calculations. The calculated STL curve of the metamaterial structure is shown in figure 4.
Figure 4. Relationship of the STL with the parameters of the bulge. (a) STL curves of various bulges’ thickness; (b) STL curves of various bulge distributions.

Figure 4(a) explores the influence of the quality of the bulge on the sound insulation performance of the acoustic metamaterial. The height of the bumps is gradually increased from 0.3mm to 0.9mm. Comparing the curves in the figure shows that as the quality of the bulge increases, the STL curve of the material shifts in the low-frequency direction. Figure 4(b) explores the influence of different distributions on the sound insulation performance of the metamaterial structure without changing the quality of the bulges. The basic structure is shown in figure 5. Comparing the STL curves shows that under the same quality condition, the sound insulation effect of Sample I is better. There are two STL peaks near 960Hz and 1500Hz, the maximum STL reaches 50.2dB, and the STL bandwidth is significantly increased.

Figure 5. Basic structure of the film surface bulge under different distributions

3.3. STL of additional mass film
This section studies the sound insulation characteristics of the additional mass film. To add the mass distribution on the membrane, a 2mm-thick mass block with a diameter of 5mm was attached to the membrane. It is made in a neodymium iron boron magnet with a density of 7400kg/m³, a modulus of elasticity of 1.61011Pa and a Poisson’s ratio of 0.28. The different placement positions of the mass blocks are shown in figure 6(a), and the calculated sound insulation curve of the metamaterial structure is shown in figure 6(b).
The tic-tac-toe structure divides the film into nine regions. The three points a, b, and c are the intersection points of the diagonals of the respective rectangular regions, and point a is the centre point of the film. As shown in figure 6(b), the first STL peak without a mass block appears near 1170Hz, and the maximum STL is 43.5dB. When the mass is added, a new STL peak appears at 330Hz, and the maximum STL reaches 51.5dB, which greatly improves the low-frequency sound insulation effect of the metamaterial. In addition, when the mass is located at centre point a of the film, the STL bandwidth and STL peak of the metamaterial at approximately 330Hz are optimal, and the frequencies corresponding to the second and third STL peaks move to high frequencies. When the mass block is located at two points b and c, except for the addition of a new STL peak at 330Hz, the STL curve above 500Hz basically coincides with that without a mass block. Therefore, it can be concluded that in the low frequency range below 500Hz, the additional mass film has better sound insulation performance than the massless film, and the metamaterial has the best low frequency sound insulation effect when the mass is located at the centre point.

3.4. Design of convex structure based on Hilbert fractal curve

The fractal structure has multiscale self-similarity, which can effectively broaden the frequency band of metamaterials and improve space utilization. The Hilbert fractal curve is the most widely used and ideal fractal structure in acoustic metamaterials. Figure 7 shows the basic structure of the first- to third-order film surface protrusions based on the Hilbert fractal design. To ensure the constant quality of the bumps, the widths of the first- to third-order bump structures are designed to be 4 mm, 2 mm, and 1 mm. The calculated sound insulation curves are shown in figure 8.
Comparing the STL curves of the fractal structure and the ordinary well-shaped structure shows that the fractal structure has more STL peaks in the same frequency range. Due to the self-similarity of the Hilbert fractal curve, the structure has more resonance modes. Comparing the first-order, second-order, and third-order STL curves of the fractal structure under three different orders shows that the second-order fractal structure has the most STL peaks, but the peak is smaller, and it cannot produce a better sound insulation effect. The first-order fractal has four STL peaks in the frequency range of 1,000–2,000Hz, and the STL peaks basically reach 40dB, which has a good broadband sound insulation effect. This self-similarity fractal structure can provide a new idea for broadening the frequency band of acoustic metamaterials.

4. Conclusion
Based on the lightweight and low-frequency sound insulation characteristics of MAMs, a new type of MAM with protrusions is designed that could be used for noise protection in ship cabins. The acoustic-structure coupling module of COMSOL software is used to analyse the influence of the metamaterial structure and its parameter changes in film prestress, film thickness, protrusion quality and protrusion structure distribution on its sound insulation performance. The STL performance of the additional mass film and the self-similar fractal convex structure are further discussed. The results of this paper provide powerful technical support for ship cabin noise control.

References
[1] Bolton J S, Shiau N M and Kang Y J 1996 Sound transmission through multi-panel structures lined with elastic porous materials. *Journal of Sound and Vibration*, **191**(3) 317-347.
[2] Wu J, Ma F, Zhang S, et al. 2016 Application of acoustic metamaterials in low frequency vibration and noise reduction. *Journal of Mechanical Engineering* **52**(13) 68-78.
[3] Yang Z, Mei, Yang M, et al. 2008 Membrane-Type Acoustic Metamaterial with Negative Dynamic Mass *Physical Review Letters* **101**(20) 204301.
[4] Cui H, Du Y and Wang H 2021 Analysis of sound insulation characteristics of acoustic metamaterial structures with different shaped masses Ship science and technology **43** (05) 33-36.
[5] Guo L, Zhang J and Zeng H. 2020 The numerical study of sound Insulation performance of membrane acoustic metamaterial cell with variable thickness. Ship science and technology **42**(01) 38-42.
[6] Lin G, Chen S, Yuan X and Tan H 2016 Transmission loss of thin membrane-type acoustic metamaterials with multi-masses *Int. Conf. on Innovative Material Science and Technology (IMST2016)* (Shenzhen, China)
[7] Zhang J, Yao H, Du J, et al. 2016 Analysis of the Sound Insulation Properties of Membrane-type Acoustic Metamaterial Plate Journal of Synthetic Crystals 45(10) 2549-2555

[8] Zhang Y, Wen J, Xiao Y, et al. 2012 Theoretical investigation of the sound attenuation of membrane-type acoustic metamaterials Physics Letters A, 376(17) 1489-1494.