Research on the Design of Sound Insulation Performance of Isolating-sound and decoupled tile Based on Local Resonance Membrane Material

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Abstract. In order to enhance the acoustic stealth performance of the underwater vehicle, we combine the resonance sound absorption and vibration suppression performance of the sound-absorption coating and the low frequency sound insulation performance of the local resonance membrane material, a new type of isolating-sound and decoupled tile with low-frequency sound insulation, sound absorption and vibration suppression performance is designed, and an acoustic enclosure composed of isolating-sound and decoupled tile is established. Research shows: the isolating-sound and decoupled tile cell has good sub-wavelength sound insulation ability, and the average sound insulation in the 100-1000Hz frequency band is 47dB. The acoustic enclosure composed of it can effectively isolate the reverberation sound field in the enclosure. Compared with the acoustic enclosure composed of Alberich sound-absorption coating, the average sound insulation has been increased by about 19dB.

1. Introduction
In terms of underwater acoustic stealth, due to processing and manufacturing problems, the operation of the rotating machinery inside the underwater vehicle will inevitably produce periodic low-frequency vibrations, which will cause the underwater vehicle to radiate low-frequency sound waves. Low-frequency sound waves travel far in the water and are easily detected by enemy low-frequency sonar, making the low-frequency radiation noise of underwater vehicles a key issue that restricts their concealment and combat performance. And the most commonly used acoustic stealth technology-sound-absorption coating are mostly in the frequency range of 1k-30kHz, which has gradually been unable to meet the low-frequency sound insulation needs of underwater vehicles. The research on local resonance membrane materials provides a new design idea for underwater low-frequency sound insulation. As an artificial acoustic structure, it is composed of an additional rigid mass on the membrane. Through the reverse resonance of the membrane-mass, the high-efficiency absorption of sound waves below 1kHz is achieved.

The isolating-sound and decoupled tile designed in this paper is laid on the inner surface of the underwater vehicle shell to reduce the radiated noise of the hull and enhance its acoustic stealth performance. This tile combines the vibration-damping and sound-absorbing performance of the acoustic coating and the low-frequency sound insulation performance of the local resonance membrane material. This paper firstly studies the acoustic characteristics of isolating-sound and decoupled tile cells through numerical analysis. In order to simulate and calculate the sound insulation
ability of isolating-sound and decoupled tile when they are laid inside the shell of an underwater structure, it is composed of an acoustic enclosure, and its sound insulation characteristics are calculated.

2. Design of isolating-sound and decoupled tile

2.1. Design ideas

At present, the sound-absorption coating on underwater vehicles is mainly an acoustic structure made of porous polymer viscoelastic materials. One of the most representative structures is a synthetic rubber sound insulation material called "Alberich" developed by Germany in the late World War II. Its thickness is about 4mm, and there are periodically distributed cylinders cavities with a diameter of 2~5mm. The cylindrical cavity can enhance the resonant sound absorption of the sound-absorption coating, and when laid on the shell, it is equivalent to a layer of free damping structure, which can suppress the elastic wave to a certain extent, and increase the flexural vibration damping of the shell, so that the acoustic radiation of the hull structure is reduced. When local resonance membrane materials are excited by low-frequency sound waves, the membrane and the mass will resonate to form a "spring-mass" vibration absorber system. When the membrane is deformed, a large amount of elastic wave energy will be dissipated, and the sound absorption effect is remarkable in the low frequency band. Combining the two structures into isolating-sound and decoupling coating, the basic principle of reducing the self-noise intensity of the underwater vehicle is shown in Figure 1.

![Figure 1. The mechanism of Isolating-sound and decoupled tile reducing the Submarine noise](image)

When the mechanical noise $p_i$ of the underwater vehicle is incident on the local resonant thin film material, part of the sound wave is absorbed, and the reflected sound wave $p_1$ and the transmitted sound wave $p_2$ are generated simultaneously. After the transmitted sound wave $p_2$ reaches the surface of the sound-absorption coating, part of it will be reflected on the local resonance membrane material for "secondary absorption", and part of it will be gradually lost and attenuated when propagating in the cover layer, and reflection and transmission will occur at the boundary of the shell. Due to the impedance mismatch between the sound-absorption coating and the hull, the sound waves can be reflected back into the sound-absorbing cover layer to the maximum. The sound waves reflected from the shell once again experience the loss and absorption of the sound-absorption coating and the local resonance membrane material, and a small amount of sound waves are reflected to the shell. By analogy, the sound wave passing through the submarine shell is the superposition of the transmitted wave after multiple losses and sound absorption.
2.2. Sound insulation performance calculation method

The evaluation of the sound insulation performance of the isolating-sound and decoupled tile can be described by the transmission loss, that is, $TL = 10 \log (1/\tau)$, Where $\tau$ is the sound pressure transmission coefficient. The transmission coefficient $\tau$ of the acoustic decoupled tile structure can be expressed as the ratio of the transmission coefficient of the local resonance element and the sound-absorption coating element $t_1/t_2$. When a plane wave is perpendicular to the surface of a locally resonant membrane materials, the forced vibration equation of the membrane can be expressed in matrix form.

$$-\omega^2 \left[ [M] + [Q] \right] [W] + j\omega [C][W] + [K][W] = 2A[F]$$

Where $[M]$ and $[Q]$ are the stiffness matrices of the membrane and the mass, respectively, $[C]$ is the damping matrix, $[K]$ is the tension matrix of the membrane, $[F]$ is the acoustic pressure excitation matrix, and $A$ is the incident sound pressure amplitude. The transmission coefficient of local resonant membrane can be obtained by the transmission and incident sound pressure.

$$t_1 = \frac{\left\langle \hat{F} \right\rangle}{Ae^{\omega t}} = \frac{2j\rho_s c_a \omega \left\langle F \right\rangle^T}{-\omega^2 \left[ [M] + [Q] \right] + j\omega [C] + [K]}$$

In formula 2, $\rho_s$, $c_a$ denote the density and sound velocity of air respectively, and $l_x$, $l_y$ denote the width and length of the membrane.

The low-frequency resonance of the cavity of the sound-absorption coating is similar to the Minnaert resonance, in which the cavity resonance frequency is expressed as

$$\omega_0 = \frac{1}{a} \sqrt{\frac{3\beta_s + 4\mu}{\rho}}$$

Where $\beta_s$ is the volume modulus of the cavity, $\mu$ and $\rho$ are the shear modulus and density of the elastic medium, and $a$ is the cavity radius. The coupling between cavities and the influence of shear wave in elastic medium need to be taken into account when calculating the transmission coefficient of sound-absorption coating, so a simple model is established to calculate the transmission coefficient.

$$t_2 = 1 + \frac{iKa}{\omega^2} - I - i(\delta + Ka)$$

Where, $K = 2\pi / (kd^2)$, $I = 1 - Ka \sin (kd / \sqrt{\pi})$, $k$ is the wave number, $\omega$ is the incident wave angular frequency, and $\delta$ is the dissipative damping constant. The transmission coefficient and sound insulation quantity of the isolating-sound and decoupled tile can be obtained.

3. Numerical results and discussion

According to the design idea of isolating-sound and decoupling, the finite element model of its cell is established, and its sound isolation performance is analysed. As shown in figure 2, The shell is a square steel material with a thickness of 1mm and a side length of 30mm. the Alberich sound-absorption coating with a thickness of 4mm was laid on the shell, the base material of the sound-absorption coating was PDMS (polydimethylsiloxane), inside the sound-absorption coating, a cylindrical cavity with a radius of 1mm or 2mm and a height of 2mm is periodically distributed, the bottom of the cavity is in contact with the shell. The thickness of the membrane is 0.2mm and the radius of the mass is 6mm. In order to
ensure that the membrane material can have resonance insulation under acoustic excitation, there is an air layer with a thickness of 1mm between the sound-absorption coating and the local resonance unit. Figure 3 shows a sectional view of the Alberich sound-absorption coating.

Through the analysis of the sound insulation performance of an isolating-sound and decoupled tile cell, the sound propagation loss curves of local resonance unit, sound-absorption coating unit and isolating-sound and decoupled tile cell in figure 4 are obtained. As shown in figure 4(a), the local resonance unit is affected by the membrane-mass local resonance. There are three sound insulation peaks at 260Hz at 380Hz and 880Hz. The corresponding sound insulation is 34dB, 18dB, 14dB, and the average sound insulation is 9.7dB in the 100-1000Hz frequency band, which can achieve effective sound insulation in the 210Hz-410Hz frequency band. In figure 4(b), the impedance of the sound-absorption coating is very different from that of the steel shell, the impedance mismatch leads to very little sound wave passing through the steel shell, the transmission coefficient is correspondingly small, and the average sound insulation reaches 44dB. It can be seen in figure 4(c) that the combination of Alberich sound-absorption coating unit and local resonance unit has strong sound insulation ability, and the appearance of sound insulation peaks and valleys reflects the characteristics of local resonance sound absorption. In the frequency band of 100-1000Hz, the lowest sound insulation is as high as 45dB, and the average sound insulation is 47dB, which increases 3dB compared with Alberich sound-absorption coating.

Figure 2. Finite element model of isolating-sound and decoupling coating.  
Figure 3. Schematic diagram of Alberich sound-absorption coating

Figure 4(a). The transmission loss of local resonance unit  
Figure 4(b). The transmission loss of sound-absorption coating
Figure 4(c). The transmission loss of isolating-sound and decoupling coating

The previous calculations on the sound insulation performance of isolating-sound and decoupled tile reflect the sound insulation performance of a single plane sound wave. The following is a simulated isolating-sound and decoupled tile’s ability to isolate sound waves when it is laid inside the shell of an underwater vehicle, which is formed into an acoustic enclosure. Place an ideal point sound source with $P_{rms} = 1W$ at the midpoint of the sound acoustic enclosure. And use the insertion loss to analyse the sound insulation performance of the acoustic enclosure. IL (Insertion Loss) represents the difference in sound pressure level at a certain distance from the sound source before and after the acoustic enclosure is installed, that is $IL = L_{w1} - L_{w2}$, here $L_{w1}$ and $L_{w2}$ respectively represent the sound pressure level of the same measuring point before and after the acoustic enclosure is installed. Since the six sides of the rectangular acoustic enclosure have the same structure, it can be predicted that the sound pressure level of the spherical surface at the same distance from the sound source point is approximately the same, that is, only the field point (50, 0, 0). Figure 5 shows the insertion loss of the acoustic enclosure composed of the isolating-sound and decoupled tile and the Alberich sound-absorption coating at the field point (50, 0, 0).

Figure 5(a). The Insertion loss of Alberich sound-absorption coating composed of an acoustic enclosure.

Figure 5(b). The Insertion loss of isolating-sound and decoupled tile composed of an acoustic enclosure.

As shown in Figure 5(a), the acoustic enclosure composed of Alberich sound-absorption coating has a small change of the overall insertion loss curve within the frequency range of 100-1000Hz, the overall sound insulation is above 55dB, and the average sound insulation is 56.8dB. Figure 5(b) is the insertion
loss of the acoustic enclosure composed of isolating-sound and decoupling coating. The curve also reflects the local resonance sound absorption characteristics of the local resonance membrane material. The sound insulation peak appears at a frequency of 414 Hz, and the sound insulation is up to 82 dB. The average sound insulation is 75.9 dB. Compared with the sound insulation of the acoustic enclosure composed of Alberich sound-absorption coating, the sound insulation performance is significantly enhanced.

To sum up, the sound insulation curve of the isolating-sound and decoupled tile reflects the high reflection and low transmission performance caused by the impedance mismatch between the sound-absorption coating and the shell, and the local resonance sound absorption characteristics of local resonance membrane materials. In the frequency band of 100-1000Hz, the lowest sound insulation is as high as 45dB, and the average sound insulation is 47dB. The acoustic enclosure composed of isolating-sound and decoupling coating, compared with the sound insulation cover composed of Alberich sound-absorption coating, has an average sound insulation increase of about 19dB, the low-frequency sound insulation performance has been enhanced, which can achieve effective sound absorption and isolation of the reverberant sound field in the acoustic enclosure.

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