Analysis of Sound Insulation Mechanism and Optimization Design of an Acoustic Coating Layer with Multi-section Cylindrical Cavities

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Abstract. Introducing the insulation layer is an effective way to reduce sound radiation from underwater structures. Impedance mismatch properties between water and layer is closely related to sound insulation performance. Finite element method with COMSOL is used to calculate sound insulation loss in this paper. In order to investigate the insulation mechanisms of coating layer embedded with multi-section cylindrical cavities, the coating layer is approximated to a homogeneous layer with equivalent material properties. The results show that acoustic coating layer with multi-section cylindrical cavities, which causes a higher impedance mismatch has a better sound insulation performance than cylindrical cavity acoustic coating layer of the same cavity volume. The coating layer with optimized multi-section cylindrical cavities structure has obvious sound insulation advantages in the range of 200Hz to 4000Hz. Finally the theoretical analysis is verified by experiments.

1. Introduction
Sound insulation of underwater structures is generally achieved by introducing an acoustic coating layer with acoustic unit. The coating layer is used to establish an acoustic barrier between underwater target and water, reducing sound waves radiating into the water. There are various types of acoustic unit could be used to reduce the radiated noise. Ivansson S M [1] studied acoustic properties of Alberich coating with superellipsoidal cavities of mixed size. Huang[2], Tao[3] analysis acoustic transmission characteristics of coating layer on both sides of the shell. Most of the papers mainly focus on the study of acoustic insulation characteristics of the coating layer embedded with cavities, but lack of analysis of its low frequency sound insulation characteristics and mechanism. This paper draws on the multi-scale cavity design idea, design a multi-section cylindrical cavity structure[7-9], and studies its sound insulation characteristics by finite element simulation method, and reveals its sound insulation mechanism by equivalent parameter method. On this basis, the differential evolution optimization algorithm is used to optimize the cavity structure, and the cavity structure with good low-frequency sound insulation effect is obtained.
2. Model
The sound insulation coating which consisted of rubber matric and cavities periodically distributed in the rubber is studied in this paper. For an infinite periodic structure, one cell can be selected for analysis. Figure 1 is the schematic diagram of insulation coating model. Figure 2 is the three-dimensional finite element model of one cell. The lattice constant of the cell is a. The coating is attached to a 10mm thick steel backing. The model is infinite in the x direction. The upper and lower ends of the model are semi-infinite waters. Sound waves are incident vertically from the upper waters. Periodic boundary conditions are set on four sides of the cell. The material parameters involved in the model are shown in Table 1.

![Figure 1. Schematic diagram of insulation coating model.](image1)

![Figure 2. Three-dimensional finite element model of one cell.](image2)

| Material | Density/kg·m³ | Young modulus/Pa | Poisson’s ratio | Loss factor              |
|----------|----------------|------------------|----------------|-------------------------|
| rubber   | 1136.6         | 3.83+1.23×f^{0.4551} | 0.497          | 0.5+0.2918×f^{0.1471}   |
| steel    | 7850           | 2×10^{11}        | 0.33           | 0                       |

*f is frequency of the sound waves*

3. Simulation and analysis method
In this paper, sound insulation parameter R is defined as the evaluation index of sound insulation performance, \( R = \frac{I_i}{I_t} \), \( I_i \) represents the sound intensity of the incident waves and \( I_t \) represents the sound intensity of transmitted waves. COMSOL Multiphysics is used for finite element modelling and analysis. In order to analyze the sound insulation mechanism of the coating containing cavities, it is equivalent to a uniform medium. The equivalent parameter of uniform material is obtained by the transfer matrix method based on acoustic parameter inversion, and the sound insulation mechanism is revealed by the change of equivalent parameters.

![Figure 3. Plane wave transmission model of the layer.](image3)

Figure 3 shows the coating transmission model under plane wave incidence. In the incident sound field, the sound pressure and the acoustic-solid coupling surface point velocity can be expressed as:

\[
p_i = p_i + p_r
\]
\[ v_1 = v_i + v_r \]  \hspace{1cm} (2)

In the transmitted sound field, the sound pressure and the acoustic-solid coupling surface point velocity can be expressed as:

\[ p_2 = p_i \]  \hspace{1cm} (3)

\[ v_2 = v_i \]  \hspace{1cm} (4)

As shown in equation 5, the uniform coating layer has a transmission relationship between the sound pressure and the velocity of the incident surface and the transmission surface when the acoustic wave is normally incident:

\[
\begin{bmatrix}
  p_1 \\
  v_1
\end{bmatrix}
= \begin{bmatrix}
  \cos(k_e h) & -iz_e \sin(k_e h) \\
  -i \frac{\sin(k_e h)}{z_e} \cos(k_e h)
\end{bmatrix}
\begin{bmatrix}
  p_2 \\
  v_2
\end{bmatrix}
\]  \hspace{1cm} (5)

Suppose there is a uniform coating layer. When the sound wave is incident, the reflected sound wave and the transmitted sound wave are the same as the reflected and transmitted sound wave of the layer with cavity structure, the layer with cavities can be equivalent to a uniform coating, further obtaining the equivalent impedance \( z_e \) and equivalent wave number \( k_e \) of the coating layer.

\[
z_e = -i \frac{\sin(k_e h) p_2}{v_1 - v_2 \cos(k_e h)} \]  \hspace{1cm} (6)

\[
k_e = \frac{1}{h} \arccos \left( \frac{v_2 p_2 + v_1 p_1}{p_2 v_1 + p_1 v_2} \right) \]  \hspace{1cm} (7)

### 4. Sound insulation characteristics and mechanism

The acoustic coating layer exhibits good sound insulation performance because of its acoustic unit. In order to enhance its sound insulation performance and improve the low frequency sound insulation characteristics, a multi-section column formed by three cylindrical cavities with different diameters is designed. Figure 4(a) shows four different forms of the new cavity structure. The four cavities are of the same volume and same height. Sound waves are incident from the upper end of the cavity. Figure 4(b) shows the sound insulation curves of four coating layers with multi-section cavities.

![Figure 4](image)

**Figure 4.** (a) Different types of multi-section cavity. (b) Sound insulation curve of a layer with different multi-section cavities.
It can be seen from figure 5 that when the diameter of the cavity at the incident end of the sound wave is large, the sound insulation performance in the low frequency band is good, and when the diameter of the intermediate cavity is the smallest, the sound insulation performance in the high frequency band of the cavity is good. Therefore, for a multi-section cavity structure in which three cylindrical cavities are connected in series, the two ends are large, the middle is small, and when the sound waves are incident from the large end of the diameter, the sound insulation performance is better in the entire research frequency band.

In order to reveal the sound insulation mechanism of a layer with the multi-section cylindrical cavities, the equivalent parameters of the layer is obtained by the equivalent parameter method. Define the impedance mismatch ratio as \( L = \left| \frac{Z_e - Z_0}{Z_0} \right| \), \( Z_e \) is the equivalent impedance of the sound insulation coating and \( Z_0 \) is the acoustic impedance of the water. The acoustic impedance of water and uniform rubber is the same. The greater the impedance mismatch ratio, the better the sound insulation performance of the coating layer.

The impedance mismatch ratio and the real part of equivalent sound velocity of the coating layer with multi-section cylindrical cavities and cylindrical cavities, which of the same volume and same height, are compared respectively. It can be seen from figure 5(a) that the impedance mismatch ratio of the multi-section cylindrical cavity coating layer is higher than that of the cylindrical cavity coating layer, the multi-section cylindrical cavity makes the coating layer increase the reflection of sound waves. It can be seen from figure 5(b) that the real part of the equivalent sound velocity of the matrix material is significantly reduced after the cavity is introduced, and the value of the multi-section cylindrical cavity coating layer is smaller. If the real part value of the equivalent sound velocity is small, the dissipation effect of the coating layer on the sound wave is stronger. Therefore, the multi-section cylindrical cavity coating layer improves the sound insulation performance of the coating layer by the combination of reflection and absorption.

5. Cavity structure optimization design and experimental verification
Through the above analysis, the coating layer with multi-section cylindrical cavities has better sound insulation performance than the layer with cylindrical cavity cover of the same volume. In order to obtain a multi-section cavity structure with better sound insulation effect, a differential evolution algorithm is used to optimize the cavity structure.

In this paper, the optimization goal is the transmission coefficient, and the diameter and height of three small cylindrical cavities are optimized parameters. The total volume and height of the cavity remains the same when optimized. Figure 6 shows the size diagram of the optimized model. The total volume of the cavity can be expressed as \( \pi r_1^2 h_1 + \pi r_2^2 h_2 + \pi r_3^2 h_3 = \pi R^2 h_c \). \( R \) represents radius of...
To reduce the number of optimization parameters, define parameter \( a = \sqrt{\frac{R^2 h_c}{h_1}}, \) \( b = \sqrt{\frac{R^2 h_c}{h_2}}, \) \( c = \sqrt{\frac{R^2 h_c}{h_3}}, \) so \( r_1 = a \cos \phi, \) \( r_2 = b \sin \phi \sin \theta, \) \( r_3 = c \sin \phi \cos \theta, \) then 6 optimization parameters can be converted into 4 optimization parameters. Table 2 shows the optimized parameters and their value ranges, and the optimal results are shown in the table 3.

Table 2. Optimization parameter table.

| optimize parameters | content | value range |
|---------------------|---------|-------------|
| \( p_1 \)           | \( h_1/h_c \) | (0.2, 0.8) |
| \( p_2 \)           | \( h_2/(h_c - h_1) \) | (0.2, 0.8) |
| \( p_3 \)           | \( \phi \) | \( \frac{\pi}{6}, \frac{3\pi}{8} \) |
| \( p_4 \)           | \( \theta \) | \( \frac{\pi}{6}, \frac{3\pi}{8} \) |

Table 3. Optimization result table.

| optimize parameters | \( r_1 \) | \( r_2 \) | \( r_3 \) | \( h_1 \) | \( h_2 \) | \( h_3 \) |
|---------------------|---------|---------|---------|---------|---------|---------|
| result(mm)          | 13.4    | 5.7     | 1.2     | 5.6     | 4.8     | 17.9    |

The optimized structure is shown in the figure 7(a). It can be seen from the results that the optimized cavity is a large two-headed structure with a small intermediate structure, and the cavity diameter of the acoustic wave incident surface is large. It can be seen from the sound insulation curve before and after optimization that the optimized multi-section cylindrical cavity has better sound insulation performance in the range of 200Hz~10kHz than the cylindrical cavity model under the same volume. The optimized structure has a sound insulation peak around 1.65 kHz, and the sound insulation advantage is obvious in the range of 200 Hz to 4 kHz.

In order to verify the reliability of the theoretical results, two experimental samples of cylindrical cavity and multi-section cavity were prepared and tested in a hydroacoustic tube. The experimental results are shown in figure 8.
Figure 7. (a) Schematic diagram of optimized structure (b) Sound insulation curve of layer with structure before and after optimization. (The dash line represents the layer with cavities before optimization, and the solid line represents the layer with cavities after optimization.)

Figure 8. The sound insulation curve of layer with structure before and after optimization under 0.1 MPa(a) and 1 MPa(b). (The dash line represents the layer with cavities before optimization, and the solid line represents the layer with cavities after optimization.)

The sound insulation properties of the two kinds of cavity-type coverings under normal pressure and 1.0 MPa were compared. It can be seen that under normal pressure, the multi-section cavity has obvious sound insulation advantages in the low frequency range. When the pressure is increased, the sound insulation performance of the two cavity covering layers is decreased, but the sound insulation of the multi-section cavity is still higher than that of the cylindrical cavity covering layer.

6. Conclusion

Based on comsol finite element software, the sound insulation characteristics of multi-section cavity cover are analyzed. Firstly, the simplified model is verified. The equivalent parameter method is used to analyse that the multi-section cylindrical cavity cover layer has a special structure of the cavity, so that the cover layer has stronger reflection and absorption of sound waves, and the final transmitted sound wave is much lower than the same volume of the cylindrical space. Furthermore, the differential structure algorithm is used to optimize the cavity structure, and the optimal multi-section cavity structure is obtained. Finally, the results of theoretical analysis were verified by experiments.

References
[1] Ivansson S M. Numerical design of Alberich anechoic coatings with superellip soidal cavities of mixed sizeds[J].Journal of the Acoustic Society of America,2008,124(4):1974~1984.
[2] Huang ling zhi, Xiao yong, Wen jihong, Yang haibin, et al. Analysis of decoupling mechanism of an acoustic coating layer with horizontal cylindrical cavities[J].Acta Phys. Sin. 2015,64(15):154301.
[3] Tao meng. Sound insulation performance of viscoelastic coating which contains horizontal distributed cylindrical holes [C]. International Conference on Materials Engineering and Industrial Applications. Hong Kong. 2015:9-14.

[4] Li jingru. Band-gap structure design for reducing vibration and sound and topology optimization of anechoic coating[D]. Dalian University of Technology, China. 2018.

[5] Panigrahi S N, Jog C S, Munjal M L. Multi-focus design of underwater noise control linings based on finite element analysis[J]. Applied Acoustics. 2008, 69(12): 1141-1153.

[6] Zhao dan, Zhao honggang, et al. A method of enhancing low-frequency and bandwidth of absorption of coatings with cavities[J]. The sixteenth conference on underwater ship noise. 2017, 549-553.

[7] Zhao yingkun, Sheng meiping, Wang chaojie, et al. Sound insulation properties of underwater honeycomb truss structures[J]. Mechanical Science and Technology, 2006, 25(6).

[8] Ivansson S M. Anechoic coatings obtained from two and three dimensional monopole resonance diffraction gratings [J]. J. Acoust. Soc. Am, 2012, 131(4).

[9] Zhang chao, Shang dejiang, Zheng fangyuan, et al. Research on sound isolation characteristics of underwater cavity particles layer by FEM[J]. Technical Acoustics, 2017, 36(5).