Research Article

Numerical Design of Sound-Insulating Material with Combined Cavities of Mixed Sizes

Xu-wen Wang¹, Shao-wei Li², Wei Cheng¹, Jing-rui Li¹, Zhi Fang³, and Bing Wang¹

¹Luoyang Ship Material Research Institute, Luoyang 471039, China

²Bohai Shipyard Group Co. Ltd, Huludao 125004, China

³Huazhong University of Science and Technology, Wuhan 430074, China

Correspondence should be addressed to Xu-wen Wang; 31866413@qq.com

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In view of the low-frequency acoustic insulation performance and poor pressure resistance of a single cavity at present, finite element software COMSOL is used to establish an analysis model to calculate the sound transmission loss (TL) and compression performance of the sound-insulating material with combined cone cavities. The effectiveness of the numerical method is validated by comparing with the experimental results, and influence of the structural parameters of the cone cavity, the perforation, and the mixed cavity shape on the sound transmission loss is investigated.

1. Introduction

The sound absorption and noise reduction of underwater submersible have been paid great attention by many countries. At present, acoustic covering technology is the only comprehensive technology that can reduce the target intensity of underwater submersible and suppress the radiation noise of underwater submersible. In the Second World War, the German navy for the first time added a synthetic rubber soundproof material named “Alberich” [1] to the shell of the submarine, which was the earliest resonant acoustic covering with a short cylindrical cavity.

After half a century of development, the resonator cavity has been spherical, conical, circular, and exponential [2–8]. At present, the underwater resonant acoustic overlay with the exponential cavity is the most widely used. Ivansson [9] compared anechoic coatings containing cylindrical holes having different cross-sectional shapes (circle, ellipse, and superellipse) and used the Markov-chain Monte Carlo method to obtain optimal solutions. Shang et al. [10] found that conical holes are superior to cylindrical holes for enhancing the sound absorption performance of anechoic layers.

Ye et al. [11] established a theoretical model to evaluate the sound absorption performance of underwater anechoic layers containing periodically distributed axial holes. Three different types of axial holes are considered: the cylindrical, the conical, and the horn-shaped one. Results obtained with full finite element simulations are used to validate the model predictions, and the effect of the hole shape at different incidence angles is studied. The results show that two new absorption peaks appear since the oblique incidence excites two horizontal modes. Among the three hole types, the horn one achieves the best absorption performance at relatively low frequencies both in normal incidence and in oblique incidence.

To explore better decoupling performance, an optimal design of acoustic coating with complex-shaped cavities is attempted by Huang et al. [12]. An analytical vibroacoustic model is developed for the prediction of the sound radiation from an infinite plate covered with an equivalent fluid layer (as a replacement of original coating) and immersed in water. Numerical examples are provided to verify the equivalent fluid model. Based on combining use of the analytical vibroacoustic model and a differential evolution algorithm, optimal designs for acoustic coatings with cavities

are conducted. A number of connected cavity structures are arranged along the thickness of the acoustic overlay so that multiple resonances of sound waves occur in multiple cavities, increasing the acoustic insulation performance of the acoustic overlay. Numerical results demonstrate that the decoupling performance of acoustic coating can be significantly improved by employing special axisymmetrical cavities as compared to traditional cylindrical cavities.

A paper published in Applied Acoustics [13] proposed a new kind of cavity structural-acoustic overlay. It was named an inverted cyathiform cavity, that is, an inverted conical structural cavity. Compared with the coating with isochoric cylindrical cavities, the optimized coating can achieve better sound absorption in low frequencies. This phenomenon is attributed to the larger pore-aperture radius of the optimized cavity than that of the cylindrical cavity. Besides, the frequency-dependent parameters of the rubber material play an important role in the broadband high absorption of the optimized coating.

In the above literature studies, many acoustic structures of acoustic overlay have been tried, but there is still a large space for optimization, and the influence of structural parameters on its sound absorption performance needs to be further analyzed and refined.

In this paper, commercially available FE code COMSOL Multiphysics is used to obtain the sound transmission loss and deformation of the sound-insulating material under a hydrostatic pressure, and a combined cavity structure is proposed. The effectiveness of the analysis method is validated by comparing with the experimental results, and the influence of the structural parameters of the cone cavity, the perforation, and the mixed cavity shape on the sound transmission loss is investigated.

2. Numerical Calculation Model

The finite element simulations are carried out by using COMSOL. Due to periodicity, a single cell is simulated using “free triangular” elements. In the “physics” section, “acoustic-elastic wave interaction” is adopted. The rubber domain is simulated by the “elastic wave” component, while the air domain in the hole as well as the external water domain are simulated by the “pressure acoustic” component.

In COMSOL, the acoustic sound tube is simulated to calculate the sound transmission loss of the acoustic cover material. In software COMSOL, the PML (perfectly matched layer) is used to model an open or infinite domain for both the elastic waves and the pressure waves, which can simulate the nonreflective boundary conditions. As the PML boundary condition is used in the simulation, the end termination is designed to unreflected sound wave energy. So, the sound pressure of the sound filed in the downstream of the setup can be explained by one hydrophone, namely, the three-hydrophone technique. Comparing with the four-hydrophone method, the model using the three hydrophones can be less time consuming. The three-hydrophone transfer function method is used in the simulation. The calculation principle of the three-hydrophone transfer

function is shown in Figure 1. The entrance sound source generates the signal. The incident wave p_i is generated by the sound source at the entrance, propagating in the incident tube. Two sound waves are formed due to the absorption of the test sample when the forward-propagating incident wave p_i encounters the test sample, and one is noted by the transmitted wave p_t , which continues to propagate forward in the transmission tube. The other is marked by the reflected wave p_r due to the reflection of the test sample, which propagates in the opposite direction in the incident tube. After reaching the acoustic end with perfect absorption performance, the sound wave at the end is completely absorbed. In COMSOL software, the PML nonreflective terminal is used to perfectly match the layer boundary conditions to simulate a completely nonreflective end.

If the measured sound pressure at the hydrophone P_1 is noted as p_1 , the measured sound pressure at the hydrophone P_2 is noted as p_2 , and the measured sound pressure at the hydrophone P_3 is noted as p_3 , the relationship between the wave sound pressure p_i , the transmitted wave sound pressure p_t , and the reflected wave sound pressure p_r with the measured sound pressures p_1 , p_2 , and p_3 can be obtained from the acoustic wave equation:

$$\begin{cases} P_1 = P_i e^{jk(S_1+L_1)} + P_r e^{-jk(S_1+L_1)}, \\ P_2 = P_i e^{jkL_1} + P_r e^{-jkL_1}, \\ P_3 = P_t e^{jk(L_2+d)}. \end{cases} \quad (1)$$

The simplified solutions of the three formulas above are as follows:

$$\begin{aligned} P_i &= \frac{P_1 - P_2 e^{-jkS_1}}{e^{jkS_1} - e^{-jkS_1}} e^{-jkL_1}, \\ P_t &= e^{-jk(L_2+d)}. \end{aligned} \quad (2)$$

The sound pressure transmission coefficient t_p is expressed by the incident wave sound pressure and transmission wave sound pressure as follows:

$$t_p = \frac{P_t}{P_i}. \quad (3)$$

The sound transmission loss of the test sample is obtained as follows:

$$TL = -20 \lg |t_p|. \quad (4)$$

In the present study, with focus placed on the representative underwater applications, the thickness of the anechoic layer l_a is fixed at 30 mm and the height of the hole l_h at 23 mm.

3. Results and Discussion

3.1. Numerical Calculation. To validate the numerical calculation model, the sound transmission loss of the underwater sound absorption coating presented in [14] is calculated and compared with the simulation results [14] and the experimental measurements provided by [15]. The

FIGURE 1: The three-hydrophone transfer function method is used in the simulation.

FIGURE 2: Validation of the simulation calculation from COMSOL.

four-hydrophone technique is used in the experiment, and the sound-absorption wedge is applied at the end of the tube to absorb the transmitted sound wave energy. The comparison of the sound transmission loss results is shown in Figure 2. The finite element simulation results of the COMSOL model agree well with the finite element simulation results in the literature, and the trend is the same as the experimental results, but there are some differences. The existence of this difference may be due to the inconsistency between the setting of the nonreflecting end in the simulation calculation and the setting during the measurement. It may also be due to the coupling effect between the underwater acoustic tube wall and the sound insulation material and the water medium in the experiment, which cannot be considered in the simulation calculation. The change of the cavity type does not affect the accuracy of the simulation calculation method. It can be verified that the sound transmission loss calculation obtained by COMSOL is credible.

3.2. Effects of the Structural Parameters on the Sound Transmission Loss. The combination of the cone cavity is designed into a combined cavity structure to calculate the sound transmission loss and deformation under pressure. A

FIGURE 3: Schematic diagram of the single cell structure of the sound insulation material with the combined cavity.

schematic diagram of the combined cavity structure is shown in Figure 3.

The influence of structural parameters on the sound transmission loss is analyzed by changing the diameter of the sound-insulating material cell and the maximum diameter of the cavity. In the analysis of this section, the diameter of the small section of the cone is taken as $d = 2$ mm, the height of the upper and lower cones is both taken as $h_1 = h_2 = 11.5$ mm, the radius of the larger section of the cone

FIGURE 4: Effect of the diameter of the sound-insulating material cell and the maximum diameter of the cavity on TL.

FIGURE 6: TL curves with different distances between two adjacent cavities.

FIGURE 5: Effect of the diameter of the sound-insulating material cell and the maximum diameter of the cavity on deformation under the hydrostatic pressure of 3 MPa.

$r_1 = 0.5d_1 = 0.5d_2$ is taken as 6 mm, 7 mm, 8 mm, 9 mm, 10 mm, and 11 mm separately, and correspondingly, the radius of the single cell of the sound insulation material is taken as 7 mm, 8 mm, 9 mm, 10 mm, 11 mm, and 12 mm, respectively. The sound transmission loss and the maximum deformation under the hydrostatic pressure of 3 MPa results are calculated with different ratios of the maximum diameter of the cavity to the diameter of the sound insulation material cell unit, and the comparison curves are shown in Figures 4 and 5, respectively.

It can be seen from Figures 4 and 5 that when the ratio of the maximum cross section of the cavity to the cross-sectional area of the unit cell is larger, the sound transmission loss of the sound-insulating material is better, the peak of the

FIGURE 7: Deformation curves with different distances between two adjacent cavities.

sound transmission loss is gradually appeared, and the peak frequency moves to the lower frequency. However, the larger the ratio of the cross-sectional area, that is, the larger the cavity perforation rate, the worse the pressure resistance of the sound-insulating material and the bigger the deformation under hydrostatic pressure. When the maximum cross-sectional radius of the cavity structure is 10 mm and the unit cell is 11 mm, the sound insulation curve peaks around 3,000 Hz.

Reducing the perforation rate of the sound-insulating material can improve the withstand voltage performance, but the sound-insulating performance is affected. On the basis of the fixed cavity volume, the maximum cross-sectional diameter of the cavity is fixed as 10 mm, and the change trend of sound transmission loss performance and compression performance of the sound-insulating material is investigated with increased unit cell volume. The changes

FIGURE 8: Structure of the sound-insulating material with the perforated combined cavity.

in the sound transmission loss curves and the deformation amount are shown in Figures 6 and 7, respectively.

It can be seen from Figures 6 and 7 that when the cavity volume is fixed, the peak value in the sound transmission loss curve shifts to the lower frequency with increased cell unit volume, and the overall sound insulation performance becomes worse. However, as the unit cell volume increases, the amount of deformation of the sound-insulating material under a hydrostatic pressure of 3 MPa becomes smaller. Therefore, the design of the cavity should balance the sound insulation performance and the compression performance, and the volume of the cavity and the distance between two adjacent cavities should be rationally designed according to the frequency range to be improved.

3.3. Effects of Perforation on the Sound Transmission Loss.

It can be known from Section 3.2 that reducing the volume of the cavity can improve the compression performance of the sound-insulating material. In order to ensure the sound transmission loss of the sound insulation material at the low

FIGURE 9: Comparison of the sound transmission loss curve between the combined cavity and the perforated combined cavity.

frequency, the combined cavity structure is changed on the basis of Figure 3. The maximum cross-sectional area of the cone cavity is not changed to ensure that the resonance peak frequency is fixed, and the volume of the combined cavity is reduced by shortening the height of the conical cavity. It is known that the smaller cavity volume can reduce the amount of sound insulation of the sound-insulating material as a whole, so it is selected to perforate the side of the sealing layer to increase the high-frequency sound insulation. The structure of the designed perforated combined cavity is shown in Figure 8. It can be seen from the comparison of the sound transmission loss curve shown in Figure 9 that the peak frequency in the sound transmission loss curve does not change when the volume of the cone cavity is reduced with the fixed maximum cross-sectional area of the cavity. The perforation is punched in the rubber material near the sealing layer, and compared with nonperforation, the peak frequency is not changed, and the sound transmission loss performance in the medium- and high-frequency range can be improved.

3.4. Effects of the Mixed Cavity Shape on the Sound Transmission Loss. On the basis of the combined cavity shape, cylindrical or conical cavities are added to the side to form a mixed cavity shape, and the sound insulation performance and compression performance are investigated. Figure 10 shows the structural schematic view and related dimensions of the perforated hybrid cavity-shaped sound-insulating materials. The calculated sound transmission loss curves are displayed in Figure 11.

In the study of this section, the fixed radius of the unit cell of the sound insulation material is $R = 15$ mm, the maximum radius of the upper and the lower cone cavity is $r = 10$ mm, the minimum cross-sectional diameter of the

Therefore, the design of the side cavity needs to balance the sound insulation performance and the pressure resistance performance and comprehensively consider the difficulty of processing.

4. Conclusions

In view of the low-frequency acoustic insulation performance and poor pressure resistance of a single cavity at present, finite element software COMSOL is used to establish an analysis model to calculate the sound transmission loss and compression performance of the sound-insulating material with combined cone cavities. The effectiveness of the analysis method is validated by comparing with the experimental results, and influence of the structural parameters of the cone cavity, the perforation, and the mixed cavity shape on the sound transmission loss is investigated.

The results show that (1) when the volume of the single cell unit of the sound insulation material is fixed, the larger the effective maximum cross-sectional area of the cavity part is, the better the sound transmission loss performance in the low-frequency range is; (2) when the effective volume of the cavity is fixed, as the volume of the sound insulation material increases, that is, the perforation rate decreases, the peak frequency in the sound transmission loss curve moves to the low frequency, and the overall sound transmission loss will be reduced; (3) with the fixed volume of the single cell unit of the sound insulation material and the effective maximum cross-sectional area of the cavity, drilling holes in the rubber material can improve the sound insulation performance in medium and high frequencies but has no effect on the sound transmission loss performance in the frequency band before the peak frequency; (4) with the fixed volume of the single cell unit of the sound insulation material and the effective maximum cross-sectional area of the cavity, a certain number of holes with small aperture around the cavity will improve the sound insulation performance at the low frequency and make the peak frequency move to the low frequency; (5) when the volume of the sound insulation material is fixed, the smaller the volume of all cavities, the better the pressure-resistant performance of the sound insulation material; and (6) the variation in the height and diameter of the side-branch holes has little influence on the sound insulation performance; however, as the height of the mixing cavity decreases, the pressure-resistant performance of the sound insulation material can be improved.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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