Research on Acoustic Transfer Performance of Power Cabin of Underwater Craft

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Abstract. In order to study the acoustic performance of underwater vehicle including vibration and noise, two kinds of structure models of an underwater craft cabin in the air medium and in the water medium were analyzed separately by finite element method. Through modal analysis, the impedance ratios of the two kinds of models were calculated. The influence of the thickness of the pressure hull on the impedance ratio of the structure was studied, and the acoustic transfer performance was analyzed and compared between the two kinds of models.

Keywords: Vibration and noise, finite element method, underwater vehicle.

1. Introduction

As people exploring the sea world deeper and further, underwater craft becomes an important craft under the sea. Acoustic vibration performance is one of the key research directions of underwater craft. According to different mechanism, the noise of underwater craft can be distinguished as mechanical noise, propeller noise and hydrodynamic noise [1]. When the underwater craft is sailing at a low speed, mechanical noise plays a leading role, which is propagated from the shell through the equipment base as the vibration generated by the mechanical equipment working inside the cabin.

At present, the numerical methods of acoustic problems at home and abroad include statistical energy method, boundary element method, finite element method and so on. With the development of various methods, it is more commonly to combine different kinds of numerical algorithms into use. Finite element method was applied in early time, which mainly divided structure and fluid into finite element for solution, but finite element method can’t be used for infinite domain problems. Statistical energy analysis (SEA) can extract the research object from the whole by random parameters description. Instead of the specific details of the object, it only focus on the statistical mean value in time domain, frequency domain and space. In recent years, statistical energy method has made progress in optimization design, dynamic impact and so on[2][3].

The boundary element method (BEM) is an efficient and accurate engineering numerical method developed after the finite element method (FEM). Its modeling is simple, and the forming units are less, while it only needs to model on the surface of the structure, which can reduce the dimension. However, the traditional boundary element method forms a non-symmetric fully populated matrix, which can be time-consuming and memory-consuming. In order to overcome the shortcoming, many fast methods have been proposed, such as fast multipole method, fast direct solution method and adaptive cross approximation method [4][5].
It will consume a lot of memory and time to calculate and analyze the fluid structure interaction on the finite element model of underwater craft cabin structure. In contrast, structure in the air can be calculated faster without considering the fluid structure interaction. In this paper, the power cabin of a certain type of underwater craft was selected for research. The finite element method was adopted to establish the model to calculate the impedance ratio to reflect the match degree of vibration and noise transmission as well as the acoustic characteristics. And its parameters were changed to compare the change rules of acoustic characteristics of the cabin with the change of parameters. The impedance ratio of structure in the air and in the water was compared to reach a general conclusion of fluid structure interaction. The impedance ratio is the ratio of the impedance of two coupled structures, which can reflect the matching degree of vibration and noise transmission and the acoustic performance of underwater craft cabin.

2. Fundamental Principles of Finite Element Method and Calculating Impedance Ratio

2.1. Fundamental Principles of Finite Element Method

A set of solutions for finite element structure in infinite liquid field are introduced. Set $\omega$ as the vibration circular frequency of the structure, $M$ as the structure mass, $B$ as damping, especially the stiffness coefficient, $u$ as the displacement response, $F$ as the driving force, $P$ as the fluid pressure, $r$ as the radius of outer boundary of the artificial fluid, and $R$ as the radius of the spherical shell. The dynamic equations is as follows:

$$\left[ -\omega^2M + j\omega B + K \right]u = F + GAP$$

\(\{u\}\) is displacement complex amplitude vector, \(\{p\}\) is the fluid pressure complex amplitude vector, which are unknown quantities to be solved. Because the amplitude of \(\{p\}\) depends on \(\{u\}\), while the magnitude of \(\{u\}\) is affected by the amplitude of \(\{p\}\), which is called fluid-solid coupling as they interact with each other. It is necessary to introduce a set of equations as follows to solve the problem. The acoustic equation is written as:

$$\nabla^2P + K^2P = 0$$

The boundary condition equation of fluid solid coupling is as follows:

$$\frac{\partial P}{\partial n} = \omega^2 \rho u_n$$

The radiation condition equation is as follows:

$$\lim_{r \to \infty} \left( \frac{\partial P}{\partial r} - iKP \right) = 0$$

It is difficult to calculate and analyze due to the large amount of calculation when calculating the fluid unit of infinite fluid field by NASTRAN software. The finite element method is used. By using the finite element method, construct an outer boundary whose diameter is far greater than that of the spherical shell to approximate meet equation (4). The radiation condition equation is changed as follows:

$$\lim_{r \to \infty} \left( \frac{\partial P}{\partial r} - iKP \right) = 0$$

And the boundary impedance is as follows

$$Z_p = \rho C_v$$
$\rho$ is the fluid density and $C_0$ is the velocity of the fluid.
The rest of the equations keep the same. $\{u\}$ can be obtained by equation (1) to (5). From the equation that $v = i\omega u$, the average method velocity can be obtained.

2.2. *Fundamental Principles of Calculation for Impedance Ratio of Single-mode Structural Vibration*
Consider the single-mode structural vibration system as shown in the figure: structure A vibrates in the normal direction of its structural plane due to an additional excitation, and the structure is analyzed by isolation method.

![Figure 1. Single-mode structural vibration diagram.](image)

When structure B is not considered, the normal vibration displacement response amplitude of structure A is $W_A$. While taking structure B in consideration, both structure A and B have the same normal vibration displacement response amplitude written as $W_{AB}$, and the interaction force amplitude at the interface is $F$,

$$\begin{align*}
    w_{ab} &= \frac{F}{Z_B} \\
    w_{ab} - w_A &= \frac{-F}{Z_A}
\end{align*}$$

(7)

where $Z_A$ and $Z_B$ are the displacement impedance of structure A and B respectively. The following results are obtained by transforming equation (7):

$$\frac{Z_B}{Z_A} = \frac{w_A - w_{ab}}{w_{ab}} - 1$$

(8)

It can be seen from equation (2) that displacement impedance ratio of the structure B and structure A can be directly calculated when $W_A$ and $W_{AB}$ are known in the single-mode vibration system. For that transfer of vibration energy between structure A and B is closely related to their impedance ratio, their impedance compatibility can be measured by their impedance ratio.

3. *Establishing the Model and Determining the Mode*

3.1. *Establishing the Model*
Part of the structural models of the underwater craft are given, and the finite element modeling is carried out, as shown in figure 2. The model includes pressure hull structure, non pressure hull structure, rib structure, brace structure, end cover structure, surface structure, fluid structure and outer boundary structure. The parameters are as follows: the length of cabin is 22 m, the diameter of pressure hull is 8 m, the diameter of non pressure hull is 10 m. The thickness of pressure shell plate is 30 mm, that of non pressure shell plate is 9 mm, that of the rib plate is 10 mm. The thickness of bracket plate is 7 mm, and that of bulkhead plate is 10 mm. The ribs are arranged with a spacing of 500 mm in pressure hull.

When only the dynamic cabin is studied, in order to consider the effect of the cabin at both ends and approximately simulate the structural vibration characteristics, the boundary condition is simplified as
the simply supported at both ends. The bottom of the center of the cabin is subjected to a unit excitation force which is straight down. The frequency ranges from 2Hz to 100Hz, and the step size is 2Hz.

Figure 2. Longitudinal section of the finite element model of the cabin.

Figure 3. Middle section of the finite element model of the cabin.

3.2. Determining the Mode
Make modal analysis on the finite element model of the cabin structure in the air with NASTRAN software and figures out the mode shape. Then, the response of the cabin at different frequencies under the original given condition is obtained by calculating the model in the frequency range from 2Hz to 100Hz with the step of 2Hz. Through comparison, it can be seen in figure 4 and figure 5 that the modal shape of order 23 is similar to the response of the structure when the excitation frequency is 12Hz. The mode is selected as the main mode of the structural model and recorded as mode A.

For the structure in the water, take the isolation method to analyze the pressure hull and non pressure hull structure. So the vibration mode of pressure hull is not affected when considering the effect of fluid. For the case of parameter change, as long as the geometric characteristics do not change, such as length, diameter and so on, the mode shape does not change. Although the corresponding frequency of the corresponding complex mode will change, it does not affect the mode selection. It can be seen that the mode A is the mode shape to be selected. The impedance ratio corresponds to the main part of the impedance ratio of complex structure.

Figure 4. Mode A at order 23.

Figure 5. Structural response when frequency is at 12 Hz.

4. Calculation Results of Impedance Ratio of the Structures

4.1. Characteristics of Impedance Ratio of the Structure in the Air
For the finite element model of the structure in the air, the impedance ratio of the typical mode, namely mode A, was calculated by changing the thickness of the pressure hull plate at different frequencies. The impedance ratio was compared with that of the original structure, and the change rules of the impedance ratio with thickness of the plate is given, which is represented in logarithmic, as shown in figure 6 and figure 7.

In the condition of mode A, the impedance ratio varies little as the thickness of pressure hull changes at low frequency; When the frequency increases, the logarithm peak value of impedance ratio decreases with the increase of plate thickness, and the logarithm peak value of impedance ratio moves
backward; As the thickness of the plate decreases, the logarithm peak value of the impedance ratio increases and the logarithm peak value of the impedance ratio moves forward.

Figure 6. Comparison of impedance ratio of structure in the air in mode A with the thickness of 25mm and 30mm.

Figure 7. Comparison of impedance ratio of structure in the air in mode A with the thickness of 30mm and 35mm.

4.2. Characteristics of Impedance Ratio of the Structure in the Water

For the finite element model of the structure in the water, the impedance ratio of the mode A is calculated at different frequencies by changing the thickness of the pressure hull plate. The impedance ratio is compared with that of the original structure, and the changing rules of impedance ratio of the thickness of the plate is given in logarithm, as shown in figure 8 and figure 9.

Figure 8. Comparison of impedance ratio of structure in the water in mode A with the thickness of 25mm and 30mm.

Figure 9. Comparison of impedance ratio of structure in the water in mode A with the thickness of 30mm and 35mm.

In the condition of mode A, it can be seen that, the logarithm of impedance ratio changes little at low frequency after the thickness changes, and the impedance ratio increases and the match degree increases when the thickness decreases. At high frequency, the increase of plate thickness causes the logarithmic peak value of impedance ratio to move backward, while the decrease of plate thickness causes the logarithmic peak value of impedance ratio to move forward.
4.3. Comparison Between Structures in the Air and in the Water

For mode A, the logarithm of the impedance ratio of the structure in the water is larger than that of the structure in the air. But when it is at high frequency, the impedance ratio difference between the two kinds of structures in different conditions increases rapidly, so the conclusion is given in different frequency bands. The conclusions are shown in the tables below.

| Table 1. Comparison of impedance ratio between structure in the air and in the water at the frequency from 2Hz to 78Hz in mode A. |
|---|---|---|
| Range of frequency (Hz) | Thickness (mm) | Difference of impedance ratio between the two structures(1) |
| 2-78 | 25 | 0.348 |
| 2-78 | 30 | 0.325 |
| 2-78 | 35 | 0.317 |

| Table 2. Comparison of impedance ratio between structure in the air and in the water at the frequency from 78Hz to 100Hz in mode A. |
|---|---|---|
| Range of frequency (Hz) | Thickness (mm) | Difference of impedance ratio between the two structures(1) |
| 78-100 | 25 | 1.463 |
| 78-100 | 30 | 0.889 |
| 78-100 | 35 | 0.317 |

5. Conclusion

The finite element method is used to calculate the cabin structure model of underwater craft. The result shows that: (1) The common changing rules of structures both in the air and in the water are that: the impedance ratio decreases and the impedance matching becomes better with the increase of pressure shell thickness. The peak value of impedance ratio moves forward. So in simulation and calculation for whether structure in the air or in the water, reducing the thickness of the pressure hull can decrease the transmission of mechanical noise so that decrease the vibration noise radiated by underwater craft. So it is beneficial to the acoustic performance to reduce the thickness of pressure shell properly. (2) The difference of changing rules between structures in the air and in the water is that: for the structure in the air and the other one in the water, the impedance ratio of the structure in the water is greater, and the impedance matching performance will be worse.

For the study of acoustic transmission performance of typical cabin structure of underwater craft, the following work should be further carried out: the acoustic transmission performance of the structure should be calculated by changing other parameters, such as thickness of non pressure hull, cabin density and so on. And the relationship of impedance ratio between the structure in the air and in the water should be further studied.

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References

[1] Wei Chen 2009 The Numerical Methods Research of Coupled Vibration and Sound Radiation of Underwater Structures
[2] Ruxin Gao and Yahui Zhang 2019 Reduction of Hybrid FE-SEA Model for the Mid-Frequency Vibration of Vibro-Acoustic Systems Using Dynamic Condensation Approach
[3] Richard D J and Gordon E 2017 Using the Modal Response of Window Vibrations to Validate SEA Wind Noise Models
[4] Leilei Chen and Chuang Lu 2020 Subdivision Surfaces-Boundary Element Accelerated by Fast Multipole for the Structural Acoustic Problem
[5] Leslie G and O’neil M 2021 multipole methods for evaluation of layer potentials with locally-corrected quadratures