Research on radiation noise field reconstruction of underwater vehicle shell structure

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Abstract. When studying the radiation noise of underwater vehicle, it is more realistic to simulate the underwater vehicle by using the volume source shell structure model. However, in the process of using COMSOL to simulate the radiation noise of the underwater vehicle shell structure, the far field calculation cannot be realized with the software because the calculation amount is too large. This paper proposes to measure the noise of underwater vehicle shell structure model in the near field. According to the theory of acoustic holographic and the idea of equivalent source, it is achievable to obtain the equivalent sound source of underwater vehicle shell structure noise source, and thus realizing sound field reconstruction. Studies have shown that underwater vehicle radiation noise field reconstruction and far-field calculation can be achieved by transformation within the tolerance of error. At the same time, this paper also compares the reconstructed sound fields obtained by different methods.

1. Introduction

Underwater vehicles are vital essential for defending the rights of our ocean and territory. Therefore, radiation noise as an important indicator for evaluating the performance of underwater vehicle needs to be measured accurately[1-2]. This is not only about measuring the advanced nature of underwater vehicle, but also relating to the survival of underwater vehicle. Three methods are usually used when simulating underwater vehicle, which are point source method, four bright points model and volume source model, respectively[3]. Among them, the use of volume source model to simulate underwater vehicle is more consistent with the actual situation. Underwater vehicle is large and complex structure. The radiated noise of internal noise sources is transmitted to the shell through complex bases and rail joints, and then the radiated noise propagates into the seawater. Therefore, when studying the radiation noise of underwater vehicle, the volume source model is the most accurate among the three methods. However, when the simulation is implemented on COMSOL, the far field calculation cannot be realized because the calculation amount of volume source model is too large. At present, Wan Haibo et al. [4] of Naval Engineering University used cylindrical acoustic holography to reconstruct the noise field in order to solve the problem of localization and identification of underwater vehicle noise sources. Ji Qing [5], also from the Naval Engineering University, studied the location of internal noise sources for underwater vehicle. Yang Desen, Hu Bo et al. [6] of Harbin Engineering University studied the acoustic holographic parameters of underwater sports sound sources. Sun Chao et al. [7] conducted a detailed study on the near-field acoustic holography method of underwater sound source in a finite space. However, there are few studies on the overall reconstruction of the noise field in the
measurement of radiated noise of underwater vehicle. In this paper, near-field acoustic holography is used to transform the sound field by conformal transformation and non-conformal transformation, respectively. Combined with the equivalent source theory, the equivalent sound source of the underwater vehicle is solved. And the sound field of the equivalent sound source is used to replace the radiation noise of underwater aircraft, thereby achieving the far field calculation of the sound field. This study also provides a reference for more accurate simulation and calculation of underwater vehicle radiated noise, which has great significance for the more advanced structural design and accurate measurement of radiated noise by underwater vehicle.

2. Acoustic holography theory

Acoustic holography is a widely used technique in recent years. By measuring and inverting sound waves in the sound field, the amplitude and phase information in the sound wave can be used to obtain the sound field parameters at any position in the sound field [8]. When applying the near-field acoustic holography to reconstruct the sound field, the following three points need to be satisfied: firstly, the sound field satisfies the homogeneous wave equation; secondly, for any coordinate point \( r_1 (x_1, y_1, z_1) \) in space, there is one Green's function satisfies the Helmholtz equation for this point; thirdly, the sound field parameters on the measurement surface can be obtained by sensor measurement.

2.1. Planar acoustic holography

Figure 1. Near field acoustic hologram schematic diagram.

The measuring surface of the planar acoustic holography [8,9] is a plane, as shown in figure 1. Firstly, the sound field information such as sound pressure of the measuring plane in the sound field is measured, and then the equivalent sound source expression of the sound field is solved according to equation (1).

\[
p(x, y, z) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} p(x_H, y_H, z_H) \cdot G_D dx_H dy_H
\]

Where \( G_D \) is the Green's function and can be expressed as:

\[
G_D = g_D(x-x_H, y-y_H, z-z_H)
\]

From the knowledge of plane waves, any plane sound field in space can be expressed as:

\[
p(x, y, z) = \frac{1}{4\pi^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \hat{P}(k_x, k_y, z)e^{jk_x(x-x') + jk_y(y-y')} dk_x dk_y
\]
The angle spectrum is given by:
\[ \hat{P}(k_x, k_y, z) = \hat{P}(k_x, k_y, z_H) \hat{G}_n(k_x, k_y, z - z_H) \]  
\[ \hat{G}_n(k_x, k_y, z - z_H) = e^{i(z - z_H)k_1^2 + k_2^2} \]  

By the Rayleigh formula, the reconstructed surface sound pressure distribution can be calculated and inverted, and then the reconstructed sound field can be obtained.

2.2. Cylindrical acoustic holography [4,10]

The underwater vehicle can be regarded as a cylinder structure roughly. In cylindrical coordinates, the Laplacian can be written as:
\[ \nabla^2 = \frac{\partial^2}{\partial r^2} + \frac{1}{r} \frac{\partial}{\partial r} + \frac{1}{r^2} \frac{\partial^2}{\partial \theta^2} + \frac{\partial^2}{\partial z^2} \]  

Combining the Helmholtz equation in the cylindrical coordinate system, which is:
\[ \frac{1}{p_r} \frac{d^2 p_r}{dr^2} + \frac{1}{rp_r} \frac{dp_r}{dr} + \frac{1}{r^2 p_\theta} \frac{d^2 p_\theta}{d\theta^2} + \frac{1}{p_z} \frac{d^2 p_z}{dz^2} + k^2 = 0 \]  

According to the Hankel function, the sound pressure and vibration velocity expressions are obtained:
\[ P_n(k_z, R_z) = \frac{H_n^{(1)}(k_z, R_z)}{H_n^{(1)}(k_z, R_h)} P_n(k_z, R_h) \]  
\[ V_n(k_z, R_z) = \frac{k_r}{\rho c k_z} \frac{H_n^{(1)}(k_z, R_z)}{H_n^{(1)}(k_z, R_h)} P_n(k_z, R_h) \]  

2.3. Spherical acoustic holography [11-12]

In spherical coordinates, the Helmholtz equation can be written as:
\[ \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial p}{\partial r} \right) + \frac{1}{r^2 \sin \theta} \frac{\partial}{\partial \theta} \left( \sin \theta \frac{\partial p}{\partial \theta} \right) + \frac{1}{r^2 \sin^2 \theta} \frac{\partial^2 p}{\partial \phi^2} + k^2 p = 0 \]  

Similarly, the sound pressure expression in the spatial sound field can be obtained:
\[ p(r, \theta, \phi) = \sum_{n=0}^{\infty} \sum_{m=-n}^{n} D_{mn} j_n(kr) Y_n^m(\theta, \phi) \]  

In the equation (11), \( n \in (0,1,2,...N) \), \( m \in (-n,-n+1,...,n) \), through the inverse Fourier transform of the spatial sound field, the reconstructed surface sound pressure can be written as:
\[ p(r, \theta, \phi) = \sum_{n=0}^{N} \sum_{m=-n}^{n} P_{nm}(r) Y_n^m(\theta, \phi) \]  

3. Simulation research by using acoustic holography

The simulation study of underwater vehicle radiated noise is based on acoustic holography. Firstly, we need to simulate the underwater vehicle model, and use the COMSOL software to simulate the underwater vehicle model as shown in figure 2.
For simulating underwater vehicle based on the COMSOL software, the dimensions of underwater vehicle are as follows: the distance from the head to the tail is twenty-five meters, and the internal diameter of the cylinder is five meters, it is similar to the cylindrical shell structure, the thickness of the shell is set to ten centimeters. Two excitation points are used to simulate the engine and main motor radiated noise. The positions of the two excitation points are set to (2, 2.5, 0) and (-2, 2.5, 0). The model after the excitation is shown in figure 3.

According to the foregoing, when the acoustic holography technology is used to reconstruct the radiation noise field of the underwater vehicle, it is necessary to measure the sound field parameter information of a certain area in the sound field. Therefore, some sensors are regularly arranged in the sound field, as shown in the figure 4.

3.1 Sound field reconstruction by using planar acoustic holography
The distance between the sensors on the measuring plane is ten centimeters. Similarly, the distance between the measuring surface and the excitation points is also 10 centimeters. Through the inversion
of the sound field information of the measuring surface, the plane, cylinder and spherical equivalent sound sources are obtained as shown in figure 5.

![Figure 5. Equivalent sound source of planar acoustic holography.](image)

After the plane, cylinder and spherical equivalent sound sources are determined, respectively, and the radiated sound fields of the three sound sources can be obtained and compared with the sound field measured by the original measuring surface, as shown in figure 6.

![Figure 6. Planar acoustic holographic measurement surface and equivalent sound source reconstruction surface.](image)

In order to facilitate the analysis and comparison with the original sound field, the position of the sound field reconstructed by the three equivalent sound sources is the same as the position of the measuring surface. The picture of figure 6a is planar acoustic holographic measurement surface, and the pictures of figure 6b-d are reconstruction surfaces of the plane, cylinder and spherical equivalent sound sources, respectively. It can be seen from figure 6 that the sound field reconstructed by the three equivalent sound sources is in accordance with the original sound field well. At the same time, the selection of a suitable holographic surface and more dense sensors can make the grid division more delicate during simulation, thus improving the accuracy of sound field reconstruction.

3.2. Sound field reconstruction by using cylindrical acoustic holography

The shape of the underwater vehicle is similar to that of the columnar structure. Therefore, this paper continues to explore the measurement and reconstruction of the radiation noise field of the underwater vehicle by cylindrical acoustic holography. Similarly, the equivalent sound sources are flat sound source, cylindrical sound source and spherical sound source, as shown in figure 7.
Figure 7. Equivalent sound source of cylindrical acoustic holography.

The three equivalent sound sources are used to reconstruct the sound field and compare it with the measuring surface, as shown in figure 8.

Figure 8. Cylindrical acoustic holographic measurement surface and equivalent sound source reconstruction surface.

The picture of figure 8a is cylindrical acoustic holographic measurement surface, and the pictures of figure 8b-d are reconstruction surfaces of the plane, cylinder and spherical equivalent sound sources, respectively. The measurement surface of the cylindrical acoustic hologram and the reconstruction surface of different types of sound sources in figure 8 are compared, respectively. It can be seen that the reconstruction surface of the cylindrical sound source matches the original measurement surface better. Given that the underwater vehicle is a cylindrical structure, therefore, the use of cylindrical measurement is more suitable for the actual situation and the effect is better.

4. Conclusions

Based on the COMSOL software to simulate the underwater vehicle volume source model, this paper focuses on resolving the problem that it can not calculate the long-distance sound field. The simulation results show that the technology of acoustic holography combined with the theory of equivalent source can reconstruct the radiation noise field of underwater vehicle well, which makes the far field calculation of underwater aircraft radiation noise possible. It can be concluded that (1) as a cylindrical sound source, the underwater vehicle is holographic measured by cylindrical acoustic holography, and the reconstructed sound field is more consistent with the original sound field; (2) selecting a suitable holographic surface and sensor array can improve the accuracy of the reconstructed sound field and reduce the reconstruction error.
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