Numerical Study of Hydrodynamic Noise of a Cone-column Combined Structure

Chen Yu¹, Zhihua Shen²*, Guobing Huang² and Jiangtao Liu¹

¹College of Shipbuilding Engineering, Harbin Engineering University, Harbin, 150001, PR China
²China Ship Development and Design Center, Wuhan, 430064, China
E-mail: huoruidong@hrbeu.edu.cn

Abstract. Hydrodynamic noise is one of the main sound source of underwater vehicle. Flow noise and flow-excited noise are important part of hydrodynamic noise. In this paper, large eddy simulation is applied to simulate the flow field around a cone-column combined structure to obtain dipole sound source and turbulence fluctuating pressure. The surface pressure distribution is validated by experiment measured data. Structure dynamic response can be obtained by solving fluid-structure coupling equation. The flow noise and flow-excited noise of the structure are calculated according to acoustic analogy theory. From the numerical result, it can be seen the spectra characteristic of flow-excited noise is different from flow noise. The flow-excited noise obviously increases when system resonance occurs.

1. Introduction

Underwater vehicles are distinguished from other crafts, surrounded by viscous water. Irregular motion on the surface of the underwater vehicle will generate noise, often called hydrodynamic noise. Researchers usually divide hydrodynamic noise into three categories, including flow noise, flow-excited noise and cavitation noise. Both of them have become a research hotspot.

In order to simplify the study of hydrodynamic noise, researchers often regard underwater vehicle as a rigid body. Based on the acoustic analogy theory proposed by Lighthill, it is possible to predict the flow noise generated by the dipole sound source on the surface of the underwater vehicle. However, the actual situation is that the underwater vehicle will have a fluid structure interaction (FSI) with the water flow, and the structural surface will generate dynamic response and radiated noise under the action of turbulence flow. This will cause the predicted noise smaller than the real value. Currently, related research has been conducted on hydrodynamic noise with consideration of FSI using the boundary element method (BEM). Yao and Zhang[1] predicted the flow noise and flow-excited noise of fully appended submarine by using CFD and BEM methods. Wei and Wang[2] used the CFD to obtain the...
hydrodynamic load during the rotation of the propeller. Based on this, the BEM method was used to calculate the radiated noise.

In this paper, the underwater vehicle is simplified into a cone-column combined structure. The flow field around the cone-column combined structure is simulated by applying the large eddy simulation (LES). Finally we use BEM to calculate the flow noise and flow-excited noise generated by the dipole source and turbulent pulsating pressure. A series of hydrodynamic noise experiments were conducted to verify the effectiveness of the above calculation methods.

2. Mathematical formulations

2.1. Large eddy simulation

LES is used to simulate the turbulence field around the cone-column combined structure. Based on incompressible Navier-Stokes Equation and spatial filtering function, we can divide the turbulence flow into large-scale and small-scale two parts. The processed N-S Equation and filter function can be written as:

\[
g(x, x', \Delta) = \begin{cases} 
\frac{1}{\Delta x_1 \Delta x_2 \Delta x_3}, & |x'_i - x_i| \leq \frac{\Delta x_i}{2} \quad i = 1, 2, 3 \\
0, & |x'_i - x_i| > \frac{\Delta x_i}{2} \quad i = 1, 2, 3
\end{cases} 
\]

(1)

\[
\frac{\partial \bar{u}_j}{\partial t} + \frac{\partial}{\partial x_i} \left[ \bar{u}_j \frac{\partial}{\partial x_i} \right] = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 \bar{u}_j}{\partial x_i \partial x_j} - \frac{\partial}{\partial x_j} \tau^s_{ij} 
\]

(2)

In Eq.1 \(G(x, x', \Delta)\) is a boxy filter function, \(\Delta\) is the grid scale. We apply a filtering operation to N-S Equation, then we can obtain Eq.2. In Eq.2 \(\bar{u}_j\) means the filtered average velocity components, \(\tau^s_{ij} = \bar{u}_i \bar{u}_j - \bar{u}_j \bar{u}_i\) is so-called sub-grid scale stress (SGS).

2.2. Acoustic analogy theory and FSI

Ffowcs-Williams and Hawking\(^{(3)}\) extended Lighthill’s acoustic analogy theory and raised the famous FW-H Equation which can be written as follows:

\[
\frac{1}{c^2} \frac{\partial^2 p}{\partial t^2} - \nabla^2 p' = \frac{\partial^2}{\partial x_i \partial x_j} \left[ T_{ij} H(f) \right] - \frac{\partial}{\partial x_i} \left[ \rho_{ij} \delta(f) \right] + \frac{\partial}{\partial x_j} \left[ \rho_{ij} \delta(f) \right] 
\]

(3)

Where \(p'\) represents far field sound pressure, \(\delta(f)\) and \(H(f)\) are Dirac delta function and Heaviside function. In Eq.3, its right source term contains three components, and both of them represent different physical meanings. The first component contains Lighthill stress tensor, representing the quadrupole source’s contribution to flow noise; the second component refers to wall pressure fluctuation, representing the contribution of dipole source to flow noise; the third component is related to the velocity of structure surface, it can be regarded as monopole source. Due to the low velocity of flow, quadrupole source and monopole source are negligible. We can just take dipole source into consideration to calculate the flow noise.

As for flow-excited noise, we should regard wall pressure fluctuation as external load to calculate system dynamic response. The governing equation can be written as:

\[
\begin{bmatrix} M_f & K_f^h \\ M^h & K_f \end{bmatrix} \begin{bmatrix} U_f \\ P_f \end{bmatrix} = \begin{bmatrix} F_s \\ 0 \end{bmatrix} 
\]

(4)
In Eq.4 \( \left[ M^R \right] = \rho \left[ R \right]^T \), \( \left[ K^R \right] = -\left[ R \right] \), \( \left[ F_s \right] \) means external load, \( \left[ R \right]^T = \int \left[ N \right]^T \left[ N \right]^T \{ n \} d(s) \),

\( \{ N \} \) represents pressure shape function and \( \{ N' \} \) is the structure displacement shape function. By solving Eq.4, we can obtain the displacement and sound pressure of structure surface. Then the sound pressure of the whole acoustic field can be obtained by solving the following equation according to the normal speed and sound pressure of structure surface.

\[
p(x) = \int p(y) \left( \frac{\partial G(x,y)}{\partial n_x} - \frac{\partial p(x,y)}{\partial n_y} \right) G(x,y) dS(y)
\]

(5)

3. Numerical simulation and experiment

3.1. Flow field simulation

The cone-column combined structure was chosen for the study of flow noise and flow excited noise. The overall length is 0.95m, the diameter of the structure is 0.1m, and the thickness of the structure is 6mm. Both ends of the structure are two hemispheres. The velocity inlet boundary is one structure length away from the cone-column combined structure and the inflow velocity is 2.46m/s. The pressure outlet boundary is two times structure length from the model. The Reynolds number of the structure model is 1.25E6. The surface of the model is set as no-slip boundary condition.

In order to decrease the total number of the grid, the grid in the computational flow field near the structure surface is quite fine, whereas the grid in the non-interesting region is sparse.

The computation domain is discretized by applying multi-block strategy and the number of hexahedral grids of the computational domain is nearly 1.8 million. In order to ensure the non-dimensional spacing wall \( y^+ \) on the hull surface is within 10, we set the height of first layer grid as 5\% of the overall length. Due to the sampling frequency was up to 12.5kHz, the time-step was set as 4E-5 and the total calculation time was 10s. The structure design and details of the mesh used in this paper are separately shown in Figure 1 and Figure 2.

![Figure 1](image1.png)

Figure 1. Designed structure (a) Front view, (b) Bottom view and (c) Model photograph.

![Figure 2](image2.png)

Figure 2. Computational domain.

For excluding the influence of grid scale, grid independent verification should be implemented. Four sets of grids with different mesh scale are simulated to check the accuracy of simulation. Along longitudinal direction, 11 pressure sensor are set to obtain the surface pressure distribution. Due to the space limitation, we just choose point 5 and 8 to compare the simulation data with measured data. The arrangement of measuring point and calculated result are shown in Figure 3 and Figure 4.

According to the simulation result, it is clear that when the grid cell is set as 2mm, we can get minimal error between simulation and experimental results. So the following fluid field simulation will use the same mesh resolution.

Finally we get the fluid field information of inflow velocity equals 2.46m/s by using above mesh resolution and calculation method.
3.2. Flow noise and flow-excited noise simulation

The flow noise and flow-excited noise of cone-column combined structure are calculated by BEM. The distributions of the overall sound pressure level (OASPL) of flow noise and flow-excited noise along the longitudinal direction are presented in Figure 5. According to the Figure 5, the OASPL of flow-excited noise is smaller than that of flow noise in the near field. The flow-excited noise decreases by 43.8% while flow noise decreases by 28.6% after spreading 8.5m. It can be seen that flow-excited noise decreases rapidly in the near-field which need us to pay attention to. In the far-field, the difference between the OASPL of flow noise and flow-excited noise is nearly 30dB.

The sound directivity diagrams in axial direction at the center of the structure are shown in Figure 6. From the comparison result, it is clear that the sound directivity patterns of flow noise and flow-excited noise are different from each other. The sound directivity of flow noise is almost the same at every direction of the acoustic field and its OASPL is nearly 74.5dB. But the OASPL of flow-excited noise in height direction is larger than that in lateral direction, its maximum OASPL appears in the directions of 90 and 270 degrees.

The spectrum of flow-excited noise received at the location of hydrophones is compared with that of the flow noise in Figure 7. It’s clear that flow noise doesn’t have obvious peak value while flow-excited noise has its maximum scale SPL at about 400Hz. Through modal analysis in Figure 8, we know that the first natural frequency of the structure is 390Hz and it is close to the peak frequency of spectrum curve of flow-excited noise.
4. Conclusion
In this paper, LES is applied to simulate the flow field around the cone-column combined structure and BEM is applied to calculate the flow noise and flow-excited noise. The flow-excited noise is smaller than flow noise along the longitudinal direction and rapidly decreases in the near-field. The sound directivity of flow noise is different from that of the flow-excited noise. The flow-excited noise has its own peak frequency which is similar to the structure natural frequency at 390Hz.

Acknowledgments
This study was funded by Major innovation projects Of High Technology Ship Funds of Ministry of Industry and Information of P. R. China and High Technology Ship Funds of Ministry of Industry and Information of P.R. China.

Reference
[1] Yao H, Zhang H, Liu H, and Jiang W 2017 Numerical study of flow-excited noise of a submarine with full appendages considering fluid structure interaction using the boundary element method Engineering Analysis with Boundary Elements 77 pp 1-9
[2] Wei YS and Wang YS 2012 Structure noise prediction of submarine by propeller excitation Appl Mech Mater 105 pp 43-6
[3] Fhowcs Williams J E and Hawkings D L 1969 Sound generation by turbulence and surface in arbitrary motion Philosophical Transaction of the Royal Society of London Series A 264 pp 321-342