Noise Study of Small Ships during Sailing in Near-wake Field based on Body Force Model

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Abstract. Noises of ships during sailing and in the near-wake field are both important factors in the ship design, which is of great significance to the ship structure and personnel health. A convenient body force model is adopted to replace the action of a real propeller through the computational fluid dynamics (CFD) method, meanwhile, FW-H equation is used to calculate the radiated noise in the near-wake field of small ships and forecast the noise characteristics of small ships during sailing in the near-wake field. The variation law of noise spectrum at different monitoring points during the evolution of the near-wake field is analyzed, and the simulating results are in good agreement with the testing data. Research proves that the body force model is efficient and feasible to the noise characteristics of small ships during sailing in the near-wake field, which can provide some reference for the design of small ships and also for the noise prediction in the near-wake field.

1. Introduction

During sailing of ships, the cavitation caused by the movement of propellers, rolling and breaking of sea waves, and the air involved from the waterline, which together form an air curtain belt with a great deal of bubbles at the tail of ships, that is “wake”. The geometrical characteristics of wake are closely related to the size and the speed of ships, and the wind speed of the sea surface; moreover, the acoustical characteristics of wake also have some relations with these physical characteristics. The acoustical characteristics mainly include: absorption and attenuation, reflection and scattering, impedance characteristics and noise characteristics.

The geometrical model of wake is determined by the size and the number of propellers, the draft depth and the speed of ships, and also varies with the life time and the length of wake itself. The wake has an expansion angle starting from the tail of ships, about 30°-60°, which is not related to the speed or types of ships. When it expands to a certain distance (0m ~ 100m), the expansion angle decreases sharply. After that, the average expansion speed is about 4m/s ~ 6m/s, and the expansion angle is no more than 1°.

Many scholars at home and abroad have carried out long-term and in-depth theoretical research and experimental research. In foreign countries, as early as the 1940s, the United States began to study the wake characteristics of ships, in 1946, measured the distribution characteristics of wake bubbles of destroyers at a speed of 15 knots by sonar[1]. Later, from 1960s to 1980s, Urick[2],Straberg[3], Blacke[4]
et al. studied the radiated noise of ships. At the same time, the United States began to study the wake characteristics of ships on a large scale. Garretts on and Stewart et al. used Boltzmann transport equation and Lagrange method to study the dynamics of bubbles in the ocean environment [5-6]. Miner et al. used Navier-Stokes equation and bubble transport theory to study the distribution in wake bubbles of ships [7]. Carrica et al. used a two-phase flow model to calculate the influence of bubble field of ships at a background of ocean [8]. Jong [9] et al. presented an algorithm for predicting the pressure pulsation and the radiation field on the surface of ships, which was based on the predicted results in the time domain. Gloza [10] [11] focused on the frequency domain and the time domain results of the radiated noise of small ships. Francesco [12] et al. used RANS, LES and BEM methods to numerically simulate the wake field of propellers. Goran [13] used implicit LES method and Kunz cavitation model to simulate dynamic behavior of propellers in non-uniform flow field and the structure of the flow field with small and medium scales. In China, Wu Guoqing [14] [15] et al. studied the noise identification of ships, overall framework, linear spectrum analysis and extraction, as well as the stability and uniqueness of the linear spectrum. Du Xuanmin [16] et al. studied the simulation technology of the radiated noise of ships. Luo Jian [17], Zhu Zhifeng [18] et al. reconstructed the time domain and noise characteristics of ships.

In this paper, CFD software is used for the numerical calculation, and a virtual propeller is constructed through a body force model. On the basis of ignoring unnecessary flow details, saving computational grid and improving calculation efficiency, the noise in the near-wake field during sailing of small ships is numerically simulated, and underwater noise characteristics under different depths in the near-wake field are analyzed. It reveals the variation law of the near-wake field of small ships, and studies the variation law of noise and frequency spectrum at different positions in the flow field, which is of great significance.

Since the numerical calculation of the body force model refers to the solution of the flow field around the ship according to RANS equation, the hydrodynamic performance of the propeller is calculated based on the lifting surface or surface element method based on the potential flow theory. Use an actuating disk (pressure or speed jump) to replace a propeller to calculate the effect of the flow field around the ship, use a body force model to replace a real propeller [19][20], the model is introduced as the source term into RANS equation of the flow field of ships, that is, a body force term is added to the space occupied by the propeller in RANS equation. The body force is calculated by performance program of the propeller, and then the viscous flow field around the ship by this interaction is obtained through substitution calculation between RANS equation and the performance of the propeller [21][22][23][24][25]. This model has the advantages of saving computational grid and improving calculation efficiency, and can reflect the effect of the propeller, solve the flow field around the ship and forecast the information of the flow field. However, few scholars use the body force model to make research on noise. Therefore, in this paper, CFD software is applied to the numerical calculation, and on the basis of constructing virtual propeller by the body force model, the noise of small ships during sailing in the near-wake filed is numerically simulated, and the underwater noise characteristics under different depths in the near-wake region are analyzed. It reveals the variation law of the near-wake filed of small ships, and studies the variation law of noise and frequency spectrum at different positions in the flow field, which is of great significant.
\[
\frac{\partial \rho_m}{\partial t} + \nabla \cdot (\rho_m u_m) = 0 \tag{1}
\]

In this equation, \( u_m \) is the velocity of the mixed phase, the density of mixture is \( \rho_m = \sum_{k=1}^{n} a_k \rho_k \), and \( a_k \) is the volume fraction of the phase of \( k \); \( \rho_k \) is the density of the phase of \( k \).

Momentum equation:
\[
\frac{\partial \rho_m u}{\partial t} + \nabla \cdot (\rho_m u u) = -\nabla p + \nabla \cdot \tau + S_M \tag{2}
\]

Where, \( \tau = \mu \left( \nabla u + (\nabla u)^T - \frac{2}{3} \nabla \cdot u \right) \), \( \mu \) is the viscosity of mixture.

### 2.2. Turbulence model (SST-Komega)

SST-Komega turbulence model is used to close RANS equation.

SST-Komega transport equations (Transport equation):
\[
\frac{\partial}{\partial t} \left( \rho_m k \right) + \nabla \cdot \left( \rho_m k \nu \right) = \nabla \cdot \left[ \left( \mu_m + \frac{\mu_k}{\sigma_k} \right) \nabla k \right] + P_k - \rho \beta f^* \left( \omega \nu \right) + S_k \tag{3}
\]

\[
\frac{\partial}{\partial t} \left( \rho_m \omega \right) + \nabla \cdot \left( \rho_m \omega \nu \right) = \nabla \cdot \left[ \left( \mu_m + \sigma_{\omega} \mu_{\omega} \right) \nabla \omega \right] + P_{\omega} - \rho \beta f^* \left( \omega^2 - \omega_\nu \right) + S_{\omega} \tag{4}
\]

Among them: \( \nu \) is the mean velocity. \( \mu \) is the dynamic viscosity, and, \( \sigma_k \) and \( \sigma_{\omega}, C_{\omega1} \) and \( C_{\omega2} \) are coefficients of model, \( P_k \) and \( P_{\omega} \) are production terms, \( f^* \) is the free-shear modification factor, \( f^*_\beta \) is the vortex-stretching modification factor, \( S_k \) and \( S_{\omega} \) are the user-specified source terms, \( k_\nu \) and \( \omega_\nu \) are the ambient turbulence values that counteract turbulence attenuation.

### 2.3. Body force source term equation

Based on the vortex lattice method of potential flow lifting surface theory, the propellers produce a body force, which conforms to the boundary conditions through a body force model. A body force is applied to the region grid of the propeller, and a thrust and a torque are also applied to the propeller, which can substitute the surface load of areal propeller, namely, a descriptive body force model is used to replace the action of a real propeller. The radial distribution of the component forces obeys to an optimal distribution of Goldstein, and the equations are shown as follows:

\[
F = \iiint_f fbdV \tag{5}
\]

\[
f_{hs} = \frac{\rho U^2}{L_{pp}} A_h r^* \sqrt{1 - r^*} \tag{6}
\]

\[
f_{so} = \frac{\rho U^2}{L_{pp}} A_0 \frac{r^* \sqrt{1 - r^*}}{(1 - Y_H)r^* + Y_H} \tag{7}
\]
\[ r^* = (r_1 - R_H) / (R_p - R_H) \]  
\[ Y_H = R_H / R_p \]  
\[ A_c = \frac{C_i}{\Delta x'} \frac{105}{16(4 + 3Y_H)(1 - Y_H)} \]  
\[ A_o = \frac{K_Q}{J^2 \Delta x'} \frac{105}{\pi(4 + 3Y_H)(1 - Y_H)} \]

Where, \( C_i = 2T / (\rho U^2 \pi R_p) \) is the dimensionless thrust coefficient; \( K_Q = Q / \rho n^2 D_p^5 \) is the torque coefficient; \( n \) is the speed of propeller; \( D_p = 2R_p \) is the diameter of propeller; \( r_i \) is the distance between any point within the region of propeller and the propeller axis; \( R_p \) and \( R_H \) are the propeller radius and the hub radius respectively; \( L_{pp} \) is LBP (length between perpendiculars) of hull; \( \Delta x' = \Delta x / L_{pp} \) is the ratio between the hub thickness and LBP; \( J = V_a / nD_p \) is the advance speed coefficient of propeller, and \( V_a \) is the advance speed of propeller.

### 2.4. Noise equation

FW-H (Kirchhoff – Ffowcs Williams and Hawkings) equations, according to the free space Green's function to calculate the sound pressure at the monitoring point \( X \). FW-H equations are as follows:

\[ p'(x,t) = p_r'(x,t) + p_L'(x,t) + p_Q'(x,t) \]

The monopole term is as follows:

\[ p_r'(x,t) = \frac{1}{4\pi} \left( \frac{\partial}{\partial t} \right) \int_S \left[ \frac{Q}{r(1-M_r)} \right] dS \]

The dipole term is as follows:

\[ p_L'(x,t) = \frac{1}{4\pi} \left( \frac{\partial^2}{\partial x_i \partial x_j} \right) \int_P \left[ \frac{L_i}{r(1-M_r)} \right] dV \]

The quadrupole term is as follows:

\[ p_Q'(x,t) = \frac{1}{4\pi} \left( \frac{\partial^2}{\partial x_i \partial x_j} \right) \int_P \left[ \frac{T_{ij}}{r(1-M_r)} \right] dV \]

\[ Q = \rho_0 U_i n_i, \quad U_j = \left( 1 - \frac{\rho}{\rho_0} \right) v_j + \frac{\rho u_i}{\rho_0}, \quad L_i = P_i n_i + \rho u_i (u_n - v_n), \quad P_i = (p - p_0) \delta_{ij} - \sigma_{ij}, \]
\[ T_{ij} = \rho u_i u_j + \delta_{ij} \left[ (p - p_0) - c_0^2 (\rho - \rho_0) \right] - \sigma_{ij}. \]

Where, \( u_i \) is the fluid velocity component in the direction of \( i \), \( u_n \) is the fluid velocity component perpendicular to the surface, \( v_i \) is the surface velocity component in the direction of \( i \), \( v_n \) is the surface...
velocity component perpendicular to the surface, \( n_i \) is the surface normal vector, \( \sigma_{ij} \) is the viscous stress tensor, \( \rho_0 \) is the far-field density, \( P_{ij} \) is the compression stress tensor, and \( T_{ij} \) is the Lighthill stress tensor.

### 3. Computational model and boundary conditions

Rectangular computational domain is adopted. During straight sailing, ships move at a constant speed with zero acceleration. The research object of this paper selects a small ship as the model, and the testing data of propulsion performance of the model are obtained from document [26]. The dynamic fluid-solid interaction (DFBI) model simulates the motion of a ship based on the action forces. For this simulation, allow the ship to move with two freedom degrees to account for heave and trim. The simulation conditions: ship length of 14.9m, width 4.9m, depth 2.04m, displacement 16T, speed of ship 3.5m/s, damping length of VOF wave 15m; the propeller adopts a form of virtual disk, and a body force propeller model is used for calculation. The forward rotating velocity of propeller (J), thrust coefficient (Kt), torque coefficient (Kq) and open-water efficiency (Eta) are shown in Table 1. The speed of propeller is 1627rpm.

| J   | Kt         | Kq         | Eta       | J   | Kt         | Kq         | Eta       |
|-----|------------|------------|-----------|-----|------------|------------|-----------|
| 0.00| 0.330745   | 0.038427   | 0.000000  | 0.35| 0.196752   | 0.025822   | 0.424445  |
| 0.05| 0.314894   | 0.037068   | 0.067601  | 0.40| 0.023614   | 0.468982   | 0.468982  |
| 0.10| 0.297814   | 0.035530   | 0.133406  | 0.45| 0.150496   | 0.021364   | 0.504513  |
| 0.15| 0.279584   | 0.033830   | 0.197295  | 0.50| 0.126436   | 0.019091   | 0.527036  |
| 0.20| 0.260284   | 0.031991   | 0.258986  | 0.55| 0.101859   | 0.016813   | 0.530310  |
| 0.25| 0.239993   | 0.030029   | 0.317988  | 0.60| 0.076845   | 0.014552   | 0.504278  |
| 0.25| 0.239993   | 0.030029   | 0.317988  | 0.65| 0.051473   | 0.012326   | 0.432016  |
| 0.30| 0.218789   | 0.027967   | 0.373530  | 0.70| 0.025822   | 0.010155   | 0.283298  |

**Table 1. Propeller parameters of J, Kt, Kq and Eta**

**Figure 1.** Computational domain of ship model  
**Figure 2.** Grid partition in the computational domain

(a) Hull grid  
(b) Virtual disk of the hull and propeller

**Figure 3.** Grid partition diagram of small ships
4. Noise analysis
Fifteen noise monitoring points are set, and the radial distances of the stern are 18m, 28m and 38m, and the corresponding axial coordinates are -1.25m, -2.5m, -3.75m, -5m and -6m respectively as shown in Figure 5. The pressure distribution of the instantaneous hull and propeller is shown in Figure 4 shows.

To analyze SPL spectrum at each monitoring point, the spectrum analysis of noise level at monitoring points is carried out at different time domains, namely, T1: [0s-0.5s], T2: [0s-1s], T3: [0s-1.5s] and T4: [0s-3s]. Figure 6 - Figure 9 respectively represents noise spectrum variation at T1, T2, T3, T4; (a), (b) respectively represents SPL curve at Points 1-5 and SPL curve at Points 6-10.

(a) SPL curve at Points 1-5 at T1
(b) SPL curve at Points 6-10 at T1

Figure 5. Locations of the monitoring points in the near-wake region

Figure 4. Pressure distribution of the instantaneous hull and propeller
According to the analysis, T1 is from 0s to 0.5s. Figure 6 shows SPL spectrum curve at the monitoring points 1-5 and points 6-10. It can be clearly seen from (a) and (b) that SPL of each monitoring point is the same, and SPL of noise at each monitoring point does not change significantly in depth, so does it at points 11-15. T2 is from 0s to 1s. It can be clearly seen from Figure 7, SPL at each monitoring point is the same, and the noise change of SPL at different depth is not obvious. T3 and T4 are the same.
5. Verification by experiment

In the data processing of the near-wake noise generated by a small testing ship in a lake experiment, the deviation due to the propeller speed, the speed error during self-navigation and the error of testing equipment were corrected. The experiment is different from simulation; many factors that may influence the near-wake noise were collected, for instance, the change of wind speed, the cabin noise, the superstructure flow noise and the vibration noise of the hull. Results comparison between the experiment and the simulation is as follows (With a depth of 3.75m):

![Experiment and simulation curve at T1](image1)
![Experiment and simulation curve at T2](image2)
![Experiment and simulation curve at T3](image3)
![Experiment and simulation curve at T4](image4)

Figure 10. SPL Spectrum comparison between experiment and simulation

Based on the above data comparison between experiment and simulation, it can be concluded that the spectrum energy of near-wake noise is mainly concentrated within 3 kHz; the noise spectrum level in the low frequency band is higher than that in the high frequency band. In the low frequency band, the amplitude of noise changes sharply and the spectrum component is complex. The noise in the near-wake field attenuates rapidly with the increase of frequency band. In the frequency band of (0-1) kHz, the attenuation is about 50dB. With the increase of frequency, SPL tends to be stable and attenuates to the ambient background noise level at a fast rate. Meanwhile, the testing equipment is greatly disturbed in this environment, and with the increase of frequency band, the influence factors decrease.

The deviation of the simulation results and the testing results is large in the frequency band of (0-100) Hz, and the simulation results in other frequency bands are similar to the testing results and the variation trends are basically the same. At T1, the simulating SPL is about 15dB more than the testing SPL in the frequency band of (0-5) kHz. At T2, the simulating SPL is about 11dB more than the testing SPL in the frequency band of (0-1.5) kHz, and the simulating SPL is about (6-8)dB more than the testing SPL in the frequency band of (1.5-5) kHz. At T3, the simulating SPL is about 11dB more than the testing SPL in the frequency band of (0-1.5) kHz, and the simulating SPL more than the testing SPL in the frequency band of (1.5-5) kHz is (5-6) dB. At T4, except the simulating SPL is (6-8) dB more than the
testing SPL in the frequency band of (2.4-2.8) kHz; the simulating SPL in the other frequency bands are in good agreement with the testing SPL.

6. Conclusion

Use the computational fluid dynamics (CFD) method and a body force model to build virtual propeller. On the basis of saving computational grid and improving the calculation efficiency, ignore unnecessary flow details, and numerically simulate the radiated noise of small ships in the near-wake field by FW-H equation; meanwhile, analyze the underwater noise characteristics in the near-wake field according to the testing results.

(1) In the near-wake field of small ships, the noise is mainly concentrated in the low-frequency band; the spectrum energy of near-wake noise is mainly concentrated within 3 kHz.

(2) The noise spectrum level in the low frequency band is higher than that in the high frequency band. In the low frequency band, the spectrum component is complex and the noise amplitude changes dramatically. The noise in the near-wake field attenuates rapidly with the increase of the frequency band, and the attenuation is about (50-60) dB in the frequency band of (0-1) kHz. With the increase of frequency, SPL tends to be stable and attenuates to the ambient background noise level at a fast rate. If the radius distance is the same, SPL of noise for each monitoring does not change significantly at depth.

(3) A virtual propeller is constructed by a body force model. Ignore unnecessary flow details, take FW-H equation to numerically simulate the radiated noise of the near-wake field of a small ship and verify it with the testing data. It shows that except for the frequency band of (0-100) Hz, the simulation result in the other frequency bands are in good agreement with the testing value, which proves the body force model is feasible to a certain extent and this model can provide some reference for the design of small ships and the noise prediction of near-wake field.

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