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An investigation into added resistance of vessels advancing in waves

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ABSTRACT

The hydrodynamic forces and motions of ship advancing in waves are estimated by using 3D frequency domain potential flow theories. The 3D translating and pulsating (3DTP) source panel method is employed to solve the radiation and diffraction potential problems, in which a semi-analytical scheme is established to get more robust results of integration of Green's function over panels. Added wave resistance is mainly categorized into the contributions of radiation and diffraction. The added wave resistance due to radiation motion of ship is evaluated by the radiation energy principle according to 3D hydrodynamic coefficients and ship motions, while the one due to diffraction is calculated based on steady-state force formula. The motions and added wave resistances of Wigley III hull and S175 containership advancing in waves with various forward speed are calculated and analyzed in frequency domain based on the above mentioned methods. The numerical results are validated for the models by comparing them with experimental data. The results by classic methods commonly used in engineering and the data from published papers are plotted together for comparison and discussion. Better agreement with experimental data in the prediction of peak value and its frequency of added resistance is achieved by present method. It also indicates that the correction of relative motion amplitude should be taken into account so as to improve the accuracy. Component analyses of added wave resistance are carried out and the results show the percentages of radiation part and diffraction part at various frequency respectively. The present method is of satisfactory accuracy and efficiency, which provides a rapid and robust approach to predict added wave resistance of ships voyaging in waves.

1. Introduction

The resistance acting on ships advancing in waves increases comparing with those in calm water, which will undoubtedly effect the ability of ships to keep speed in seaway. Added resistance represents the margin of the former over the latter, which is induced by winds or waves. It is also the key to the calculation of ocean factor f_w in EEDI formula presented by IMO. So added wave resistance is one of the important factors which should be taken into account in ship's design stage.

The study on added wave resistance of ship advancing in waves (Added resistance) started from middle twentieth century. Most of earlier methods are established based on strip theory. The far field method was firstly introduced by Maruo (1960) and it pointed out that added resistance was mainly caused by heave and pitch motion of ship; Jossen (1966) analyzed wave drifting force and derived a method to obtain added resistance; Gerritsma and Beukelman (1972) established radiated energy approach to obtained added wave resistance through the energy of radiation waves; Salvensen (1978) developed a numerical method in which the effect due to second order terms of disturbing forces and moments is taken into account; Faltinsen et al. (1980) calculated added wave resistance by integrating pressure on average wetted surface of ship hull based on strip method; Arribas (2007) produced a comparison of different methods for the added resistance by using strip theory. Kihara et al. (2000) developed a nonlinear time domain method based on strip theory for high speed ship.

With the development and application of 3D potential flow theories, 3D time/frequency domain boundary element methods are used more frequently in ship's hydrodynamic calculation. Papanikolaou and Zaraphonitis (1987) obtained ship's motion and wave loads by 3D pulsating source and extended it to cases with forward speed; Zakaria (2008) solved the problem of ship's motion with forward speed in waves using 3D translating and pulsating source, and estimated added wave resistance by near field method. In addition, some scholars calculated added resistance by time domain method. Kim and Kim (2011) adopted 3D ranking panel method in time domain in hydrodynamic calculation for voyaging ship and then obtained added resistance by integration of pressure on wetted surface of ship hull.

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Generally speaking, available methods of added resistance calculation could be divided into two categories. One is near field method and another one is far field method. For far field method, energy and momentum flux of radiation and diffraction wave at infinity are taken into account. Added wave resistance could be evaluated by analyzing the change rate of total momentum. In near field method, added resistance are estimated by integrating second order pressure on average wetted surface of ship hull, which could be done based on accurate calculation of first order velocity potential. and its partial derivatives. Theoretically, results by the two methods should be coincide with each other, but it can be hardly achieved for different numerical accuracy between near field and far field. Added wave resistance is a kind of second order wave force, which is far smaller than first order wave force and better accuracy in velocity potential is requested. Even the same potential flow theory and corresponding numerical methods are used to solve the linear hydrodynamic problem, there are still some differences between the results by these two methods.

In this paper, hydrodynamic forces and motion of ship advancing in waves are estimated by using 3D frequency domain potential flow theory. The 3D translating and pulsating (3DTP) source panel method is employed to solve the radiation and diffraction potential problems, in which a semi analytical scheme is established to get more robust results of integration of Green's function over panels. Added wave resistance is mainly categorized into the contributions of radiation and diffraction according to the decomposition of unsteady velocity potential. Added resistance due to radiation motion of ship is evaluated by the radiation energy principle based on 3D hydrodynamic coefficients and ship motions. The diffraction added resistance is calculated by using the method based on steady-state force formula. Added resistance of Wigley III hull and S175 containership advancing in waves with various forward speed are carried out and analyzed in frequency domain. The results by classic methods (strip theory, 2.5D theory and 3D speed correction method) which are commonly used in engineering and the data obtained by time domain method from published papers are plotted together for comparison and discussion. The numerical results are validated for the models by comparing them with experimental data. Better agreement with experimental data in the prediction of peak value and its frequency of added resistance is achieved by present method. It also indicates that the correction of relative motion amplitude should be taken into account so as to improve the accuracy. Component analysis of added resistance are carried out and the results show the percentages of radiation part and diffraction part at various frequency respectively. The present method is of satisfactory accuracy and efficiency, which provides a rapid and robust approach to predict added wave resistance of ships advancing in waves.

2. Mathematical formulation

2.1. Coordination system

As shown in Fig. 1, a set of right-handed mean-body fixed coordinates with the x-axis directed in the direction of the forward speed and the z-axis positive upwards is considered. The ship is advancing at a constant mean forward speed U_0 in sinusoidal waves with an arbitrary heading. The translatory displacements in the x, y and z directions are X_1 (surge), X_2 (sway) and X_3 (heave), and the angular displacement of rotational motion about the x, y, and z axes are X_4 (roll), X_5 (pitch) and X_6 (yaw) respectively.

2.2. Boundary value problem

Potential theory is one of the most typical approaches in solve the problem of ship motion which is adopted in this paper. Assuming that the fluid is incompressible and inviscid, the flow is irrotational. And both incoming wave elevation and body oscillation are small. The total potential $\Phi(x,y,z,t)$in the flow field can be written as:

$$\begin{aligned}\Phi(x, y, z, t) &= \Phi_S(x, y, z) + \Phi_D(x, y, z, t)\\ &= \Phi_S(x, y, z) + \phi e^{-i\omega_e t}\end{aligned} \tag{1}$$

where Φ_S is time independent potential due to ship's steady forward motion, Φ_D is the periodic potential due to ship's oscillatory motions. And the periodic potential can be separated into three parts: the incident wave potential, the diffraction potential and the radiation potential:

$$\phi = \phi_0 + \phi_7 + \sum_{j=1}^{6} (-i\omega_e \overline{X}_j \phi_j) \tag{2}$$

where ω_0 is incident wave frequency, ω_e is encounter frequency, ϕ_0 is the incident wave potential, ϕ_7 is the diffraction potential of the restrained ship, ϕ_j is the normalized velocity potential due to forced motions in six degrees of freedom, $\bar{X}_j$ is the complex amplitude of the jth degree of freedom. The incident wave potential can be expressed as,

$$\phi_0 = \frac{Ag}{i\omega_0}\cdot\frac{\cosh k(z+H)}{\cosh kH} e^{ik(x\cos\beta + y\sin\beta)} \tag{3}$$

where A is the amplitude of incident wave, ω_0 is wave frequency,$k = \omega_0^2/g$ is wave number, H is water depth.

For diffraction and radiation wave potential, the boundary value problem to be solved is:

$$\begin{cases} \dfrac{\partial^2\phi_j}{\partial x^2} + \dfrac{\partial^2\phi_j}{\partial y^2} + \dfrac{\partial^2\phi_j}{\partial z^2} = 0, \text{ in fluid domain} \\ -\omega_e^2\phi_j + 2U_0 i\omega_e \dfrac{\partial\phi_j}{\partial x} + U_0^2 \dfrac{\partial^2\phi_j}{\partial x^2} + g\dfrac{\partial\phi_j}{\partial z}, \text{ on } z = 0 \\ \dfrac{\partial\phi_j}{\partial n} = n_j - U_0 m_j, j = 1, \ldots, 6 \\ \qquad ;\ \dfrac{\partial\phi_7}{\partial n} = -\dfrac{\partial\phi_0}{\partial n}, \text{ on ship hull} \\ \lim\limits_{R\to\infty} \sqrt{R}\left(\dfrac{\partial\phi_j}{\partial R} - ik\phi_j\right) = 0 \end{cases} \tag{4}$$

where $(n_1, n_2, n_3) = \vec{n}$ is the normal vector of ship hull. $(n_4, n_5, n_6) = \vec{r} \times \vec{n}$ is the normal vector of ship hull with respect to rotational motion. m_j is the m-term, which represents the interaction between the steady forward motion and periodic oscillatory motion of ships. By assuming that the steady potential is small $|\nabla\Phi_S| << U_0$, a simplified m-term can be written as:

$$\begin{aligned}(m_1, m_2, m_3) &= (0, 0, 0)\\ (m_4, m_5, m_6) &= (0, U_0 n_3, -U_0 n_2)\end{aligned} \tag{5}$$

2.3. Hydrodynamic forces and ship motion

To solve the boundary value problem, the mixed source and dipole distribution model and 3D translating & pulsating source Green's function (3DTP) are used. And the boundary integral equation can be written as: