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Numerical study on local steady flow effects on hydrodynamic interaction between two parallel ships advancing in waves

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ABSTRACT

Underway replenishment is an essential component of long-term naval operations. During underway replenishment, two ships travel in close proximity at a moderate forward speed. For this issue, frequency domain analysis methods with and without incorporation of local steady flow effects are developed to investigate wave loads and free motions of two parallel ships advancing in waves, which are based on analytical quadrature of the Bessho form translating-pulsating source Green function over a panel or a waterline segment and a direct velocity potential approach. The local steady flow effects were taken into consideration through m-terms in the boundary conditions; meanwhile, the Neumann-Kelvin linear free surface condition was combined. By comparing present added mass, damping coefficient and motion results of Wigley I to those of experiments and other numerical solutions; it is found that present computational results show good agreement. In order to verify these methods for hydrodynamic interaction between two parallel ships, two experiments are carried out respectively to measure the wave loads and free motions for adjacent parallel ship models advancing with an identical speed in head regular waves. Results obtained by the present solution are in favorable agreement with the model tests, meanwhile, results of methods taking the local steady flow effects into consideration show better agreement. Further, the component of wave loads and the interaction effects of speeds and different clearances are deeply investigated. It is found that the effect of clearance and the speed are important factors relating to the interaction effect.

1. Introduction

Due to its particular importance, the analysis to the hydrodynamic problem for multiple bodies at sea has been paid attention not only by hydrodynamicists but also by ship designers. A typical example of this topic is to determine the wave loads and motions of two vessels during underway replenishment for navies. Under these cases, the hydrodynamic interacting effects impact on motions and wave loads of the two ship due to the excitation of the coupled and complex waves scattering from the two ships.

By far, well-developed methods of dealing with seakeeping performance of a single ship in waves, such as the 2D potential flow method, e.g. Tasai [1], Salvesen et al. [2], or the three dimensional potential flow method, e.g. Chang [3], and the domain-decomposition method combining potential and viscous theories, have been expanded to investigate the hydrodynamic interaction effects between two parallel ships. Among these, the 2D strip or slender body theories have been investigated by Okhusu [4], Oortmerssen [5], Duncan et al. [6], Fang and Kim [7], and Skejic and Faltinsen [8]; nevertheless, the limitations of 2D potential theories are well documented and usually overestimate the coupled motions in resonance frequency due to the wave energy trapping between two hulls. The domain-decomposition method combing potential and viscous flow theories has been developed by Kristiansen and Faltinsen [9], but no attempts have been carried out to depose the present problem. The 3D theories in frequency domain or time domain based on Green functions satisfying the linearized free surface conditions or Rankine source have been studied by Xie et al. [10], Chen and Fang [11], Li [12], and McTaggart et al. [13], Wang [14], Zhang et al. [15], Kim and Kim [16], Deng et al. [17], Xiang and Faltinsen [18], Xiang [19], Xu [20], Nam et al. [21], Graefe et al. [22] and Yuan et al. [23–26]. The predicting accuracy is much better than that of the 2-D method because the 3D fluid hydrodynamic effects are taken into account. However, the transient Green function method has disadvantages in convergence; the pulsating source Green function method satisfies the zero speed linearized free surface condition and the

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correction of the speed effects on the free surface neglects interactions between the motions of oscillation and translation.

In contrast, the 3D translating-pulsating source Green function (3DTP) which satisfies the classical linearized free surface condition with a forward speed and the Rankine source may be more genuine and stricter than the other methods. As for 3DTP method, the linear free surface condition and the far field radiation condition was automatically satisfied, and panels can only be distributed on the mean wet ship surface; when the fast numerical integration method for this kernel Green function was established, it can be used to analyze hydrodynamic interaction between two adjacent ships. As for Rankine source method in frequency domain, the advantages are obvious, such as, the flexible choice of free surface conditions, can be extended to investigate shallow water effects and the resonance on the free surface in the gap between two ships; however, there are still some attentions should be specially paid on for the extensive use of the this approach, such as, the proper and effective radiation condition should be proposed, the domain size and panel distributions of free surface should be paid special attention and adjusted according to the incident wave lengths and the Brard number τ ($\tau = u\omega/g$) (to accurately capture the complex wave patterns of the free surface, including outer, inner V wave systems and ring or fan wave systems). In present study, 3DTP method was adopted for unsteady problem.

The mathematical formulations of the translating-pulsating source Green function method have been well established, but the numerical solutions have been presented in limited circumstances. For example, the interaction terms between the local steady flow and unsteady wave fields (the so-called m-terms), have been overlooked. This is because the second derivatives of the steady potential in the m-terms are complicated and difficult to implement in an accuracy manner. In many cases, the steady potential has been taken from a free stream for simplicity. Relevant issue has been investigated by Nakos [27], Inglis and Price [28], Iwashita and Ohkusu [29], Iwashita and Bertram [30], Fang and Lin [31], Chen and Malencia [32], Duan and Price [33], Ahmed et al. [34]. They found that the effect of the steady wave flow could be remarkable on the local wave pressure near the bow region of a single ship. More recent and comprehensive researches on this issue were presented by Zhang et al. [35], Xie and Dracos [36], and Shao and Faltinsen [37]. It can be found that Neumann-Kelvin formulation (both for the free surface and body boundary conditions) show less satisfactory; double-body m-terms play a more important role for many cases and method based on Neumann-Kelvin formulation for free surface condition and double body m-terms for body boundary conditions can also give fairly good results, despite of incomplete consistence in boundary value problem. According to the published literatures, few reports about influence of local steady flow effects on hydrodynamic performance of two parallel ships in waves have been made.

In present study, the Neumann-Kelvin linear free surface condition and combination of local steady flow effects into m-terms for body boundary conditions were used (which was similar to the case of "LFS,DB m-terms" in Zhang et al.). Then, this method was used to investigate the local steady flow effects on hydrodynamic interaction between two parallel ships. By comparing the experimental data with various numerical results, validation of the present method can be obtained. Further, the influence of clearances and speed effects on motions of these two ship model was analyzed.

2. Mathematical formulation

2.1. Coordinate system

To solve this problem, an earth-fixed system o-xyz and two body coordinate systems of o_a-$x_a y_a z_a$ for ship-a and o_b-$x_b y_b z_b$ for ship-b, as shown in Fig. 1, are established. The systems are all right-handed. The origin of each system is placed on the undisturbed free surface, and the x-axis is positive in the direction of the speed U of the two ships. The z-axis of each body system is positive upward and crosses the center of gravity respectively. Planes of o-xy, o_a-$x_a y_a$ and o_b-$x_b y_b$ locate on the calm free surface. D_x and D_y are defined as longitudinal and transverse distances between the two ships, respectively.

2.2. Velocity potentials

The regular incident wave is coming from a direction with an angle β, which is the angle between the positive x-axis and the incident wave direction. Thus 180° means heading sea and the other wave directions can be found in Fig. 1. The incident potential Φ_0 is given as below,

$$\Phi_0(x,y,z,t) = \phi_0 e^{-i\omega_e t} \tag{1}$$

$$\phi_0 = -\frac{ig\varsigma}{\omega_0} e^{k_0 z} e^{k_0(x\cos\beta + y\sin\beta)} \tag{2}$$

where $k_0 = \omega_0^2/g$ is wave number of the incident wave, ω_0 and ς are the frequency and amplitude. ω_e is the encounter frequency. The fluid is assumed ideal and incompressible of constant density. The irrotational flow is assumed throughout, and the surface tension effects are neglected. The velocity potential $\Phi_T(x,y,z,t)$ is introduced and can be written as,

$$\Phi_T(x,y,z,t) = -Ux + \phi_s(x,y,z) + \Phi(x,y,z,t) \tag{3}$$

where ϕ_s and Φ are the steady disturbance potential and unsteady potential, respectively. In the first order problem, all unsteady motions are assumed to be sinusoidal in time with the encounter frequency ω_e, and by the linear decomposition, the unsteady potential Φ can be expressed in the form as below,

$$\Phi(x,y,z,t) = \Phi_R + \Phi_7 + \Phi_0 = (\phi_R + \phi_7 + \phi_0)e^{-i\omega_e t} \tag{4}$$

Here Φ_R and Φ_7 are the coupled radiation and diffraction potentials in the field, and ϕ_R and ϕ_7 are the time-independent part of them.

2.3. Boundary conditions

The free surface condition, body boundary conditions for the radiation and diffraction problem can be summarized as follows:

2.3.1. Body boundary conditions for the radiation and diffraction problem

Due to hydrodynamic interactions, definite conditions for the radiation problem are more complicated for two parallel ships. This problem can be simplified and divided into two separated conditions: (1) Ship-a is in motion and oscillations of ship-b are fixed; (2) Ship-b is in motion and oscillations of ship-a are fixed. Then the coupled radiated velocity potential of ϕ_R can be written as $\phi_R = \phi_R^1 + \phi_R^2$, where ϕ_R^1 and ϕ_R^2 are assumed as the radiation velocity potential corresponding to the two conditions and can be further decomposed as in Eq. (5). Where by, ϕ_R can be expressed as shown in Eq. (6).

$$\phi_R^1 = \sum_{j=1}^{6} \phi_{aj}\overline{\eta}_{aj}, \quad \phi_R^2 = \sum_{j=1}^{6} \phi_{bj}\overline{\eta}_{bj} \tag{5}$$