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Numerical and experimental study on seakeeping performance of ship in finite water depth

Chao-Bang Yao*, Xiao-Shuai Sun, Wei Wang, Qing Ye

Department of Naval Architecture Engineering, Naval University of Engineering, Wuhan 430033, China

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ABSTRACT

Vessels operating in shallow waters require careful observation of the finite-depth effect. In present study, a Rankine source method that includes the shallow water effect and double body steady flow effect is developed in frequency domain. In order to verify present numerical methods, two experiments were carried out respectively to measure the wave loads and free motions for ship advancing with forward speed in head regular waves. Numerical results are systematically compared with experiments and other solutions using the double body basis flow approach, the Neumann-Kelvin approach with simplified m-terms, and linearized free surface boundary conditions with double-body m-terms. Furthermore, the influence of water depths on added mass and damping coefficients, wave excitation forces, motions and unsteady wave patterns are deeply investigated. It is found that finite-depth effect is important and unsteady wave pattern in shallow water is dependent on both of the Brard number τ and depth Froude number F_h.

1. Introduction

With the increasing activities of vessels operating in shallow waters, much attention is paid to the determination of the behavior of a ship due to waves in finite depth. Knowledge to predict the seakeeping performance of a ship in such water depth is important for naval architects, ship owners, harbor authorities and harbor designers, especially due to the fact that the scale enlargement in the maritime fleet and the rapid development of large floating-type offshore structures.

Ship motions are directly affected in two ways by the restricted water depth (see Yuan et al. [1]): (1) the incident waves are changed and as a result, the wave exciting forces exerted on ship differ from those in deep water; (2) the hydrodynamic coefficients of the ship are changed by the nearness of the sea bottom. As for these topics, many solution schemes have been introduced, such as strip theory method (Tuck [2], Chu [3], Tasai et al. [4], Andersen [5], Perunovic et al. [6]), a unified theory (Kim [7]). Because the strip method has a computational time advantage, it is still widely used for practical purposes. Nevertheless, the limitations of 2D potential theories are well documented and usually overestimate the coupled motions in resonance frequency; and researchers suggested that methods including the three-dimensional effect in the solution of the strip method, showing a significant improvement in accuracy.

Nowadays, three-dimensional panel method programs in time domain and frequency domain that include the finite-depth effect based on Green functions satisfying the linearized free surface conditions or Rankine source are available, such as, Li [8], Kim and Kim [9], Oortmerssen [10], Grant and Holboke [11], Clauss et al. [12], Fonseca et al. [13], Yuan et al. [1], Xiong et al. [14] and Feng et al. [15]. Because the panel method constitutes a whole domain with panels, it can formulate an arbitrary bottom topology if waves can be modeled appropriately. The predicting accuracy is better than that of the 2-D method because the 3D fluid hydrodynamic effects are taken into account. Among these methods, the pulsating source Green function method satisfies the zero speed linearization free surface condition and the speed effects on the free surface neglects interactions between the motions of oscillation and translation; 3-D translating-pulsating source Green function in finite water depth is complex to describe and evaluate (see Takagi [16]).

In contrast, the Rankine source method is more proper to analyze seakeeping performance of a ship advancing in finite water depth in seaways. This approach for deep water case has been used by many investigators since it has been first proposed by Hess and Smith [17]. Such as Sclavounos and Nakos [18], Kring [19], He et al. [20], Shao et al. [21], Das and Cheung [22,23], Yuan et al. [24,25]. But there are still some issues should be paid attention to. First of all, the Rankine source method requires much more panels which will

* Corresponding author.
E-mail address: hgycb2004111@163.com (C.-B. Yao).

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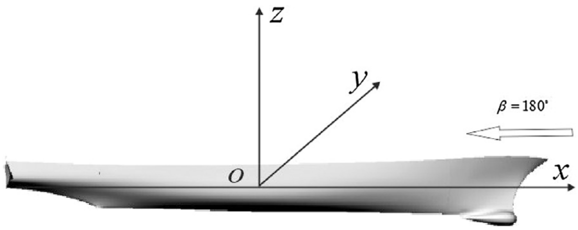

Fig. 1. Coordinate systems.

considerably increase the computation time. However, with the development of computer and technology of parallel computing, the computation time might be acceptable for practical application. Besides, the Rankine source method requires a suitable radiation boundary condition to account for the scattered waves in current. Two methods to model this problem are popular. One is so-called upstream radiation condition, which was proposed by Nakos [26]. The free surface was truncated at some upstream points, and a quiescent boundary condition was imposed at these points to ensure the consistency of the upstream truncation of the free surface. Another method is to move the source points on the free surface at some distance downstream (Jensen et al. [27], Iwashita [28] and Elangovan et al. [29]). Recently, Das and Cheung [22,23] provided an alternative solution to the boundary-value problem, who corrected the Sommerfeld radiation condition by taking into account the Doppler shift of the scattered waves at the control surface that truncates the infinite fluid domain. And the validation of this new form of radiation condition has been confirmed by Yuan et al. [1,24,25].

In present study, a Rankine source panel method taking the effect of steady flow based on Das and Cheung's radiation condition is developed to analyze motion, wave loads and unsteady wave patterns of a ship advancing in shallow water. By comparing the experimental data with various numerical results, validation of the present method can be obtained. Further, the influence of water depths on ship hydrodynamic characteristics was analyzed.

2. Mathematical formulation

2.1. Coordinate system

Let *o-xyz* be the right-hand Cartesian coordinate system moving together with the hull, with *xoy* plane on the mean free surface. The origin is located on the still water plane, and the x-axis is positive in the direction of the speed u_0 of the ship. The z-axis is positive upward as shown in Fig. 1.

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. The incident potential Φ_0 is given as below,

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

$$\phi_0=-\frac{ig\varsigma}{\omega_0}\frac{\cosh\ k_0(z+h)}{\cosh\ k_0 h}e^{ik_0(x\ \cos\beta+y\ \sin\beta)} \tag{2}$$

Where $k_0\tanh k_0 h=\omega_0^2/g$ 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,

$$\Phi_T(x,y,z,t)=-u_0x+\phi_s(x,y,z)+\Phi(x,y,z,t) \tag{3}$$

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,

$$\begin{aligned}\Phi(x,y,z,t)&=\Phi_R+\Phi_7+\Phi_0=(\phi_R+\phi_7+\phi_0)e^{-i\omega_e t}\\&=\left[\sum_{j=1}^{6}(\eta_j\phi_j)+\phi_7+\phi_0\right]e^{-i\omega_e t}\end{aligned} \tag{4}$$

Here Φ_R and Φ_7 are the coupled radiation and diffraction potentials in the field; ϕ_R and ϕ_7 are the time-independent part of them; η_j is the j-th mode motion of ship, the values of j = 1,. . ., 6, corresponding to the order of surge, sway, heave, roll, pitch and yaw. ϕ_j is radiation velocity potential due to per unit amplitude motion in the j-th mode of ship.

2.3. Boundary conditions

2.3.1. Boundary conditions for steady potential

The steady potential ϕ_s, which accounts for the near-field modification of the uniform current, is important to wave scattering around non-slender vessels with a forward speed U. In the boundary-value problem, it satisfies the zero flux condition on the still water surface at z = 0, the seabed at z = $-h$, and the body surface as,

$$\nabla^2\phi_s=0 \tag{5}$$

$$\frac{\partial\phi_s}{\partial n}=0\quad \text{at } z=0 \text{ and }\quad z=-h \tag{6}$$

$$\vec{W}\cdot\vec{n}=0\quad \text{at } S_B \tag{7}$$

Where $\vec{W}=\nabla(\phi_s-u_0x)$. According to Das and Cheung [22], in this so-called double-body flow, $\nabla\phi_s$ attenuates rapidly and ϕ_s becomes a constant away from the body. Both are set equal to zero at the control surface to complete the boundary-value problem.

2.3.2. Boundary conditions for unsteady potential

The unsteady perturbation potential ϕ_j can be solved by the following boundary value problem:

$$\nabla^2\phi_j=0 \tag{8}$$

in the fluid domain

$$\begin{aligned}&-\omega_e^2\phi_j-2i\omega_e u_0\frac{\partial\phi_j}{\partial x}+u_0^2\frac{\partial^2\phi_j}{\partial x^2}+g\frac{\partial\phi_j}{\partial z}-i\omega_e\nabla_1^2\phi_s\phi_j-2i\omega_e\nabla_1\phi_s\cdot\nabla_1\phi_j\\&=\begin{cases}0 & (j=1,\ldots,6)\\ i\omega_e\nabla_1^2\phi_s\phi_0+2i\omega_e\nabla_1\phi_s\cdot\nabla_1\phi_0 & (j=7)\end{cases}\end{aligned} \tag{9}$$

on the undisturbed free surface S_f. ∇_1 is the horizontal gradient operator.

$$\frac{\partial\phi_j}{\partial n}=\begin{cases}-i\omega_e n_j+m_j, & j=1,2,\ldots,6\\ -\dfrac{\partial\phi_0}{\partial n}, & j=7\end{cases} \tag{10}$$

on the mean wetted part of the body surface S_b. And the so-called m-terms are defined as

$$(m_1,m_2,m_3)=-(\vec{n}\cdot\nabla)\nabla(\phi_s-u_0x) \tag{11}$$

$$(m_4,m_5,m_6)=-(\vec{n}\cdot\nabla)[\vec{r}\times\nabla(\phi_s-u_0x)] \tag{12}$$