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Numerical Computations of Ship Motions and Added Resistance in Head Waves Using Fully Nonlinear Potential Flow Method and Body-Exact Method

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HIGHLIGHTS

- A fully nonlinear potential flow method is applied for the seakeeping simulations.
- The formula for added resistance is established based on the body-exact method.
- The results by the fully nonlinear potential flow method and the body-exact method are compared with the linear numerical solutions using the double-body and Neumann-Kelvin methods.

1 INTRODUCTION

The seakeeping performance is one of the key factors for ship design and hull form optimization. Traditionally, the numerical investigations on ship motions and added resistance are primarily based on the strip theory which may have limited applications due to the slende-body assumption. In the last two decades, with the swift development of computing hardware, many three-dimensional time-domain approaches have been developed. However, most of the previous studies are conducted using the linear or weakly-nonlinear potential flow methods with the linearized free-surface and body boundary conditions. As the added resistance in the resonant wavelength region is mainly contributed by the radiation-related component, it is necessary to investigate the nonlinear effects of the body boundary condition due to the large vertical motions. Therefore, the body-exact theory proposed in Zhang & Beck (2007) and Bandyk & Beck (2008) is extended for the simulations of ship motions and added resistance in the present paper. In recent years, some fully nonlinear potential flow (FNPF) methods have been developed for the investigations on ship hydrodynamic responses, such as Mola *et al.* (2017), Tang *et al.* (2021) and Irannezhad *et al.* (2022). There is still lack of systematic works studying the added resistance and the nonlinear effects using a FNPF method.

In the present study, two time-domain nonlinear seakeeping models, employing the desingularized-Rankine panel method (DRP), are extended to study the motion responses and added resistance problem: a fully nonlinear potential flow (FNPF) method and a body-exact (BE) method. The mixed Euler-Lagrange free-surface time stepping scheme is employed. In the present two methods, the updating of panel arrangement on the instantaneous wetted hull surface is implemented based on NURBS curves. The proposed methods have been validated by comparing with the experimental data and the numerical solutions by double-body (DB) and Neumann-Kelvin (NK) methods (Song *et al.*, 2022). In the double-body method, the ship induced double-body free-surface elevation is assumed to be small, and the interaction between the steady and unsteady flows is taken into account through the so-called m-terms.

2 MATHEMATICAL FORMULATION

Two nonlinear seakeeping models are developed to study the motions responses and added resistance for ships with a constant speed $\vec{W} = (U, 0, 0)$ in head waves. Three right-handed Cartesian coordinate systems are employed: the earth-fixed system $x_0y_0z_0$, the xyz system which is fixed to the mean position of the ship, and the body-fixed system XYZ.

In the xyz system, the velocity potential ϕ is introduced to describe the fluid motion so that the fluid velocity can be expressed as

$$\vec{V}(\vec{x},t) = \nabla\left(-Ux + \phi(\vec{x},t)\right). \tag{1}$$

The velocity potential ϕ and the free-surface elevation η are decomposed as $\phi = \phi_d + \phi_I$ and $\eta = \eta_d + \eta_I$, respectively. The subscripts $_d$ and $_I$ denote the disturbed and incident waves, respectively.

In the XYZ system, the equations of motions are solved, where the Euler angles are taken into account.

2.1 Body-Exact Method

In the body-exact (BE) method, the linearized free-surface boundary conditions and the nonlinear body boundary condition are applied, which are satisfied on the calm water surface and the exact submerged hull surface, respectively. The boundary value problem for the disturbed wave potential can be written as

$$\nabla^2\phi_d = 0 \quad \text{in the fluid domain,} \tag{2}$$

$$\frac{\delta\eta_d}{\delta t} = \vec{W}\cdot\nabla\eta_d + \frac{\partial\phi_d}{\partial z} + \vec{v}\cdot\nabla\eta_d \quad \text{on} \quad z=0, \tag{3}$$

$$\frac{\delta\phi_d}{\delta t} = \vec{W}\cdot\nabla\phi_d - g\eta_d + \vec{v}\cdot\nabla\phi_d \quad \text{on} \quad z=0, \tag{4}$$

$$\nabla\phi_d\cdot\vec{n} = \vec{W}\cdot\vec{n} + \vec{V}_H\cdot\vec{n} - \vec{n}\cdot\nabla\phi_I \quad \text{on} \quad S_{B_0}, \tag{5}$$

where g is the gravitational acceleration; $\vec{n}$ is the inward unit normal on the body surface (out of fluid) in the xyz system; $\vec{V}_H$ is the motion velocity including rotational modes of a point on the ship's surface; S_{B_0} represents the instantaneous submerged hull surface below the calm water surface. $\frac{\delta}{\delta t}$ is the time derivative following a fluid particle along a prescribed path, and is defined as

$$\frac{\delta}{\delta t} = \frac{\partial}{\partial t} + \vec{v}\cdot\nabla, \tag{6}$$

where the velocity of the particle is $\vec{v} = (-U, v, 0)$. Here, v is the prescribed velocity of a collocation point such that it moves along a given path around the hull.

For the computation of ship resistance, the pressure integrations over the instantaneous wetted surfaces below and above the calm water surface should be both taken into account. Assuming that the normal and the flare angle are constant around the waterline within the wave elevation, the fluid force in the longitudinal direction can be approximated by

$$F_1 = \iint_{S_{B_0}} p n_1 \mathrm{d}s + \int_{WL} \frac{1}{2}\rho g\eta^2 \frac{n_1}{\sin\alpha}\mathrm{d}l, \tag{7}$$

where p represents the pressure; α denotes the flare angle measured at the instantaneous calm water surface, with $\alpha = 90°$ being for the wall-sided case. The added resistance is defined as the difference between the average resistances on the ships in waves and in calm water.

2.2 Fully Nonlinear Potential Flow Method

In the fully nonlinear potential flow (FNPF) method, the boundary value problem for the disturbed wave potential can be writtem as

$$\nabla^2\phi_d = 0 \quad \text{in the fluid domain,} \tag{8}$$

$$\frac{\mathrm{D}\eta_d}{\mathrm{D}t} = \frac{\partial \phi_d}{\partial z} + \frac{\partial \phi_I}{\partial z} - \frac{\partial \eta_I}{\partial t} + \left(\vec{W} - \nabla\phi_I - \nabla\phi_d\right) \cdot \nabla\eta_I \quad \text{on} \quad z = \eta(x, y, t), \tag{9}$$

$$\frac{\mathrm{D}\phi_d}{\mathrm{D}t} = -g\left(\eta_d + \eta_I\right) - \frac{\partial \phi_I}{\partial t} + \left(\vec{W} - \frac{1}{2}\nabla\phi_I\right) \cdot \nabla\phi_I + \frac{1}{2}\nabla\phi_d \cdot \nabla\phi_d \quad \text{on} \quad z = \eta(x, y, t), \tag{10}$$

$$\nabla\phi_d \cdot \vec{n} = \vec{W} \cdot \vec{n} + \vec{V}_H \cdot \vec{n} - \nabla\phi_I \cdot \vec{n} \quad \text{on} \quad S_B, \tag{11}$$

where S_B denotes the instantaneous wetted hull surface; $\frac{\mathrm{D}}{\mathrm{D}t} = \frac{\partial}{\partial t} + \vec{V} \cdot \nabla$ is the material derivative.

The fluid force in the longitudinal direction can be obtained by

$$F_1 = \iint_{S_B} p n_1 \mathrm{d}s. \tag{12}$$

3 RESULTS AND DISCUSSION

The present results of heave and pitch motions of the S-175 containership are compared with the experimental data (Tasaki & Mizoguchi, 1981; Fonseca & Soares, 2004) and the numerical solutions using DB and NK methods (Song *et al.*, 2022). As shown in Fig. 1, the heave motions near the resonant wavelengths are obviously overestimated by the DB and NK methods, while the FNPF and BE methods give better predictions which generally agree well with the experimental data. This indicates the significance of the nonlinearity of body boundary condition for the ships with flare, like the S-175 containership.

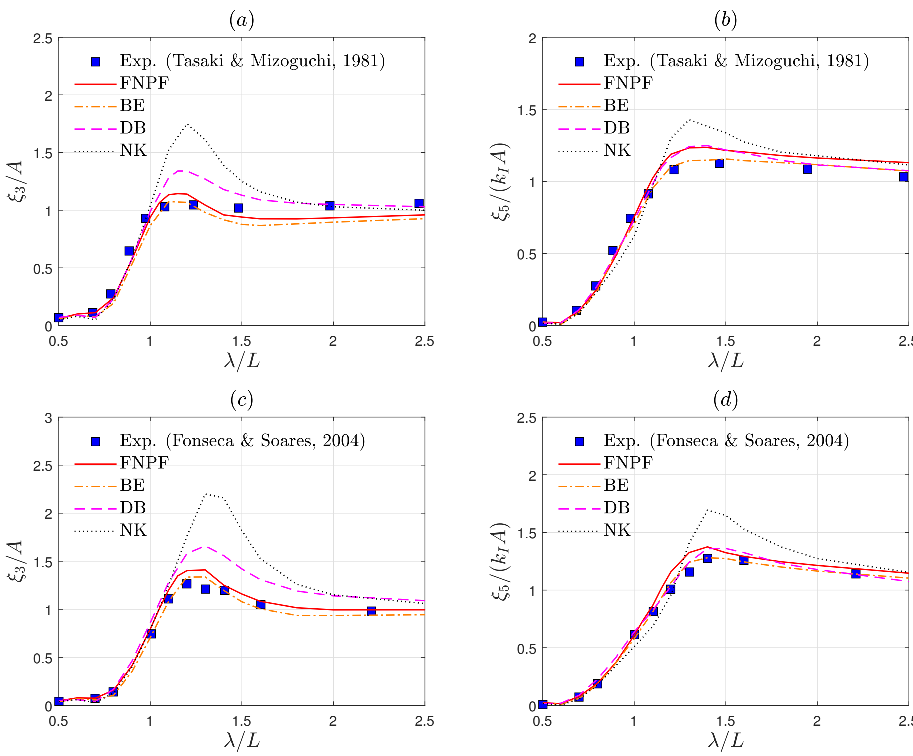

Figure 1: Heave and pitch RAOs of the S-175 containership in head waves, $A/L = 0.003$: (a) Heave, $F_n = 0.2$; (b) Pitch, $F_n = 0.2$; (c) Heave, $F_n = 0.25$; (d) Pitch, $F_n = 0.25$.

The present results of added resistance are illustrated in Fig. 2, together with the comparative experimental measurements (Fujii & Takahashi, 1975; Nakamura & Naito, 1977) and the linear numerical solutions using the DB and NK methods (Song *et al.*, 2022). At $F_n = 0.2$, the numerical results by the FNPF and DB methods are almost the same. However, at high forward speed

($F_n \geq 0.25$), the resonant wavelength of added resistance by the DB method is slightly larger than that by the FNPF method. This is consistent with the phenomenon observed in the motion responses computed by the two methods. As can be seen in Figs. 2(c) and (d), the FNPF method gives better predictions of the added resistance around the resonant wavelength than the DB method at high forward speed ($F_n \geq 0.25$), which suggests that the nonlinearity of the free-surface boundary condition has significant effects on the added resistance at high forward speed.

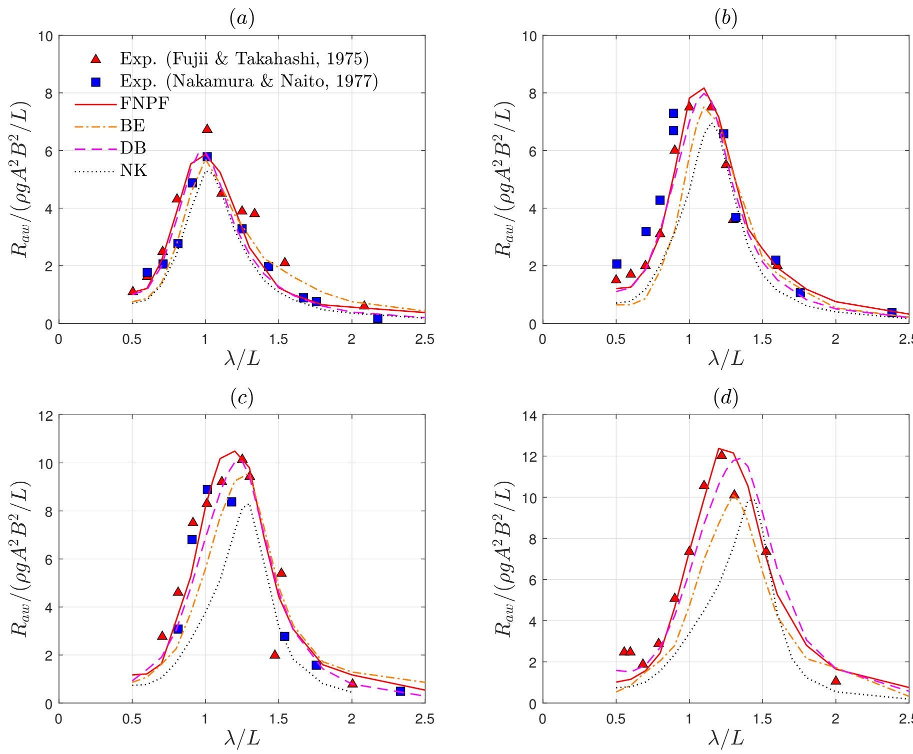

Figure 2: Added resistances of the S-175 containership in head waves, $A/L = 0.003$: (a) $F_n = 0.15$; (b) $F_n = 0.2$; (c) $F_n = 0.25$; (d) $F_n = 0.3$.

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