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Seakeeping computations using double-body basis flows

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ABSTRACT

Three-dimensional, time-domain, ship–wave interactions are studied in this paper for problems with forward speed. Free surface boundary conditions are derived based on a double-body linearization and the mixed Euler–Lagrange time stepping technique. The boundary integral equations are solved at each time step by distributing desingularized sources above the calm water surface and employing constant-strength panels on the body surface.

Radiation, diffraction, and free motion results for a Wigley hull and a Series 60 hull are presented and systematically compared with the experiments and other numerical solutions using the Neumann–Kelvin approach with simplified *m*-terms, linearized free surface boundary conditions with double-body *m*-terms, and the time-domain body-exact strip theory. By comparing the present results to experiments and other numerical solutions, it is found that the present computational model using double-body linearization gives improved results. It is also demonstrated that the *m*-terms are very important to obtain accurate hydrodynamic coefficients, while the leading-order terms included in the free surface boundary conditions of the present model can also improve the computational accuracy of the cross-coupling radiation damping.

1. Introduction

In ship and offshore designs, the accurate prediction of wave-induced motions and loads is very important. It requires knowledge of the extreme value of various design parameters such as motion amplitudes, bending moments, wave-induced hydrodynamic pressures on the hull, local slamming forces, etc.

A mixed Euler–Lagrange time stepping scheme (MEL) was first introduced by Longuet-Higgins and Cokelet [1] for solving two-dimensional fully nonlinear water wave problems. Since then, MEL methods have also been successfully used to solve fully nonlinear, three-dimensional wave and wave–body interaction problems [2–12] either using a boundary element method (BEM) or a finite element method (FEM). Recently, Liu et al. [13] used a desingularized boundary element method with a MEL formulation to study the nonlinear wave scattering by a submerged horizontal plate. The problems with the fully nonlinear MEL computations include numerical instabilities of the free surface and wave breaking. The instabilities can often be eliminated by improved numerical techniques, but wave breaking is a natural phenomenon that is expected to occur in any large body motion or wave situation. Computations normally are forced to stop when wave breaking occurs. Various techniques have been proposed to continue the computations after wave breaking, but they are still not robust and can lead to nonphysical solutions.

A compromise between fully nonlinear computations and linear theory is the so-called body-exact approach. In the body-exact approach, the body boundary condition is satisfied on the instantaneous wetted surface of the body while the linearized free surface boundary conditions are retained. In order to solve for the hydrodynamic forces due to large body motions in the body-exact problem, a time-domain approach is preferred. A method to deal with the exact body boundary condition using a time-domain free surface Green's function has been developed by Beck and Magee [14] for a submerged body performing arbitrary motions. Other researchers such as Lin and Yue [15], Bingham [16] have also successfully obtained results for a surface-piercing body using the time-domain free surface Green's function method. Huang and Sclavounos [17] investigated nonlinear ship motion problems using the body-exact technique and weak-scatter theory. Sen [18] and Singh and Sen [19] solved large amplitude free motion problems using the time-domain free surface Green's function while considering the incident wave nonlinearities. Recently, Zhang and Beck [20,21] developed a computationally efficient, time-domain, two-dimensional body-exact model using Rankine sources to solve large amplitude radiation and diffraction problems including water entry and exit. Comparisons with other numerical calculations and experiments were good. Also, Zhang [22], Zhang and Beck [23] presented a three-dimensional model using the body-exact technique with desingularized sources above the free surface and panels on the body surface. As has been found in the

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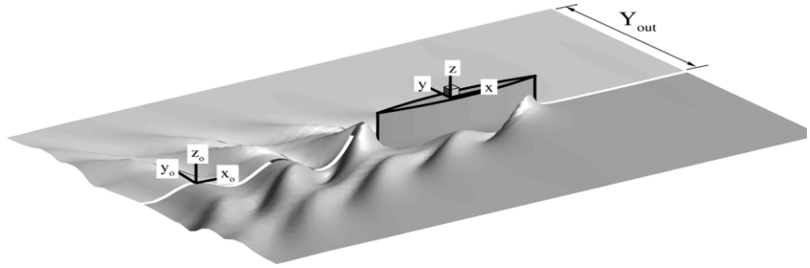

Fig. 1. Definition of the problem and coordinate systems.

previous study, for a wall-sided body, the change of hydrodynamic force due to the instantaneous wetted body surface is trivial, while for a non-wall-sided body the body-exact computation can be critical.

In this paper, we have continued to develop a three-dimensional model based on a double-body linearization and the mixed Euler–Lagrange time stepping technique. The motivation of the present study is to formulate and develop a more reliable and accurate model to simulate ship motions in waves. The second objective of this study is to identify the effects of free surface nonlinearities and the coupling effects between the steady and unsteady flow on the prediction of hydrodynamic coefficients by quantifying the differences between the present model and other numerical approaches. It should be noted that the present model is based on the assumption that disturbance due to the presence of ship is small, which means that ship induced double-body free surface elevation is small. This can be justified in the case of a slender ship.

In the present study, free surface boundary conditions are applied on the calm water surface, and the body boundary condition is applied on the mean wetted hull surface. Linear hydrostatic restoring and Froude–Krylov forces are also used in the present simulations. The present model can be extended to study the body-exact problem and the added resistance problem by satisfying the body boundary condition on the instantaneous wetted body surface. Those results will be reported elsewhere.

2. Mathematical formulation

A boundary value problem for a vessel traveling in deep water is solved. The vessel moves with speed $\mathbf{U}(t) = (U_o(t), 0, 0)$, and may be undergoing unsteady oscillations in its six degrees of freedom. The fluid is assumed to be ideal and the flow irrotational. Three coordinate systems will be employed: the $\mathbf{x_o}$ system is fixed in space, the $\mathbf{x}$ system is fixed to the mean position of the ship (moving with forward speed $\mathbf{U}(t)$ along the straight track of the ship), and the $\bar{\mathbf{x}}$ system is fixed to the ship. The boundary value problem is solved in the right hand moving coordinate system (x, y, z), as shown in Fig. 1. The x-axis points in the direction of travel and the z-axis points upward. The origin is on the calm water plane at mid-ship.

In the $\mathbf{x}$ coordinate system, a velocity potential is introduced to describe the fluid motion by using the above assumptions such that the fluid velocity can be expressed as the gradient of a potential function, $\mathbf{V}(\mathbf{x}, t) = \nabla\Phi = \nabla(-U_o(t)x + \phi(x, y, z, t))$, where ϕ is the disturbance velocity potential which may include the radiation and/or diffraction potential.

The velocity potential $\phi(x, y, z, t)$ satisfies the Laplace equation

$$\phi_{xx} + \phi_{yy} + \phi_{zz} = 0 \tag{1}$$

The exact nonlinear kinematic and dynamic free surface boundary conditions are

$$\frac{\partial\eta}{\partial t} = \frac{\partial\phi}{\partial z} - \nabla\phi\cdot\nabla\eta + U_o(t)\frac{\partial\eta}{\partial x} \quad \text{on } z = \eta(x, y, t) \tag{2}$$

$$\frac{\partial\phi}{\partial t} = -g\eta - \frac{1}{2}\nabla\phi\cdot\nabla\phi + U_o(t)\frac{\partial\phi}{\partial x} \quad \text{on } z = \eta(x, y, t) \tag{3}$$

where $\eta(x, y, t)$ represents the free surface elevation; g is the gravitational acceleration. All the velocity potentials satisfy the Laplace equation under the assumption of ideal potential flow.

The exact body boundary condition can be written as

$$\mathbf{n}\cdot\nabla\phi = U_o(t)n_1 + \mathbf{V_H}\cdot\mathbf{n} - \nabla\phi^I\cdot\mathbf{n} \quad \text{on } S_B \tag{4}$$

where S_B is the instantaneous wetted body surface; $U_o(t)$ is the time-dependent translating velocity of the body in the x direction; $\mathbf{n}$ is the inward unit normal on the body surface (out of fluid); n_1 is the component of the unit normal in the x direction; $\mathbf{V_H}$ is the motion velocity including rotational modes of a point on the ship's surface; ϕ^I is the velocity potential for an incident wave.

By applying Green's theorem, using desingularized sources above the calm water surface and constant-strength panels on the hull, the velocity potential can be written as (see [24])

$$\phi(\mathbf{x}) = \sum_{N_F} G(\mathbf{x}; \boldsymbol{\xi})\sigma(\boldsymbol{\xi}) + \iint_{S_B} G(\mathbf{x}; \boldsymbol{\xi})\sigma(\boldsymbol{\xi})\mathrm{d}s \tag{5}$$

where $G = \frac{1}{r(\mathbf{x};\boldsymbol{\xi})}$; σ is the source strength on the boundary; S_F is the calm water surface; N_F is the number of desingularized sources above the calm water surface.

The disturbance potential ϕ must satisfy the far field boundary conditions such that there must be no incoming waves and, in the deep water problem, $\nabla\phi$ vanishes as $z \rightarrow -\infty$. The initial conditions at $t = 0$ can be written as

$$\phi = \phi_t = 0 \text{ in the fluid domain} \tag{6}$$

After solving the boundary value problem, the pressure on the body due to the disturbance potential can be computed using Bernoulli's equation,

$$p = -\rho\left(\frac{\partial\phi}{\partial t} - U_o(t)\frac{\partial\phi}{\partial x} + \frac{1}{2}\nabla\phi\cdot\nabla\phi + gz\right) \tag{7}$$

It should be noted that the pressure due to the incident waves will be included in the next section.

The force and moment acting on the body can be determined by using

$$\mathbf{F} = \iint_{S_B} p\,\mathbf{n}\mathrm{d}s \tag{8}$$

$$\mathbf{M} = \iint_{S_B} p\,(\mathbf{x}\times\mathbf{n})\mathrm{d}s \tag{9}$$

2.1. Linearization of the free surface boundary conditions and body boundary condition

The fully nonlinear free surface boundary conditions (2) and (3) can be linearized using a double-body basis flow Ψ. The total disturbance velocity potential is decomposed into a double-body basis flow and other perturbation flows ϕ', which may include diffraction and radiation wave components,

$$\phi(\mathbf{x}, t) = \Psi(\mathbf{x}, t) + \phi'(\mathbf{x}, t) \tag{10}$$