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Fast computation of the transient motions of moving vessels in irregular ocean waves

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ABSTRACT

A fast time-domain method is developed in this paper for the real-time prediction of the six degree of freedom motions of a vessel traveling in an irregular seaway in infinitely deep water. The fully coupled unsteady ship motion problem is solved by time-stepping the linearized boundary conditions on both the free surface and body surface. A velocity-based boundary integral method is then used to solve the Laplace equation at every time step for the fluid kinematics, while a scalar integral equation is solved for the total fluid pressure. The boundary integral equations are applied to both the physical fluid domain outside the body and a fictitious fluid region inside the body, enabling use of the fast Fourier transform method to evaluate the free surface integrals. The computational efficiency of the scheme is further improved through use of the method of images to eliminate source singularities on the free surface while retaining vortex/dipole singularities that decay more rapidly in space. The resulting numerical algorithm runs 2–3 times faster than real time on a standard desktop computer. Numerical predictions are compared to prior published results for the transient motions of a hemisphere and laboratory measurements of the motions of a free running vessel in oblique waves with good agreement.

1. Introduction

Technological advances in the real-time measurement of ocean wave conditions with remote sensing devices have led to a growth in the need for fast techniques to predict ship/platform motions in real-time aboard ships and oil platforms [1–4]. The motion forecasts could be used to provide ship/platform operators advance warning of dangerous motions; evaluate in real-time the optimal path of manned/unmanned vessels to mitigate vessel motions; and design real-time motion compensation systems for ships, ocean platforms or wave energy devices.

Numerical methods based on boundary integral equations are often used to simulate transient wave-body interaction. An early formulation by Finkelstein [5] utilized a time-dependent Green's function that satisfies the linearized free surface boundary conditions. The source strengths are then determined to satisfy the kinematic boundary condition on the body surface. Practical three-dimensional computation of ship motions with a time-dependent Green's function were later obtained by a number of investigators [6–10].

Nonlinear wave effects on ship motions can be included by utilizing the simpler free space Green's function (Rankine source) and time-stepping the boundary conditions on the free surface. Several numerical methods have been developed along this line including Isaacson [11], Beck et al. [12], Kring et al. [13] and Liu et al. [14]. The Rankine panel method typically leads to a large matrix that is computationally expensive to invert since the free surface has to be discretized in addition to the body surface. Several accelerated methods have been developed to speed up the computations such as the multipole expansion method [15] and the pre-corrected FFT method [16].

Mixed spectral-panel methods have also been developed for solving transient wave–body interaction problems. Chapman [17,18] pioneered this approach by combining a discrete Fourier series representation of the free surface velocity potential with a panel method for the body motion potential. The Green's function for the body potential was chosen to satisfy the equipotential condition on the mean free surface. Chapman [18] reported good results for the heaving motions of a hemisphere although use of a pure spectral method with implicit periodic boundary conditions makes it difficult to enforce the radiation boundary condition for the scattered waves. Chapman's approach was also restricted to small-amplitude waves. An alternative spectral formulation for wave-body interaction problems that allows for higher-order non-

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linear wave effects is based on the pseudo-spectral approach. In contrast to pure spectral methods that evaluate the governing equations in Fourier space, the pseudo-spectral method evaluates linear terms in Fourier space and nonlinear terms in physical space. Pseudo-spectral methods have successfully been used to investigate nonlinear wave interaction with submerged bodies [19–21].

Another variant of the spectral-panel method is the FFT-accelerated boundary integral method developed by Nwogu [22] for nonlinear water wave propagation. For non-overturning waves, the kernels of the free surface boundary integrals are expanded in a wave steepness parameter and efficiently evaluated with FFTs. Nwogu and Beck [23] extended this approach to surface-piercing bodies of arbitrary shape by applying the boundary integral equations to both the physical fluid domain outside the body and a fictitious fluid region inside the body. The FFT method is then used to evaluate the integrals over the free surface in both the interior and exterior regions while the integrals over the body surface are evaluated using a panel method. Preliminary results were presented by Nwogu and Beck [23] for linear wave diffraction by a vertical circular cylinder.

In this paper, the FFT-accelerated boundary integral method is further extended to simulate the 6-dof motions of moving vessels in multidirectional wave fields. The coupled equations of motion for the free surface and body are simultaneously integrated using a fractional-step method. The velocity/pressure formulations of the equations of fluid motion are used with separate boundary integral equations solved at each time step for the fluid kinematics and total pressure. The mixed spectral-panel method is initially validated with prior published data on the forced oscillations and transient motions of a floating hemisphere. The numerical model is then used to predict the transient motions of a self-propelled vessel in oblique waves and compared to data from laboratory experiments.

2. Mathematical formulation

2.1. Equations of body motion

Consider a vessel traveling with speed $U(t)$ in a multidirectional wave field in infinitely deep water. The body motions are defined in terms of three translational (surge, sway, heave) and three angular rotations (roll, pitch, yaw) about a body-fixed coordinate system with origin at its center of gravity G and oriented along the principal axes of inertia of the body. The six degrees of freedom equations for rigid body motion can be written as:

$$[m]\{\dot{\boldsymbol{V}}_b\} = \boldsymbol{F} \tag{1}$$

$$[I]\{\dot{\boldsymbol{\Omega}}_b\} = \boldsymbol{M} \tag{2}$$

where $[m]$ is the mass matrix, $[I]$ is moment of inertia matrix, $\boldsymbol{V}_b$ is the translational velocity in the body-fixed $(\tilde{x}, \tilde{y}, \tilde{z})$ directions and $\boldsymbol{\Omega}_b$ is the angular velocity vector in the body axis. The inviscid hydrodynamic force $\boldsymbol{F}$ and moment $\boldsymbol{M}$ vectors are obtained by integrating the fluid pressure p over the wetted body surface:

$$\begin{Bmatrix} \boldsymbol{F} \\ \boldsymbol{M} \end{Bmatrix} = \int_{S_B} p \begin{Bmatrix} \boldsymbol{n} \\ \tilde{\boldsymbol{x}} \times \boldsymbol{n} \end{Bmatrix} \; dS \tag{3}$$

where $\boldsymbol{n}(\tilde{x}, \tilde{y}, \tilde{z})$ is an inward unit normal vector on the body surface in the body-fixed coordinate system.

2.2. Equations of fluid motion

The equations governing the fluid motion are defined in a right-handed $Oxyz$ coordinate system traveling with the ship with its origin at the still water level vertically in line with the ship's center of gravity, G. The x-axis is assumed to point toward the ship's bow while the z-axis is measured vertically upwards as shown in Fig. 1.

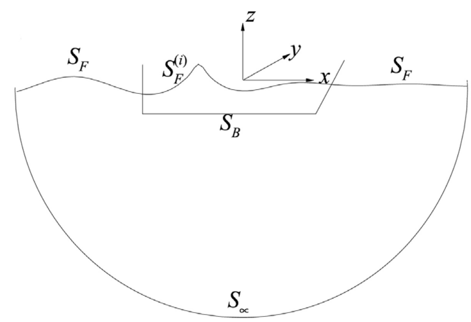

Fig. 1. Definition sketch.

The fluid is assumed to be inviscid and incompressible with the fluid motion irrotational. The governing equations for the fluid motion are the continuity equation for the conservation of mass and Euler's equations of motion for the conservation of momentum:

$$\nabla \cdot \boldsymbol{u} = 0 \tag{4}$$

$$\frac{\partial \boldsymbol{u}}{\partial t} + \nabla P = 0 \tag{5}$$

where $\nabla = (\partial/\partial x, \partial/\partial y, \partial/\partial z)$, $\boldsymbol{u} = (u, v, w)$ is the three-dimensional velocity field, $P = p/\rho + \boldsymbol{u} \cdot \boldsymbol{u}/2 + gz$ is the total pressure, p is the local fluid pressure, ρ is the fluid density and g is the gravitational acceleration. We assume small-amplitude incident waves and decompose the total pressure and velocity fields into components associated with the incident and scattered waves, resulting in:

$$P = P^{(I)} + P^{(S)}; \quad \boldsymbol{u} = \boldsymbol{U} + \boldsymbol{u}^{(I)} + \boldsymbol{u}^{(S)} \tag{6}$$

The effect of the forward speed of the vessel is included in the velocity field as an imposed current $\boldsymbol{U} = (-U, 0, 0)$.

2.2.1. Boundary value problem for pressure

The governing equation for the total scattered pressure over the fluid domain is the Laplace equation which is obtained by taking the divergence of the Euler equation (Eq. (5)):

$$\nabla^2 P^{(S)} = 0 \tag{7}$$

The total scattered pressure field has to satisfy boundary conditions on the free surface S_F, body surface S_B and far-field boundary S_∞. Given that $p = 0$ on the free surface $z = \eta$, the linear boundary condition for the total scattered pressure on S_F can be written as:

$$P^{(S)} = g\eta + \boldsymbol{U} \cdot \boldsymbol{u}^{(S)} \tag{8}$$

The pressure boundary condition on the body surface is obtained by taking the dot product of the Euler equation (Eq. (5)) with a unit normal vector on the body surface:

$$\boldsymbol{n} \cdot \nabla P^{(S)} = -\boldsymbol{n} \cdot \frac{\partial \boldsymbol{u}}{\partial t}^{(S)} \tag{9}$$

where $\boldsymbol{n}(\boldsymbol{x}, t)$ is a unit inward normal vector on the body surface in the hydrodynamic reference frame. Since the fluid pressure needs to be calculated at points fixed on a moving body surface, it is more convenient to evaluate the time derivative in the body-fixed coordinate system:

$$\begin{aligned} \boldsymbol{n} \cdot \frac{\partial \boldsymbol{u}}{\partial t}^{(S)} &= \boldsymbol{n} \cdot \frac{d\boldsymbol{u}}{dt}^{(S)} - \boldsymbol{n} \cdot [((\boldsymbol{V}_b + \boldsymbol{\Omega}_b \times \tilde{\boldsymbol{x}}) \cdot \nabla)\boldsymbol{u}^{(S)}] \\ &= \frac{d(\boldsymbol{u}^{(S)} \cdot \boldsymbol{n})}{dt} - \boldsymbol{u}^{(S)} \cdot \frac{d\boldsymbol{n}}{dt} - \boldsymbol{n} \cdot [((\boldsymbol{V}_b + \boldsymbol{\Omega}_b \times \tilde{\boldsymbol{x}}) \cdot \nabla)\boldsymbol{u}^{(S)}] \end{aligned} \tag{10}$$