A Hybrid Boundary-Element Method for Non-Wall-Sided Bodies with or without Forward Speed

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1. Introduction

This paper presents a 3-D time-domain boundary-element method using a combination of the transient Green's function and the Rankine source. The focus of this study is to solve free-surface ship hydrodynamics problems involving highly non-wall-sided ship geometries with or without forward speed.

As practical ship designs have become more complex and computer capabilities have advanced, there has been a tremendous push in the development of 3-D time-domain methods for solving sea-keeping related problems. In the context of time-domain potential flow boundary-element methods, the most commonly used approaches fall in two categories: (1) methods using the transient Green's function and (2) methods using the Rankine source. In the first category (e.g. Lin, et al, 1994), the transient Green's function satisfies the linearized free-surface boundary condition and the far field radiation condition, so that the singularities need to be distributed on the wetted body surface only. For ships with highly non-wall-sided geometry, numerical difficulties may arise in the area where the intersection angles between the body surface and the free surface become small. This is mainly due to the highly oscillatory nature of the transient Green's function adjacent to the free surface. In the second category (e.g. Nakos, Kring & Sclavounos, 1993), the Rankine source is used as a kernel in the boundary integral equation. The Rankine source is fairly robust for modeling either wall-sided or non-wall-sided geometry. To satisfy the free-surface boundary condition, the Rankine source has to be distributed not only on the body surface but also on the free surface. In order to limit the size of the computation domain, the free surface region is typically truncated at several ship lengths away from the ship and an ad-hoc numerical damping zone has to be employed to absorb the wave energy.

In view of the pros and cons of the two methods, a natural and optimal choice is to take full advantage of the two methods by using a combination of the transient Green's function and the Rankine source in formulating the approach. This hybrid method has recently been developed by the authors for motion and load computations of modern hull forms with highly non-wall-sided geometry. In this method, the fluid domain is divided, through a matching surface, into an inner domain and an outer domain. In the inner domain, the Rankine source is employed. In the outer domain, the transient Green's function is used. The transient Green's function satisfies both the linearized free-surface boundary conditions and radiation condition, implying that the matching surface can be placed fairly close to the body.

Some developments based on this type of hybrid method have been made in recent years. Dommermuth & Yue (1987) solved a nonlinear axisymmetrical flow with a free surface; Yeung & Cermelli (1993) calculated forced heaving motion of a 2-D submerged body with a free surface. Using similar approach but a different Green's function in the outer domain, Sierevogel, Hermans & Huijsmans (1996) solved the linear problem of a 3-D floating body with forward speed. The progress made in the present study includes development and validation of a body-nonliner hybrid boundary-element method as well as application of the method to highly non-wall-sided bodies with or without forward speed.

2. Approach

The fluid flow is described by the potential flow theory. As shown in Figure 1, the fluid domain is decomposed into an inner domain (I) and an outer domain (II). The inner domain is enclosed by the wetted body surface S_b, a part of the free surface S_f surrounding the body, and a matching surface S_m away from the body, while the outer domain is enclosed by S_m, the remaining free surface and an imaginary surface S_∞ at infinity. In the inner domain, the boundary integral equation in terms of the Rankine source is expressed as

$$2\pi\Phi^I(\vec{p}) + \int_{S^I}(\Phi^I G_n - \Phi^I{}_n G)dS = 0 \tag{1}$$

where Φ^I is the disturbance velocity potential in domain I, $G = 1/|\vec{p}-\vec{q}|$, $(\vec{p},\vec{q}) \in S^I = S_b \cup S_f \cup S_m$ with $\vec{p}$ and $\vec{q}$ denoting the field point and source point, respectively. The subscript n denotes the directional derivative with respect to the outward normal n on S^I. In the outer domain, the boundary integral equation in terms of the transient Green's function is written as

$$2\pi\Phi^{II}(\vec{p}) + \int_{S_m}(\Phi^{II} G_n^0 - \Phi_n^{II} G^0)dS = M(\vec{p},t) \tag{2}$$

where Φ^{II} is the disturbance velocity potential in domain II. The memory function $M(\vec{p},t)$ is

$$\begin{aligned} M(\vec{p},t) &= \int_0^t d\tau \left\{ \int_{S_M} (\Phi^{II} G^f_{\tau n} - \Phi^{II}_n G^f_\tau)\, dS \right. \\ &+ \left. \frac{1}{g}\int_{\Gamma_M} (\Phi^{II} G^f_{\tau\tau} - \Phi^{II}{}_\tau G^f_\tau) V_N \, dL \right\} \end{aligned} \tag{3}$$

where Γ_M is the water line of the matching surface, V_N is the outward normal velocity of Γ_M relative to domain I, and G^0 and G^f are associated with the transient Green's function (see Lin & Yue (1990) for details). The matching surface S_m is treated as a control surface and moves with the body. On S_m, the matching conditions are imposed, requiring the disturbance velocity potentials in the inner and outer domains are continuous, so are their normal derivatives. This forms a coupled equation system for the velocity potential Φ^I on S_b, Φ^I_n on S_f, and Φ^I and Φ^I_n on S_m.

On the body surface S_b, the nonlinear body-boundary condition is satisfied on the wetted body surface under the undisturbed incident wave profile. On the free surface S_f in the inner domain, the linearized free-surface boundary conditions are satisfied on the incident wave surface. The resulting hyperbolic equations for the disturbance velocity potential and the disturbance free surface elevation are solved with fourth order Adams-Bashforth-Moulton formulas for time integration and the second order upwind finite difference for the gradient calculations. The solution is obtained at each time step in order to update the linearized free-surface boundary condition on S_f.

3. Results

To illustrate that the present method is suitable for non-wall-sided bodies, the calculation of a flared body undergoing forced large-amplitude heaving motion is carried out. The calculated hydrodynamic force as shown in Fingure 2 agrees quite well with the experimental result (Troesch & Wang, 1994) and a fully nonlinear calculation. This is a significant improvement over the method using the transient Green's function, which gives non-physical high-frequency oscillations in the hydrodynamic force results for this non-wall-sided body.

Another example related to a non-wall-sided body moving with forward speed is presented in Figure 3. In this figure, the motion of a modern Navy ship (CG47) with a large bow flare traveling in storm-sea condition is presented. It shows that the calculation using the present hybrid boundary-element method is very close to experimental measurements.

Further validation of the method is underway concerning the calculation of large amplitude ship motions involving "bow-out-of-water" and water-entry phenomena.

References

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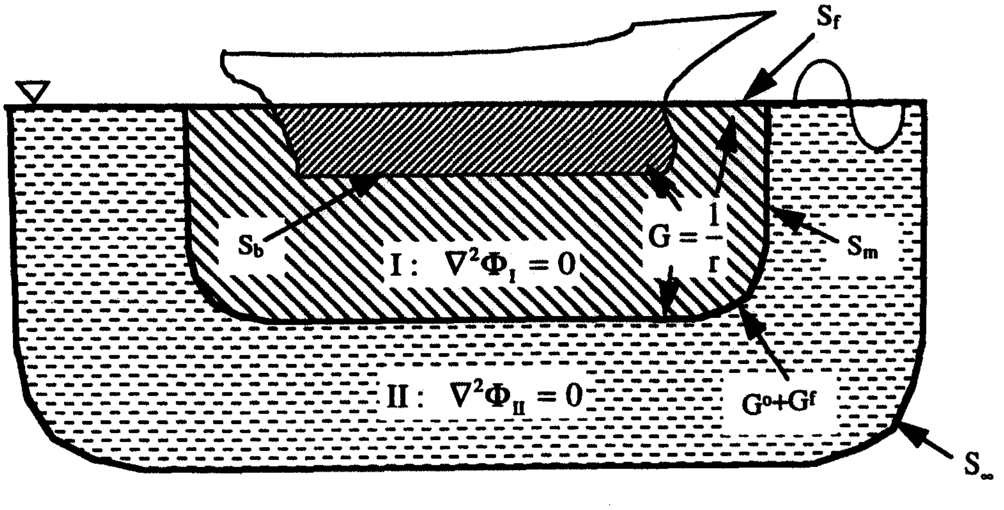

Figure 1: The definitions of the two fluid domains and boundaries used in the hybrid boundary-element method

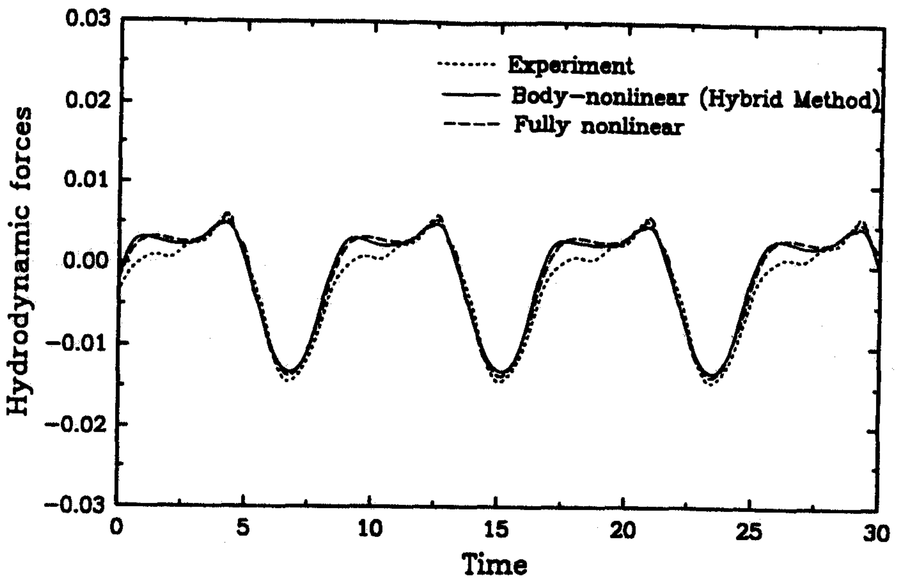

Figure 2: The nondimensional hydrodynamic heaving force versus time for a forced-heaving flared body with $f = 0.6H_z$ and $a = 2.1in$.

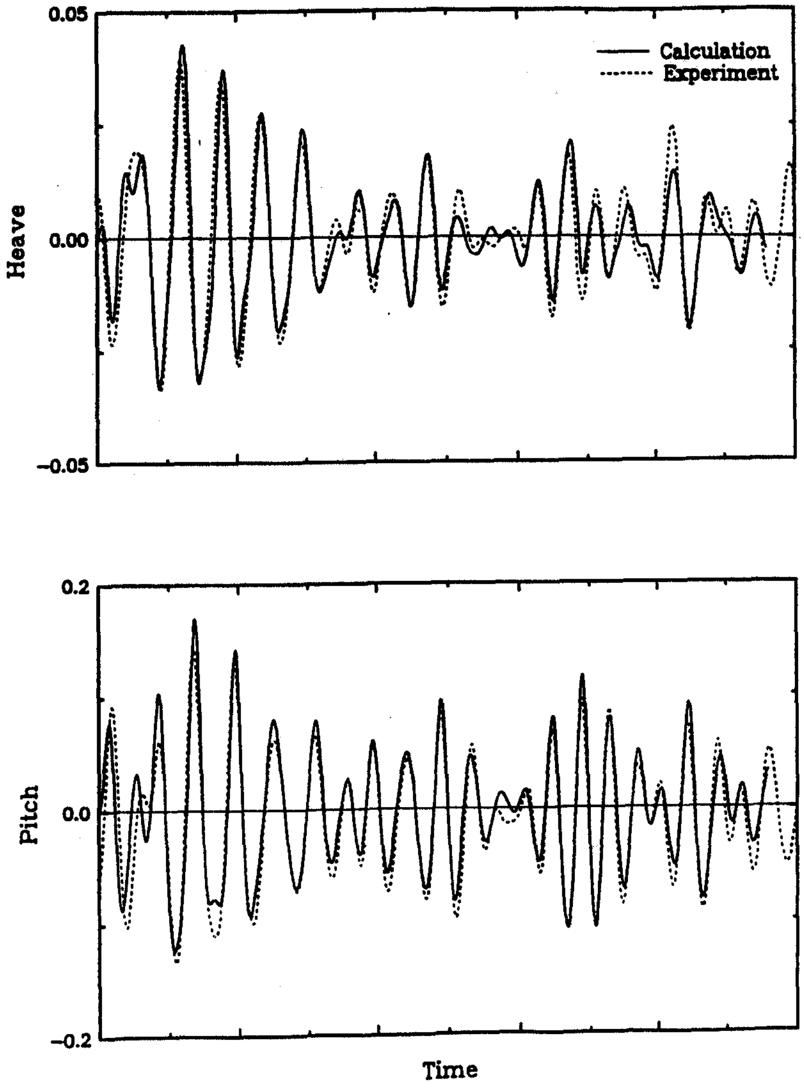

Figure 3: Nodimensional heave and pitch motions of CG47 traveling at 10 knots in head sea and storm condition.