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Nonlinear Ship Wave Simulations by a Rankine Panel Method

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1 Introduction

Nonlinear hydrostatics, Froude-Krylov and hydrodynamic effects have been found in many experimental and numerical studies to be important for the accurate prediction of the ship motion responses in waves. In this article, a linear, time-domain, three-dimensional Rankine Panel Method has been extended, on the basis of a Weak-Scatterer Hypothesis, to treat the nonlinear motions of realistic ship hulls in steep ambient waves.

The Rankine Panel Method (RPM) has enjoyed a great deal of success in recent years, for the treatment of both the steady wave resistance and unsteady seakeeping problems, owing to its flexibility to different types of free surface conditions and simplicity in using the Rankine source as the Green function in the boundary integral formulation. The time-domain treatment of the surface wave disturbance has been adopted here and demonstrated in the linear case (cf. [3][5]) to be stable, convergent and accurate. The time marching is carried out by a so-called Emplicit Euler scheme, which integrates explicitly the kinematic free surface condition and implicitly the dynamic condition. The method is able to obtain accurate and convergent ship wave patterns and ship response predictions. Building upon this solid foundation, the solution of nonlinear ship wave problems is outlined in this article.

According to the Weak-Scatterer theory, the ship wave disturbance is linearized about the instantaneous position of the ambient wave profile. The resulting boundary value problem is derived and the rationale of the hypothesis is discussed. The numerical framework of the solution is presented, along with computations of motion responses of realistic ship hulls in steep ambient waves which demonstrate a marked improvement over linear theory in waves of even moderate steepness.

2 Formulation and Numerical Method

The Weak-Scatterer hypothesis, first proposed by Pawlowski [4], relaxes two restrictions in classical linear ship motion theory: the amplitude of the incoming waves and ship motions. In contrast to linear theory, both amplitudes are allowed to be large as long as the ship radiation and diffraction disturbance is sufficiently small, and thus linearizable. Ambient waves are driven by the environment, and their amplitude is therefore not dependent on the hull shape or ship speed. The ship wave disturbance, on the other hand, is often seen in experimental studies and full scale observations to be relatively small. An extreme example is that of a thin ship moving with large amplitude in steep incident waves. This vessel is evidently not going to generate large disturbances, hence justifying the Weak-Scatterer linearization. Most ships are designed to be slender, and thus, are expected to generate wave disturbances which are not as large as steep ambient waves. Moreover, in the course of their interaction with ambient waves ships behave as compliant rigid bodies in heave and pitch which often induce small wave disturbances due to their tendency to contour the ambient waves.

The present theory allows the ambient wave amplitude and ship motions to be arbitrary and linearizes the ship wave disturbance about the incident wave profile. The hull geometric non-linearity is therefore treated more accurately than in linear theory, and is found to be essential for the accurate predictions of ship motions, especially for ships with prominent counter-top sterns and flared bows.

Within potential flow theory, the free surface conditions in the ship-fixed coordinate system are stated as follows,

$$\left[\frac{\partial}{\partial t} - (\vec{U} - \nabla\Psi)\cdot\nabla\right]\eta = \frac{\partial \Psi}{\partial z}, \qquad \text{on the exact free surface,} \tag{1}$$

$$\left[\frac{\partial}{\partial t} - (\vec{U} - \nabla\Psi)\cdot\nabla\right]\Psi = \frac{1}{2}\nabla\Psi\cdot\nabla\Psi - g\eta, \qquad \text{on the exact free surface,} \tag{2}$$

where ζ is the wave elevation. The total disturbance potential Ψ and free surface wave elevation ζ is decomposed as follows,

$$\Psi(\vec{x},t) = \Phi(\vec{x},t) + \phi(\vec{x},t) + \varphi_0(\vec{x},t) + \varphi(\vec{x},t), \tag{3}$$

$$\eta(x,y,t) = \zeta_0(x,y,t) + \zeta(x,y,t). \tag{4}$$

The basis flow Φ is the solution of a ship moving through a wavy solid ($\Phi_n = 0$) free surface boundary that is prescribed by incoming wave. The time-local flow ϕ represents the instantaneous fluid response to the ship motion and is the solution of a pressure release boundary value problem ($\phi = 0$) on the free surface. A thorough numerical stability study [3] shows that no convergent results can be obtained without separating the time-local flow ϕ from the total disturbance potential Ψ. φ_0 denotes the incident wave potential and ζ_0 is the incident wave elevation. φ and ζ stand for the remaining part of the total disturbance quantities: wave disturbance velocity potential and wave elevation, respectively. ζ records the history of the wave flow and takes the form of an initial boundary value problem.

In accordance with the Weak-Scatterer model, it is assumed that, $\Phi \sim \mathcal{O}(1); \varphi_0 \sim \mathcal{O}(1); \phi \sim \mathcal{O}(1); \varphi \sim \mathcal{O}(\epsilon)$ and $\zeta_0 \sim \mathcal{O}(1); \zeta \sim \mathcal{O}(\epsilon)$. The problem is linearized accordingly. After plugging the decompositions (3),(4) into the free surface conditions (1),(2) and performing a Taylor expansion to transfer the free surface conditions from $z = \zeta$ to $z = \zeta_0$, with the omission of high order terms $\mathcal{O}(\epsilon^2)$, the following free surface conditions are obtained,

$$\begin{aligned}[\frac{\partial}{\partial t} - (\vec{U} - \nabla\Phi - \nabla\phi - \nabla\varphi_0)\cdot\nabla]\zeta = -[\frac{\partial}{\partial t} - (\vec{U} - \nabla\Phi - \nabla\phi - \nabla\varphi_0)\cdot\nabla]\,\zeta_0 + \frac{\partial\varphi_0}{\partial z} \\ + \frac{\partial\Phi}{\partial z} + \frac{\partial\phi}{\partial z} + \frac{\partial\varphi}{\partial z} - \nabla\varphi\cdot\nabla\zeta_0 + [\frac{\partial^2\Phi}{\partial z^2} + \frac{\partial^2\varphi_0}{\partial z^2} - \nabla(\frac{\partial\Phi}{\partial z} + \frac{\partial\varphi_0}{\partial z})\cdot\nabla\zeta_0]\,\zeta, \quad z = \zeta_0(x,y,t),\end{aligned} \tag{5}$$

$$
\begin{aligned}
&[\frac{\partial}{\partial t}-(\vec{U}-\nabla\Phi-\nabla\phi-\nabla\varphi_o)\cdot\nabla]\varphi = -[\frac{\partial}{\partial t}-(\vec{U}-\nabla\Phi-\nabla\phi-\nabla\varphi_o)\cdot\nabla]\ \varphi_o+\frac{1}{2}\nabla\varphi_o\cdot\nabla\varphi_o-g\zeta_o \\
&\quad -[\frac{\partial}{\partial t}-(\vec{U}-\nabla\Phi)\cdot\nabla]\ \Phi+\frac{1}{2}\nabla\Phi\cdot\nabla\Phi-[\frac{\partial}{\partial t}-(\vec{U}-\nabla\Phi-\nabla\phi)\cdot\nabla]\ \phi+\frac{1}{2}\nabla\phi\cdot\nabla\phi-g\zeta \\
&\quad -[\frac{\partial}{\partial t}-(\vec{U}-\nabla\Phi-\nabla\phi-\nabla\varphi_o)\cdot\nabla]\ \frac{\partial\Phi}{\partial z}\zeta-[\frac{\partial}{\partial t}-(\vec{U}-\nabla\Phi-\nabla\phi-\nabla\varphi_o)\cdot\nabla]\ \frac{\partial\phi}{\partial z}\zeta \\
&\quad -[\frac{\partial}{\partial t}-(\vec{U}-\nabla\Phi-\nabla\phi-\nabla\varphi_o)\cdot\nabla]\ \frac{\partial\varphi_o}{\partial z}\zeta, \qquad z=\zeta_o(x,y,t). \quad (6)
\end{aligned}
$$

On all solid boundaries, the no-flux condition is imposed over the instantaneous submerged surfaces. Φ governs the steady translation, ϕ accounts for the rigid body oscillatory motions and φ represents the incident wave diffraction. The radiation condition is enforced by the application of a dissipative beach, which resembles the absorbing beach in a wave tank.

The resulting boundary value problems are solved by a thoroughly tested time-domain Rankine panel method. The method uses plane quadrilateral panels, but applies bi-quadratic spline representation of the unknown over their surface, with continuity in the value and slope of the unknown across panels. The time matching is carried out by the Emplicit Euler scheme and the nonlinear rigid body equation of motion is solved by a fourth-order Adams-Bashford-Moulton scheme, using a fourth-order Runge-Kutta scheme for the first four time steps. The numerical algorithm is rationally shown , (cf. [3][5]), to be stable and computationally efficient.

Unlike pure linear theory, the present method solves the boundary value problems on an incident-wave-prescribed free surface and the instantaneous submerged hull surface. Figure 1 shows a computational grid, with the free surface panel elevated at the position of the incoming wave profile and the submerged ship surface determined by the instantaneous position of the ship. The whole ship is outlined by the bold line to illustrate how much/little the ship surface could actually be submerged during the course of traveling. Figure 2 presents computed results of the heave and pitch motion responses for the S7-175 ship over a range of incident wave frequencies. In comparison with experimental measurements documented in [1], this nonlinear method is seen to offer a substantial improvement over linear theory and its nonlinear variation, which accounts for the nonlinear hydrostatic and Froude-Krylov exciting forces coupled with linear hydrodynamics. More results will be presented at the Workshop.

References

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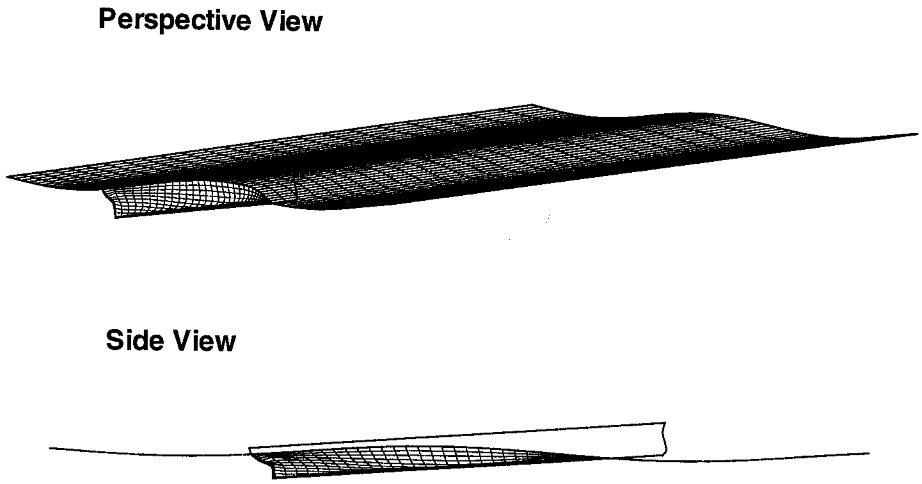

Figure 1: Typical Rectangular Computational Grid

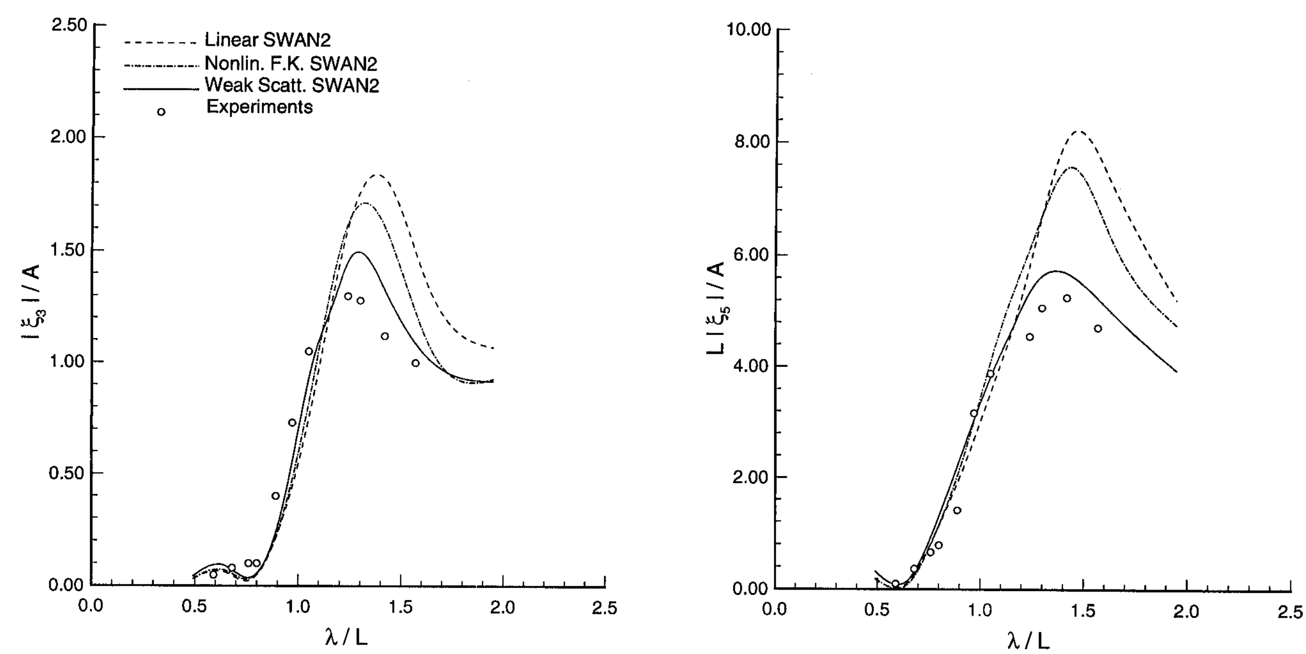

Figure 2: Amplitude of the heave and pitch response amplitude operator (RAO) for the S7-175 Containership at $\mathcal{F} = 0.275$ in head seas, with the incoming wave amplitude at $A/L = 0.015$.