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Numerical and experimental investigations of wave-induced second order hydrodynamic loads

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ABSTRACT

We present computational methods to reliably predict second order forces and moments acting on ships in waves. Second order forces and moments are useful to assess a number of operational aspects, such as minimum power requirements, maneuvering capabilities, and towing forces. Our methods comprise a boundary element Rankine source method and an extended Reynolds-averaged Navier-Stokes (RANS) equations solver. The Rankine source method accounts for the ship's forward speed by considering the nonlinear stationary flow including squat; the RANS solver is coupled with the nonlinear rigid body equations of motion. Investigations dealt with the influence of ship speed, hull shape, and encounter wave angle on second order forces and moments. Furthermore, we calculated diffraction induced added resistances. Results of experimental model test measurements of a tanker, a large containership, and a cruise ship are presented and used to validate our numerical methods.

1. Introduction

Seagoing ships often are subject to adverse weather conditions which not only influence their seakeeping behavior, but also call for increasing power requirements to keep up speed. In addition, a ship's maneuverability may be impaired under adverse conditions, which is a critical safety related issue for ships operating in restricted areas. Another safety concern is associated with the emergency towing of disabled ships, largely as a result of mechanical (engine or steering) breakdown, because the required towing force may be used to specify the bollard pull for the selection of tug boats (Shigunov and Schellin, 2014). To assess a ship's behavior under such operationally relevant conditions, it is useful to reliably predict wave-induced second order forces and moments.

The recently issued guidelines of the Marine Environment Protection Committee of IMO (Resolution MEPC.212(63)) (IMO, 2002a, 2012), specifying the method to calculate the attained Energy Efficiency Design Index (EEDI) for new ships, further underlines the relevance of second order forces and moments. By introducing EEDI limits, these guidelines represent a major step forward in implementing energy efficiency regulations for various kinds of ships. However, as such maneuvers are traditionally executed under calm water conditions, they have often been criticized for not addressing ship maneuvering characteristics under adverse weather conditions.

Early investigations of added resistance in waves published by Havelock (1937) and Maruo (1957) were based on analytical considerations in combination with the strip theory. More recently, numerical simulation methods that solve the Reynolds-averaged Navier-Stokes (RANS) equations have been developed to achieve reliable predictions of nonlinear ship responses, including second order forces and moments in waves. Although applied widely for fully nonlinear investigation and validation purposes (i.e., el Moctar et al., 2010, 2015; Ley et al., 2014), they are computer intensive and, generally, unsuitable for routine applications. Boundary element methods, such as Rankine source techniques, are more efficient as they are based on potential theory and, therefore, suitable for screening purposes to identify relevant wave scenarios. Of these, the forward speed Rankine source technique, which also considers the nonlinear stationary flow including squat, is likely to better predict the wave-induced loads on ships with forward speed and has, therefore, been applied here to analyze second order wave effects. A further justification for its use was that only a small part of wave resistance is due to viscous friction because, except for roll motions, viscous forces are insignificant.

Yeung and Bai (1974) was one of the first to apply the Rankine source method to predict ship motions. Since then, Soeding et al. (2009, 2012a, 2012b, 2014, 2015) refined the Rankine source method and also developed a computer code to simulate ship motions in waves. Xu and Faltinsen (2011) solved the initial-boundary value problem of two ships advancing in waves also using a three- dimentional Rankine

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source method. He and Kashiwagi (2014a, 2014b) developed a higher-order boundary element method with the Rankine source as the kernel function to predict hydrodynamic forces on different ships with forward speed. Liu et al. (2011) applied a new time domain Green function method and a hybrid time domain Rankine source Green function to solve the added wave resistance problem. Joncquez et al. (2008) used a three-dimensional, time domain, higher-order boundary element method to calculate second order wave loads. Their results demonstrated the accuracy and flexibility of this method. Kim and Kim (2010) investigated wave added resistance of a Wigley hull model, a Series 60 hull, and the S-175 containership using a Rankine panel method, and they obtained reasonable agreement for all models. Soeding and Shigunov (2015) studied ten ships using a newly developed potential method, a Rankine source method, a strip method, and a RANS equations solver. Their focus was on short waves. Most of the other studies focused on ship motions in head waves. Our paper, dealing with second order forces and moments for ships in waves, relied on Soeding's forward speed Rankine source method. The results of the forward speed Rankine source method are compared with results from physical tests and RANS computations. We first addressed first order motion response and only then concentrated on second order wave effects, specifically, the influence of ship speed, hull shape, and encounter wave angle on second order forces and moments. Furthermore, we calculated diffraction induced added resistances. We investigated three ship kinds, namely, a VLCC tanker, a 1400 TEU containership, and a cruise ship.

2. Numerical methods

2.1. The forward speed rankine source method

The forward speed Rankine sources boundary element method is a three-dimensional frequency domain approach based on the linearization of boundary conditions for the flow and the ship motions caused by incident waves (Soeding et al., 2014; von Graefe, 2014). Considered is the nonlinear steady flow produced by the ship's constant forward speed in calm water, taking into account ship waves and dynamic squat. Therefore, steady flow computation precede the solutions of the seakeeping problem, followed by calculation of second order wave-induced loads, i.e., wave-induced added resistance and transverse drift force and yaw moment. Wave induced forces and motions are computed in the frequency domain. The total potential (linear periodic flow) is a superposition of the nonlinear steady flow potential, the potential due to ship diffraction and incoming waves as well as six radiation potentials. The nonlinear steady flow problem potential is solved first (before performing a seakeeping computation). The resulting nonlinear steady potential is then used as a base potential for the linear seakeeping computation. The seakeeping body boundary condition is fulfilled on the time-averaged wetted surface taking into account steady ship wave. Correspondingly, the seakeeping free surface conditions are fulfilled on the deformed free surface resulting from the steady computation. Here, we briefly describe the forward speed Rankine source boundary element method. For additional details, see von Graefe (2014).

2.1.1. Nonlinear steady flow

The fluid is assumed invisced, incompressible, and irrotational. Therefore, a velocity potential ϕ^0 exists, which has to satisfy the Laplace equation as well as the kinematic and dynamic boundary conditions on the free surface:

$$\Delta\phi^0 = 0 \qquad \text{within the fluid domain} \tag{1}$$

$$(\nabla\phi^0 - \vec{U})\vec{n} = 0 \qquad \text{on the body boundary} \tag{2}$$

$$\nabla\phi^0\vec{n} = 0 \qquad \text{on the channel wall} \tag{3}$$

$$(\nabla\phi^0 - \vec{U})\vec{n} = 0 \qquad \text{on the free surface} \tag{4}$$

$$\frac{\zeta^0}{g} = \vec{U}\nabla\phi^0 - \frac{1}{2}|\nabla\phi^0|^2 \qquad \text{on the free surface} \tag{5}$$

where $\vec{U} = [u, 0, 0]^T$ is ship velocity, $\vec{n}$ is the surface normal vector, g is acceleration of gravity, and $\zeta^0 = \zeta^0(x, y)$ is free surface elevation; superscript 0 denotes the steady solution. In addition, to ensure that waves caused by the ship propagate only downstream, a radiation condition has to be fulfilled on the free surface.

Following the boundary element approach, an unstructured panel grid consisting of triangles discretizes the wetted ship hull up to the steady flow waterline, while a block-structured grid consisting of rectangles discretizes the free surface. Rankine sources are located outside the fluid at points $\vec{\xi}_j$ situated a suitable normal distance away from panel centers. The velocity potential is rewritten as a superposition of Rankine sources $G(\vec{x}, \vec{\xi}_j) = |\vec{x} - \vec{\xi}_j|^{-1}$, which automatically fulfill the Laplace Eq. (1):

$$\phi^0 = \phi^0(\vec{x}) = \sum_{j=1}^{n} q_j G(\vec{x}, \vec{\xi}_j) \tag{6}$$

Here q_j are the complex amplitudes of the source strengths with index j, and G_j is the Green function for source j, i.e., the potential of a Rankine source of strength 4π. The patch method (Soeding, 1993) is used to satisfy boundary conditions (2) to (5). The associated integrals are evaluated not at discrete collocation points, but over the average area of hull surface and the free surface panels. As the integration over each panel leads to one equation, it follows that the number of equations that have to be solved equals the number of unknown source strengths q_j. To satisfy body and free surface boundary conditions, the residuum r_i for a panel τ_j is introduced, which equals the total flow through the panel:

$$r_i = \int_{\tau_i}(\nabla\phi^0 - \vec{U})\vec{n}dS = \sum_{j=1}^{n} q_j \int_{\tau_i}\nabla G(\vec{x}, \vec{\xi}_j)\vec{n}dS - \int_{\tau_i}\vec{U}\vec{n}dS = 0. \tag{7}$$

The integrals in (7) are evaluated analytically. For large distances between $\vec{\xi}_j$ and τ_i, they are approximated to save computer time. The free-surface boundary condition is nonlinear; therefore, an iterative solution is required. Here, a Newton-like iteration for the residuum is used:

$$\sum_{j=1}^{n}\frac{dr_i}{dq_j}\Delta q_j + r_i = 0. \tag{8}$$

After each iteration, the source strengths are updated to yield $q_j^* = q_j + \kappa\Delta q_j$. Using the relaxation parameter $0 < \kappa \le 1.$, it turns out that

$$\frac{dr_i}{dq_j} = \frac{\partial r_i}{\partial q_j} + \frac{\partial r_i}{\partial\zeta}\frac{\partial\zeta}{\partial q_j}. \tag{9}$$

After solving for the potential, forces and moments acting on the ship are computed by integrating the resulting pressures. A small update of the ship's attitude is calculated after each Newton iteration step. After adapting the attitude of the ship, the new free surface elevation is determined using the dynamic boundary condition, and the grid on the submerged ship surface is updated.

2.1.2. Linear response in waves

The common approach to calculate the total flow potential $\phi^t(\vec{x}, t)$ comprises three parts, namely, the potential of the parallel incident flow, the potential of the steady disturbance of the incident flow caused by the hull, and the potential of the time-periodic flow oscillating with encounter frequency ω_e:

$$\phi^t(\vec{x}, t) = -ux + \phi^0(\vec{x}) + \mathrm{Re}(\hat{\phi}^1 e^{i\omega_e t}) \tag{10}$$