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Numerical and experimental investigation of added resistance of different ship types in short and long waves

Sebastian Sigmund, Ould el Moctar *

University of Duisburg-Essen, Institute of Ship Technology and Ocean Engineering, Duisburg, Germany

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ABSTRACT

Added resistance in short and long regular head waves for four different ship types was systematically and extensively investigated using Reynold-averaged Navier Stokes solvers. Computations, which included ship motions and added resistance, were validated against scale model test measurements. Effects of ship speed, skin friction, wave steepness, ship type, as well as wave radiation and wave diffraction on added resistance were analyzed.

1. Introduction

The installed power of a ship is usually defined by the contractual agreed design speed. The design speed needs to be proven by the shipyard during sea trials. The environmental conditions, contractually specified for these sea trials, usually represent nearly ideal fair weather conditions: the prevailing wind speed does not exceed two on the Beaufort scale, and the significant wave height of the seaway is stipulated at less than 0.5 m. The disadvantage of this approach is that a ship is optimized for conditions it may hardly ever experience, and the so-called sea margin is generally considered to be independent of ship size or type. This may lead to both underpowered smaller and overpowered larger ships operating in the same sea areas, due to size-dependent ship responses. Increasing operational costs and business competition led ship operators to critically scrutinize the fuel consumption of their fleet and, consequently, ships are requested to be designed and optimized for operational conditions. Therefore, it stands to reason to challenge and possibly adapt current design procedures to optimize ships for near-service operational conditions. Thus, prediction of the added resistance of ships in waves is of high practical interest. Naturally, therefore, a considerable amount of research effort has been devoted to this problem. The techniques used to predict added resistance can be classified in two main categories, namely, far-field methods, based on considering the diffracted and radiated wave energy and momentum flux at infinity, and near-field methods, based on direct integration of the steady second-order hydrodynamic pressure acting on the wetted ship surface. Maruo (1957) introduced the first far-field approach, which was later extended by Maruo (1960, 1963) and Joosen (1966). Boese (1970) developed the first near-field direct pressure integration method, albeit by considering a highly simplified pressure distribution. Gerritsma and Beukelman (1972) introduced the radiated energy approach, which basically followed Maruo's far-field approach. Evaluating the above approaches, Ström-Tejsen et al., 1973 found large discrepancies between the numerical results and comparative model test measurements. Using ship motions obtained from the strip theory of Salvesen et al. (1970), Salvesen (1978) obtained satisfactory predictions by applying Gerritsma and Beukelman's method, thereby confirming the importance of accurate ship motion predictions to reliably estimate added resistance in waves. By introducing a simplified added resistance formula to model the complicated interaction of diffracted waves and the steady flow around the ship, Faltinsen et al. (1980) presented a more accurate potential theory near-field direct pressure integration approach. In this way, they validated their results even for short waves. Recently, Liu et al. (2011) used a well-established frequency domain panel method and a new hybrid time domain Rankine source Green function method to predict the added resistance in waves by obtaining first-order velocity potentials and Kochin functions, terms necessary to compute added resistance according to Maruo's far-field method. They used a wide range of case studies to validate their results and concluded that their method is satisfactory to predict added resistance of ships in waves. The recently developed three-dimensional Rankine panel method accounts for the interaction of the linear periodic

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* Corresponding author.
E-mail address: ould.el-moctar@uni-due.de (O. el Moctar).

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wave-induced flow with the nonlinear steady flow caused by the ship's forward speed in calm water, taking into account nonlinear free surface conditions and dynamic squat (Söding et al., 2012). In this method, added resistance in waves is obtained by pressure integration. Kashiwagi et al. (2010) also investigated the prediction accuracy of added resistance in short waves when forward speed is present and attributed inaccuracies to hydrodynamic nonlinear effects.

Added resistance in waves was investigated by many researchers using potential theory, Kim and Kim (2011), Kim et al. (2012), Lyu and el Moctar (2017), Duan and Li (2013), Guo and Steen (2011), Kuroda et al. (2008), Seo et al. (2013, 2014), Sportelli and Huijsmans (2012), Turnock et al. (2014) and Söding et al. (2014). While boundary element methods based on Rankine sources are efficient and, therefore, predominantly used to screen relevant wave scenarios for design issues, Computational Fluid Dynamics (CFD) methods based on the numerical solution of Reynolds-averaged Navier-Stokes (RANS) or Euler equations are increasingly applied to account for nonlinearities, braking waves, etc. They demonstrated their ability to provide results of comparable accuracy to model test measurements in many problems of ship hydrodynamics (Larsson et al., 2010; Oberhagemann et al., 2012; el Moctar, 2001; el Moctar et al., 2011, 2016a; Schellin and el Moctar, 2007; Carrica et al., 2011). However, their applications to added resistance predictions are still rare. Although such methods might, in principle, directly address also the problem of power increase in irregular waves, both long waves (and the correspondingly large ship motions) and short waves (which contribute to the added resistance through diffraction) should be resolved simultaneously, which increases significantly the required grid size and computational time. Therefore, the application of CFD methods to the added resistance problem has been limited so far mainly to regular wave situations in a restricted range of wave frequencies (el Moctar et al., 2016b; Ley et al., 2014; Sadat-Hosseini et al., 2013; Simonsen et al., 2013).

The present investigation employed RANS-based field methods to systematically investigate added resistance in short and long regular head waves for four selected ship types, namely, a medium-size cruise ship, a post-Panamax containership, a tanker, and a Wigley hull. Computations, which included ship motions, were validated against scale model test measurements. Particular emphasis was placed on the following research questions:

- How accurate and reliable are Reynolds-averaged Navier Stokes (RANS) solvers to predict wave added resistance, and how are the results influenced by discretization errors?
- How does ship speed influence the added resistance in waves?
- How does friction affect the added resistance in waves?
- How does the radiation and diffraction problem interact in a nonlinear regime? Can they be considered separately?
- How do wave height and wave steepness affect the added resistance in waves, and does the assumption of the quadratic dependence on wave amplitude also hold in steep waves?

2. Numerical method

We document only a brief overview of the numerical methods used. A detailed description can be found in Ferziger and Peric (2002) and Muzaferija and Peric (1999).

The in-house modified interDymFoam (OpenFOAM, 2011–2016) and the *COMET* (CD ADAPCO, 2011) Reynolds-averaged Navier-Stockes (RANS) solvers were employed to compute the flow surrounding the subject ships in calm water and in waves. Both solvers use the Finite Volume Method (FVM) to solve the conservation equations. The solution domain is divided into Control Volumes (CV) for which the RANS equations are solved in integral form. For an incompressible, isothermal, and viscous fluid of density ρ, the conservation equations of mass and momentum in integral form read as follows:

$$\frac{\partial}{\partial t}\int_V \rho dV + \int_S \rho(\vec{v} - \vec{v}_s)\cdot\vec{n}dS = 0 \tag{1}$$

$$\frac{\partial}{\partial t}\int_V \rho\vec{v}dV + \int_S \rho\vec{v}(\vec{v} - \vec{v}_s)\cdot\vec{n}dS = \int_S \boldsymbol{T}\cdot\vec{n}dS + \int_V \vec{b}dV \tag{2}$$

In the momentum Equation (2), the surface and volume forces are included in the stress tensor, $\boldsymbol{T}$, and in the body forces, $\vec{b}$, respectively, where V is the control volume, $\vec{v}$ is the fluid velocity, and $\vec{v}_S$ is the velocity of the control volume's surface, S. The stress tensor includes viscous shear stress and a pressure term, p, multiplied by the unit tensor, $\boldsymbol{I}$:

$$\boldsymbol{T} = \mu\left\{\nabla\vec{v} + \nabla\vec{v}^T\right\} - p\boldsymbol{I} \tag{3}$$

where μ is the dynamic viscosity. A second order scheme discretizes time derivatives using constant time steps, specifically, the Implicit Three Time Level in *COMET* and the Crank-Nicholson method in OpenFOAM (Ferziger and Peric, 2002).

To obtain a dedicated pressure equation, the mass equation is converted into a Poisson equation used for pressure correction of the velocity field. The Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) algorithm implemented in *COMET* provides an implicit coupling between pressure and velocity (Ferziger and Peric, 2002). At each time step, outer iterations correct pressures and velocities iteratively. Software OpenFOAM employs the PIMPLE algorithm (Combination PISO/SIMPLE) (OpenFOAM, 2016).

To simulate a floating body at a free water surface, a two-phase flow needs to be modeled. The solvers use the interface capturing Volume-Of-Fluid (VOF) technique, which has proven to be suitable for handling complex free surface phenomena (Muzaferija and Peric, 1999). It introduces an additional transport equation to compute the spatial distribution of scalar volume fraction α in the fluid domain. Fraction α describes the fluid properties, specifically, effective density and viscosity in each control volume. The effective fluid density, ρ_{eff}, is defined as follows:

$$\rho_{eff} = \alpha\rho_{water} + (1-\alpha)\rho_{air} \tag{4}$$

where ρ_{water} and ρ_{air} are the densities of water and air, respectively. Viscosity is computed in the same manner. To guaranty a sharp free water surface, *COMET* employs the High-Resolution Interface-Capturing (HRIC) scheme to discretize α transport equation (Muzaferija and Peric, 1999). In OpenFOAM the Multidimensional Universal Limiter with Explicit Solution (MULES)-algorithm is used to compute the spatial distribution of the volume fraction.

At inlet boundaries, a transient wave boundary condition prescribes velocity and surface elevation according to linear wave theory. In the fluid domain, velocity, pressure, and α fields are initialized. Nonlinear ship motions are computed by an implicit six Degree of Freedom (DOF) solver coupled implicitly with RANS equations (Brunswig and el Moctar, 2004; el Moctar et al., 2017). Accordingly, a mesh morphing algorithm deforms the numerical grid to move ships in the computational domain (Oberhagemann and el Moctar, 2007). The two equation $k-\varepsilon$ and $k-\omega-SST$ turbulence models are used to close the system of equations (Menter, 1994). For the turbulent boundary layer, shear stresses on the hull are determined using logarithmic wall functions.

3. Selected test cases

To cover a wide range of practical needs, we investigated the phenomenon of wave added resistance for a wide range of conventional ship types as well as for a well known test case, Fig. 1. Specifically, our studies were performed for a modern medium-size cruise ship (Ley et al., 2014; Valanto and Hong, 2015), a post-Panamax 14000 TEU containership