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Estimation of added resistance and ship speed loss in a seaway

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ABSTRACT

The prediction of the added resistance and attainable ship speed under actual weather conditions is essential to evaluate the true ship performance in operating conditions and assess environmental impact. In this study, a reliable methodology is proposed to estimate the ship speed loss of the S175 container ship in specific sea conditions of wind and waves. Firstly, the numerical simulations are performed to predict the added resistance and ship motions in regular head and oblique seas using three different methods; a 2-D and 3-D potential flow method and a Computational Fluid Dynamics (CFD) with an Unsteady Reynolds-Averaged Navier-Stokes (URANS) approach. Simulations of various wave conditions are compared with the available experimental data and these are used in a validation study. Secondly, following the validation study in regular waves, the ship speed loss is estimated using the developed methodology by calculating the resistance in calm water and the added resistance due to wind and irregular waves, taking into account relevant wave parameters and wind speed corresponding to the Beaufort scale, and results are compared with simulation results obtained by other researchers. Finally, the effect of the variation in ship speed and therefore the ship speed loss is investigated. This study shows the capabilities of the 2-D and 3-D potential methods and CFD to calculate the added resistance and ship motions in regular waves in various wave headings. It also demonstrates that the proposed methodology can estimate the impacts on the ship operating speed and the required sea margin in irregular seas.

1. Introduction

Now more than ever, the reduction of ship pollution and emissions, maximization of energy efficiency, enhancement of safety requirements and minimization of operational expenditure are key priorities. Traditionally, the focus has been on ship resistance and propulsion performance in calm water during the ship design stage even though there have recently been some changes in hull form design and optimization, from a single design draught and speed to a specific range of draughts and speeds considering a realistic operating profile for the vessel. However, when a ship advances through a seaway, she requires additional power in comparison with the power required in calm water due to actual weather and ship operating conditions. This degradation of the ship performance in a seaway, which is reported to be an addition of about 15–30% of the power required in calm water (Arribas, 2007) is accounted for by the application of a “Sea Margin” onto the total required engine power and a value of 15% is typically used. A more accurate prediction of the added resistance with motions and ship speed loss is essential not only to assess the true sea margin to determine the engine and propeller design points, but also to evaluate the ship performance and environmental impact under actual weather and operating conditions. Also from a ship designer's point of view, the design could be seen as more competitive if the vessel is designed for better performance in a seaway, and for ship owners and officers, they could have safer ships in actual operation at sea.

Regarding the international regulations, the Marine Environment Protection Committee (MEPC) of the International Maritime Organization (IMO) issued new regulations to improve the energy efficiency level of ships and to reduce carbon emissions. These regulations include the Energy Efficiency Design Index (EEDI) (IMO, 2011) as a mandatory technical measure for new ships and the Energy Efficiency Operational Indicator (EEOI) (IMO, 2009) which is related to ship voyage and operational efficiency for ships in service. Recently, the ship speed reduction coefficient (f_w) has been proposed and is under discussion for the calculation of EEDI in representative sea states (IMO, 2012; ITTC, 2014).

The added resistance and ship motion problem in waves has been widely studied through experiments and numerical simulations using potential flow theory and CFD approaches. There are two major analytical approaches in potential flow methods which are used to

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calculate the added resistance: the far-field method and the near-field method. The far-field method is based on the added resistance computed from the wave energy and the momentum flux generated from a ship, and is evaluated across a vertical control surface of infinite radius surrounding the ship. The first study was introduced by Mauro (1960) using a Kochin function which consists of radiating and diffracting wave components and investigated in detail by Joosen (1966) and Newman (1967). Later on, the far-field method, based on radiated energy approach was proposed by Gerritsma and Beukelman (1972) for added resistance in head seas and has become popular in strip theory programs due to its easy implementation. This approach was modified and extended to oblique waves by Loukakis and Sclavounos (1978). Recently, Kashiwagi et al. (2010) used the far-field method to calculate the added resistance using enhanced unified theory to overcome the discrepancies originating in short waves and in the presence of forward speed with the experiments by introducing a correction factor in the diffracted wave component. They observed that the discrepancies tended to increase and became constant with the increase in the forward speed. The disadvantage of the far-field method is the dependency of the added resistance on the wave damping which cause inaccurate radiation forces at low frequencies when using the strip theory method. Liu et al. (2011) solved the added resistance problem using a quasi-second-order approach, applying the developed hybrid Rankine Source-Green function method considering the asymptotic and empirical methods to improve the results in short waves.

Another numerical approach is the near-field method which estimates the added resistance by integrating the hydrodynamic pressure on the body surface, which was first introduced by Havelock (1937) where the Froude-Krylov approach was used to calculate hull pressures. Boese (1970) proposed a simplified method where the importance of relative wave height contribution to the added resistance was first addressed. The near-field method was enhanced by Faltinsen et al. (1980) based on the direct pressure integration approach. Salvesen et al. (1970) introduced a simplified asymptotic method based on 2-D strip theory to overcome the deficiency of this approach in short waves. Kim et al. (2007) and Joncquez (2009) formulated the added resistance based on the Rankine panel method using a time-domain approach with B-spline functions and investigated the effects of the Neumann-Kelvin (NK) and Double Body (DB) linearization schemes on the added resistance predictions. Recently, Kim et al. (2012) formulated the added resistance using a time-domain B-spline Rankine panel method based on both near-field and far-field methods in addition to the NK and DB linearization schemes for the forward speed problem. They observed that, in the case of the added resistance, the far-field method was superior to the near-field method in short waves whilst, in the case of the free-surface linearization scheme, NK linearization showed better agreement with the experiments at high speeds compared to the DB linearization for slender bodies.

As computational facilities have become more powerful and more accessible, CFD techniques have been more commonly used to predict the added resistance and ship motions, taking into account viscous effects without empirical values and large ship motions as well as the effect of breaking waves and green water effect. Recently, Deng et al. (2010), Moctar et al. (2010) and Sadat-Hosseini et al. (2010) predicted the added resistance of KVLCC2 CFD tools as presented at the Gothenburgh (2010), SIMMAN (2014) and SHOPERA (2016) Workshops. Following that, Guo et al. (2012) predicted motions and the added resistance for KVLCC2 using the ISIS-CFD flow solver as a RANS code and Sadat-Hosseini et al. (2013) predicted the added resistance and motions for KVLCC2 using the in-house code CFDSHIP-IOWA which is based on a URANS approach. Simonsen et al. (2013) carried out numerical simulations for the ship motions, flow field and added resistance for the KCS containership using Experimental Fluid Dynamics (EFD) and CFD. Tezdogan et al. (2015) performed URANS simulations to estimate the effective power and fuel consumption of the full scale KCS containership in waves by predicting added resistance in regular head seas using the commercial STAR-CCM+ software.

In addition to research on accurate prediction of the added resistance and ship motions in waves, there have been studies on reduction of the added resistance by developing the hull form. Park et al. (2014) modified the forebody of the KVLCC2 to an Axe-bow and Leadge-bow to reduce the added resistance in waves by means of EFD and potential theories. Kim et al. (2014) revised the bulbous bow of a containership to optimize the hull form for both operating profile of the ship in calm water and wave conditions using CFD simulations. However, there has been no significant research on the increase of the required power and the ship speed loss in a seaway.

In the present study, in line with the energy efficiency regulations, the main focus is on the development of a reliable methodology to estimate the added resistance and the ship speed loss due to wind and waves. All calculations have been performed for the S175 containership. Firstly, numerical calculations and validation studies have been carried out for the added resistance with ship motions in regular head and oblique waves using 2-D and 3-D linearized potential flow methods and CFD. Secondly, after the validation study on the added resistance in regular waves, the ship speed loss is estimated by the proposed methodology predicting the resistance in calm water and the added resistance due to wind and irregular waves taking into account the wave height, mean wave period and wind speed corresponding to the Beaufort scale, based on IMO and ITTC guideline/recommendation (IMO, 2012; ITTC, 2014) and compared with simulation results obtained by Kwon (2008) and Prpić-Oršić and Faltinsen (2012). Finally, taking into consideration the typical slow steaming speeds of containerships, studied in detail by Banks et al. (2013) who compared the operating speeds from 2006–2008 to 2009–2012, the effect of the ship speed loss at preliminary design and other lower speeds was investigated.

2. Ship particulars and coordinate system

All calculations of the added resistance and ship speed loss have been performed for the S175 containership, which is one of the benchmark hull forms used to study seakeeping capability by several researchers. The main particulars of the S175 containership are given in Table 1. The model with scale ratio of 1/40 is employed in CFD simulations to estimate the added resistance and ship motions in regular waves and in head and wave headings.

In the numerical simulations, a right-handed coordinate system x, y, z is adopted, as shown in Fig. 1, where the translational displacements in the x, y and z directions are ξ_1 (surge), ξ_2 (sway) and ξ_3 (heave), and the angular displacements of rotational motion about the x, y and z axes are ξ_4 (roll), ξ_5 (pitch) and ξ_6 (yaw) respectively and the angle θ represents the ship's heading angle with respect to the incident waves. For head seas the angle θ equals 0° and for beam seas from the port side the angle equals 90°.

Table 1
Main particulars of S175 containership.

Particulars	Full scale	Model scale
Length, L (m)	175	4.375
Breadth, B (m)	25.4	0.635
Draught, T (m)	9.5	0.2375
Displacement, V (m^3)	23,680	0.3774
LCG(%), fwd +	−1.337	−1.337
VCG (m)	9.52	0.238
Block coefficient, C_B (-)	0.572	0.572