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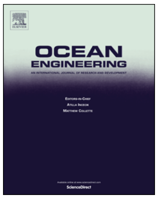

Study on added resistance of a tanker in head waves at different drafts

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ABSTRACT

In this study, added resistance was evaluated experimentally and numerically in four draft conditions: full load, ballast, and two intermediate conditions between the full load and ballast conditions. A series of towing-tank experiments for ship motion and added resistance in the four draft conditions was carried out in head sea conditions. The ship motion and added resistance were measured for the wavelength to ship length ratios of 0.4–2.0. In the numerical approach, two different seakeeping analyses were adopted: the strip method and Rankine panel method. For the strip method, analytical or empirical corrections were added in the short wave condition. The experimental and numerical results for the heave and pitch motions and the added resistance were compared for the four draft conditions. The numerical motion responses of both approaches showed good agreement with the experimental data. For the added resistance, the Rankine panel method showed reasonable results in all draft conditions. In contrast, the strip method showed poor results except in the full load condition. Based on the comparison of the experimental and numerical results, the potential application of the two numerical methods to various draft conditions was considered.

1. Introduction

Because of the Energy Efficiency Design Index (EEDI) introduced by the International Maritime Organization (IMO), a ship designer is required to estimate the added resistance in seaways due to winds and waves relative to the resistance in calm seas. The performance of a ship in an actual seaway is needed rather than the still water resistance with a sea margin. Depending on the hull type and environmental conditions, the added resistance in seaways could significantly increase. Therefore, estimating the added resistance is an important issue for the shipping industry.

For the past several decades, the problem of added resistance induced by waves has been widely studied with various experimental and numerical approaches. The experimental approach has included measuring the added resistance for the Series 60 (Gerritsma and Beukelman, 1972; Storm-Tejsen et al., 1973) and S175 container ship (Fujii and Takahashi, 1975; Nakamura and Naito, 1977) and the Wigley hull (Journee, 1992). Recently, Kashiwagi (2013) evaluated the added resistance based on the captive model test and wave analysis using a towing tank model test. Guo and Steen (2011) focused on the short-wave region considering small sea conditions, and Sadat-Hosseini et al. (2013) collected experimental and computational fluid dynamics (CFD) data about the added resistance. There are two major numerical approaches that can be used to analyze the added resistance problem: the far-field and near-field methods. The far-field method was introduced by Maruo (1960) and was further elaborated by Newman (1967), Gerritsma and Beukelman (1972) and Salvesen (1978). Recently, Kashiwagi et al. (2010) used Maruo's approach to calculate the added resistance through the application of the enhanced unified theory. Because of the significant advances in computation power, the near-field method has gained increasing attention. Faltinsen et al. (1980) used the near-field approach with good validation results. They also addressed the deficiency of this approach for short waves and introduced a simplified asymptotic method to complement this deficiency. Ye and Hsiung (1997) applied a wave Green's function to the added resistance problem. These efforts have mostly been based in the frequency domain. Joncquez (2009) analyzed the added resistance problem by using a time-domain Rankine panel method and applied both far- and near-field methods. Kim and Kim (2011) and Kim et al. (2012) also applied the higher-order Rankine panel method to the added resistance problem using far- and near-field methods. They also analyzed the added resistance in irregular waves. Söding et al. (2012) and Söding and Shigunov (2015) analyzed the added resistance using various method: a Rankine panel method and RANS (Reynolds-averaged Navier–Stokes) equations solvers. The added resistance with short wavelengths is another issue for predicting the added resistance. Accurately calculating the added resistance using the

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previous calculation methods is difficult because the hydrodynamic nonlinear effects are intensified for bow diffraction waves. To address this problem, several studies have been carried out. Fujii and Takahashi (1975) derived a semi-empirical formula by adopting some complementary coefficients. Faltinsen et al. (1980) derived a simplified asymptotic formula by assuming that the ship has a vertical side at the water plane. Recently, the National Maritime Research Institute (NMRI) in Japan proposed an improved expression that is based on the Fujii and Takahashi's method (Tsujimoto et al., 2008, Kuroda et al., 2008, 2012). They modified the complementary coefficients using experimental data.

The earlier experimental and numerical studies on the added resistance only focused on the full load condition. However, the draft of a ship can change according to the operating condition. For tanker and bulk carriers, the two most common operating conditions are the full load and ballast conditions. These ships are operated in the ballast condition for approximately half of their lifetimes. However, few studies have considered the added resistance in ballast condition (Kashiwagi et al., 2004, Orihara et al., 2008). Although these studies compared the experimental data in the ballast condition with the numerical results, a numerical method that can be applied to the ballast condition and experimental data for validation are still needed.

The present study had two objectives: providing the added resistance data of KVLCC2 hull form in various draft conditions and considering the potential application of typical numerical methods to various drafts. In the present study, a series of experiments was conducted to measure the motion responses and added resistance. To investigate the added resistance for various drafts, four conditions were considered: full load, ballast, and two conditions between the full load and ballast conditions. In the experiment, the added resistance was evaluated based on the recommendations of the ITTC (2011): the still water resistance was subtracted from the mean total resistance of waves. The frequency-domain strip method and time-domain Rankine panel method were applied to numerically predict the added resistance. Analytical or empirical corrections were added to complement the poor results of the strip method in the short-wave region. The experimental results for the added resistance and motion responses were compared with the numerical results. Based on the comparison of the experimental and numerical results, the potential application of numerical methods to various drafts was considered.

2. Theoretical background

Consider a ship advancing with a certain forward speed U in the presence of incident waves. Let a coordinate system moving with a constant forward speed U as shown in Fig. 1, where A, ω, and β represent the incident wave amplitude, frequency, and heading angle, respectively. S_B and S_F denote the body surface and free surface, respectively.

2.1. Strip method in frequency domain

It is assumed that the ship motion responses are linear and harmonic, the coupled equation of motion in frequency domain is expressed as follows:

$$\sum_{k=1}^{6}\left[(M_{jk}+A_{jk})\ddot{\xi}_k+B_{jk}\dot{\xi}_k+C_{jk}\xi_k\right]=F_je^{i\omega t}\,,\quad \text{for } j=1,\ldots,6 \tag{1}$$

where M_{jk} and A_{jk} are the mass and added-mass matrices, B_{jk} and C_{jk} are the damping and restoring coefficients, and F_j is the exciting force and moment. If the ship is symmetric about its center-plane, the surge, heave and pitch motion can be decoupled from the sway, roll and yaw motion. Supposing the ship is a slender body, the surge motion is negligible. In the head wave condition, therefore, the heave-pitch coupled motion is considered.

For the motion calculation, the total hydrodynamic coefficients were computed with the Salvesen–Tuck–Faltinsen (STF) (Salvesen et al., 1970) strip theory. Because this theory is well known, the details are not described here. If a slender body is subjected to a low forward speed and high incident wave frequency, the hydrodynamic coefficients can be obtained by integrating the sectional solutions. For the two-dimensional strip shown in Fig. 2, the velocity potential ϕ satisfies the following boundary value problem:

$$\nabla^2\varphi_k=0,\quad (k=2,3)\quad \text{in fluid domain} \tag{2}$$

$$-\omega_e^2\phi_k+g\frac{\partial\phi_k}{\partial z}=0,\quad (k=2,3)\quad \text{on } z=0 \tag{3}$$

$$\frac{\partial\phi_k}{\partial n}=V_n,\quad (k=2,3)\quad \text{on } S_b \tag{4}$$

$$\lim_{y\to\infty}\nabla\phi_k=0,\quad (k=2,3) \tag{5}$$

where $k=2$ for a sway motion, $k=3$ for a heave motion. ω_e and g refer to the encounter wave frequency and acceleration of gravity, respectively. The subscript n means the normal direction of the body. To solve the prescribed two-dimensional boundary value problem, the wave Green's function G (Newman, 1985) is applied

$$G=\left[\log\left(\frac{r}{r_1}\right)-2\int_0^\infty(k-1)^{-1}e^{-kY}\cos(kX)dk\right]-2i\pi e^{-Y}\cos X \tag{6}$$

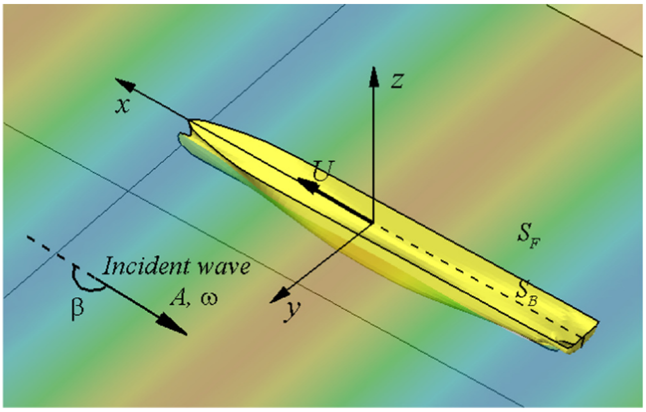

Fig. 1. Coordinate system for ship motion problem.

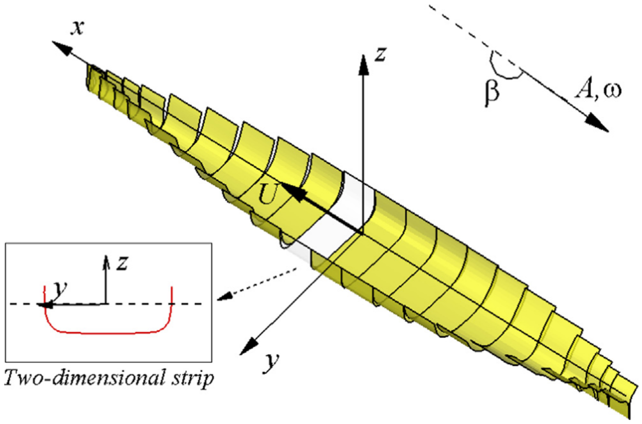

Fig. 2. Example mesh for strip method.