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Enhancement of asymptotic formula for added resistance of ships in short waves

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ABSTRACT

This paper introduces a practical formula for added resistance in short waves. Particularly, the formulation introduced by Faltinsen et al. (1980) is modified to consider the three aspects: the finite draught of ships, the local steady velocity, and the shape above still-water-level (SWL). First, an additional term due to the finite draught of ships is derived by subtracting the integration of velocity square terms along the vertical control surface from the ships draught to the negative infinite. Second, a new local steady velocity is proposed, which includes the variation of sectional area. Third, the bow shape above SWL is considered by introducing the ratio of bluntness coefficients at the mean level of steady waves and SWL. The mean level of steady waves is approximately calculated based on the steady wave elevation of an advancing wedge-shaped body in calm water. The effect of each modification has been investigated and compared to experimental results and other empirical formulae of added resistance in short waves. Finally, a practical approach to combine the modified formula and the existing computation method for the added resistance in an overall wavelength range is presented.

1. Introduction

It is well known that a ship experiences additional resistances in real sea conditions compared to the resistance in calm water. The added resistance of ships due to waves is one of the additional resistances of increasing importance in seakeeping and ship resistance communities as the International Maritime Organization (IMO) created a regulation for evaluating an energy efficiency design index (EEDI) for newly built ships to restrict greenhouse gas emissions. The weather factor, which is the ratio of ship speed in a real sea condition to that in calm water, is one of the critical parameters for the correct estimation of EEDI. Thus, an accurate and efficient method to predict the added resistance in waves is required for early stage ship design.

A significant amount of research has been performed on this issue over the last several decades based on experimental, numerical, and simplified approaches (Seo et al., 2013; references are therein). Because modern merchant ships are much larger than in the past, the waves encountered are of relatively short wavelength. The asymptotic formula (Faltinsen et al., 1980) and empirical formulae (Tsujimoto et al., 2008; Sea Trial Analysis JIP, 2006; see also International Standard Organization, 2015) of added resistance in waves are fundamental tools for predicting the added resistance of ships in short waves. Recently, Liu and Papanikolaou (2016) presented a handy calculation method based on empirical correction terms and the further improved formula considering the effects of the ship draft, trim, and forward speed was developed by Liu and Papanikolaou (2017). Even though the empirical formulae provide reasonable results compared to experimental data, the effects of each physical parameter have been merged into a simple parameter.

The asymptotic formula of added resistance in short waves shows fair agreement with experimental data for blunt ships at low forward speeds, whereas underestimation of results can be observed for slender ships at relatively high forward speeds. The modification was made in the original asymptotic formula introducing refraction of incident waves near the ship bow based on the conservation of wave action (Ohkusu, 1984). However, Ohkusu's method tends to overestimate the added resistance in short waves for blunt ships at low speed. Moreover, it provided the underestimation of added resistance in short waves for slender ships. The following two reasons for underestimation were reported in the literature: shape above still-water-level (SWL; Seo et al., 2014) and local steady velocity (Guo and Steen, 2011). As noted in the previous studies (Ohkusu, 1984; Sakamoto and Baba, 1986), the interactions between steady flow and diffraction or even incident waves are important processes in determining the added resistance in waves.

From a practical point of view, to minimize the added resistance in

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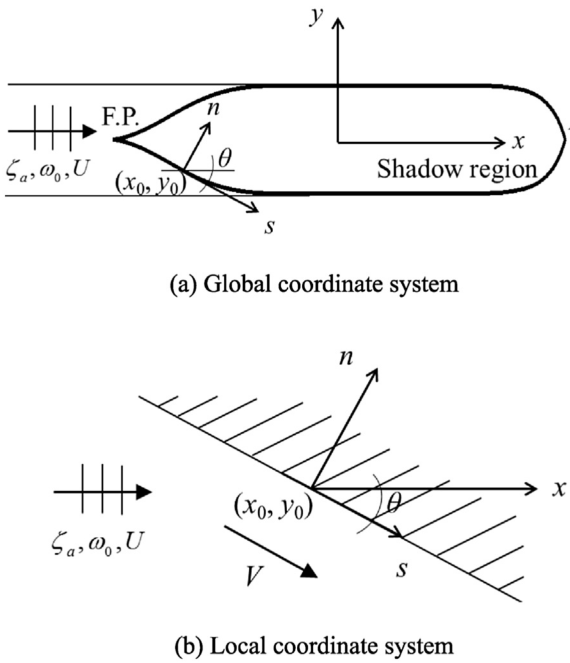

Fig. 1. Two coordinate systems for added resistance of ships in short waves.

waves the designer can only rely on the change of bow shape above SWL. For example, Ax-bow and Leadge type bow shapes were originally proposed by Matsumoto et al. (2000), and those concepts were also applied for KRISO's very large crude oil carrier (KVLCC2, Lee et al., 2017). The reduction of added resistance in short waves could be achieved by reducing the reflection wave toward the front of the ships bow. However, the existing asymptotic analyses of added resistance in short waves are not able to consider changes in bow shape above SWL. Kuroda et al. (2012) presented a practical method to take into account the effect of shape above SWL. They measured the steady wave elevation around a ship bow in experiments and the water line curve was obtained by projecting the steady wave elevation into SWL. The water line integration was then performed along this projected profile. From this method, the change of bow shape along the vertical direction is partially considered.

In this study, the original asymptotic formula, developed by Faltinsen et al. (1980), is modified by introducing the following three effects: finite draught of ships, local steady velocity, and shape above SWL. The effect of each parameter has been investigated and compared to experimental results and other empirical formulae of added resistance in short waves. The correction due to the finite draught of ships reduces the suction force below SWL and consequently increases the added resistance in short waves. A new local steady velocity is proposed which includes the variation of sectional area as opposed to the infinitely long vertical cylinder model assumed in the original asymptotic formula. Furthermore, the shape above SWL is considered by introducing the ratio of bluntness coefficients at mean steady elevation, which is approximately calculated based on steady elevation for an advancing wedge-shaped body in calm water. Validating the newly proposed formula of added resistance in short waves, a practical approach to combine the existing added resistance in an overall wavelength range is presented.

2. Mathematical backgrounds

2.1. Original asymptotic formula

Faltinsen et al. (1980) derived the asymptotic formula of added resistance of ships in short waves. In this formulation, it is assumed that a ship has vertical sides at the water plane and that the wavelength is small compared to the draught of the ship. In short waves, the ship motion can be neglected and the diffraction wave will be affected only by the part of the ship close to the water plane. Thus, the ship is considered as a stationary, vertically long cylinder, which has the same cross-section to the water plane area as the ship. The coordinate system (x, y, z) is defined at the center of the cylinder and x- and z-directions indicate the backward or "aft" direction, and vertically upward direction of the ship, respectively. The ship is moving forward with a constant speed U and the incident wave is approaching with wave amplitude ζ_a and circular frequency ω_0, as shown in Fig. 1(a). Only the regular head-wave case is considered in this paper. The local coordinate system (n, s) along the water plane area curve can be defined, where n and s are orthogonal and tangential to the water plane area curve, respectively. Stretching the coordinate by the scale of the wavelength, the cylinder can be considered a vertical wall which has angle θ with an x-direction. If the ship speed is small, there is a horizontal steady velocity V parallel to the wall as shown in Fig. 1(b).

The flow is assumed as ideal flow and the velocity potential can be introduced. Using boundary conditions and the fictitious problem where the fictitious incident wave is assumed to be totally reflected, the total velocity potential Φ in many wavelengths away from the wall can be obtained as follows:

$$\begin{aligned}\Phi &= \phi + Vs = \phi_I + \phi_D + Vs\\ &= \frac{g\zeta_a}{\omega_0}e^{k_0 z}\cos(k_0 s\cos\theta + k_0 n\sin\theta + k_0 x_0 - \omega_e t)\\ &\quad+\frac{g\zeta_a}{\omega_0}B_1 e^{k_1 z}\cos(k_0 s\cos\theta - k_2 n + k_0 x_0 - \omega_e t) + Vs\end{aligned} \tag{1}$$

where

$$k_1 = \frac{(\omega_e - Vk_0\cos\theta)^2}{g} \tag{2}$$

$$k_2 = \sqrt{k_1^2 - k_0^2\cos^2\theta} \tag{3}$$

$$B_1 = \frac{2k_1}{k_1 + k_0}\frac{k_0}{k_2}\sin\theta \tag{4}$$

Here, ϕ_I and ϕ_D are the incident and diffraction wave potentials, g the acceleration of gravity, k_0 the wave number, (x_0, y_0) the x, y-coordinates of the origin of the local coordinate system (n, s), ω_e the circular frequency of encounter, and t, the time variable.

Based on the conservation of momentum, the sectional average force normal to the wall can be obtained as follows:

$$\begin{aligned}\Delta R_n &= \overline{\int_{-\infty}^{\zeta_{-\infty}}(p+\rho V_n^2)_{n=-\infty}dz}\\ &= \overline{\frac{1}{2}\rho g\zeta_{-\infty}^2} - \overline{\frac{1}{2}\rho\int_{-\infty}^{0}\left[\left(\frac{\partial\phi}{\partial s}\right)^2 + \left(\frac{\partial\phi}{\partial z}\right)^2 - \left(\frac{\partial\phi}{\partial n}\right)^2\right]dz}\\ &= \frac{1}{2}\rho g\zeta_a^2\left[\frac{1}{2}\frac{k_1}{k_0} - \frac{1}{2}\cos^2\theta + \frac{1}{2}\frac{k_2}{k_0}\sin\theta\right]\end{aligned} \tag{5}$$

where the upper bar indicates the time average, p is the dynamic pressure, and V_n the normal velocity of fluid at the control surface. The free-surface elevation at $n = -\infty$ is given by

$$\zeta_{-\infty} = -\frac{1}{g}\left(\frac{\partial}{\partial t} + V\frac{\partial}{\partial s}\right)\phi\Big|_{z=0} \tag{6}$$

Based on the assumption of local steady velocity $V{=}U\cos\theta$ and low advancing speed, the added resistance in short waves R_{ASW} can be finally obtained as follows: