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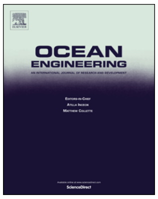

A study on the effect of parametric roll on added resistance in regular head seas

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ABSTRACT

Both parametric roll and added resistance in head seas are hot topics in ship hydrodynamics. Parametric roll with half the encounter frequency is usually not taken into account in the calculation of added resistance in regular head seas. In order to study the correlation between parametric roll and added resistance, firstly, a formula of added resistance in regular head seas with parametric roll taken into account based on Maruo theory is developed to investigate the effect of parametric roll on added resistance in regular head seas. Secondly, partially restrained free running experiments with and without roll motions are carried out respectively to investigate the effects of parametric roll on added resistance in regular head seas. The results of experiments and simulations using the C11 containership show that added resistance is affected by parametric roll, and the results of experiments also show that heave and pitch motions are distinctly affected by parametric roll.

1. Introduction

Parametric roll is induced by restoring arm variation in time. When a ship sails at seas, parametric roll is one of the dangerous phenomena. In case the roll frequency of the ship is half the encounter frequency, this roll motion could be most significant. Recent accidents of a post Panamax C11 class containership suffered heavy parametric roll in head seas in the North Pacific (France et al., 2003) and a PCTC suffered heavy parametric roll in head seas in the North Atlantic (Hua et al., 2006) forced International Maritime Organization (IMO) to start to develop second generation intact stability criteria which cover five stability failure modes including parametric roll, as an supplement to the existing prescribed criteria.

In case of following waves, the encounter frequency is much lower than the natural frequencies of heave and pitch so that the coupling with dynamic heave and pitch is not important. In addition, added resistance due to waves is generally small in following waves. Thus several successful predictions of parametric roll in following waves were reported (e.g. Munif and Umeda, 2000). In particular, clear experimental records of capsize due to parametric roll in following waves were published by one of the present authors (Umeda et al., 1995).

In case of head seas, however, the prediction of parametric roll is not so easy because the coupling of roll motion with dynamic heave and pitch is significant. In addition, the added resistance and the resulting speed loss cannot be simply ignored. So far, the effect of dynamic heave and pitch motions on parametric roll has been investigated by many researchers and its mechanism is well established. The existing research revealed that restoring arm variation depending on dynamic heave and pitch motions is essential for accurately predicting parametric roll in head waves (Taguchi et al., 2006). However, these theoretical works do not deal with the effect of added resistance on parametric roll. Umeda et al. (2008) and Umeda and Francescutto (2008) executed numerical simulations of parametric roll in regular and irregular head seas with added resistance taken into account, but their hydrodynamic prediction method for added resistance is different from that for restoring variation. Two of the present authors (Lu et al., 2011a) carried out numerical simulations of parametric roll in head seas with added resistance taken into account, in which both the restoring variation and the Kochin function for added resistance were calculated by using a strip theory.

Added resistance in waves is mainly caused by energy dissipation when a ship generates radiation waves and diffraction waves on the ship hull (Kashiwagi et al., 2010). Maruo obtained a well-established formula for added resistance in waves, within linear potential theory, based on the principle of momentum and energy conservation (Maruo, 1963). In linear ship dynamics, the frequency of ship oscillations is equal to encounter frequency, without the consideration of roll, sway and yaw motions in

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longitudinal waves. Hosoda (1973) and Maruo and Iwase (1980) extended these methods to oblique waves with roll, sway and yaw taken into account. Parametric roll could occur in head seas with half the encounter frequency, and occasionally the amplitude of parametric roll is more than 40°. All the calculation methods for added resistance mentioned above do not seem to include wave radiations due to parametric roll in head seas, and the effect of parametric roll on added resistance cannot be analyzed. Two of the present authors (Lu et al., 2011b) extended Maruo's theory to study the effect of parametric roll on added resistance in regular head seas, while the effect of parametric roll on heave and pitch motions was ignored and the experimental studies with and without parametric roll were not conducted.

Therefore, the authors attempted to use the extended formula based on Maruo's theory for added resistance with parametric roll taken into account to study the effect of parametric roll on added resistance in regular head seas. Further, the model experiments were conducted to measure roll, heave, pitch motions and wave force in longitudinal direction with and without parametric roll in regular head seas by a new experimental device.

2. Theoretical method

The following formula based on Maruo's theory (Lu et al., 2011b) is used to calculate added resistance in regular head seas with parametric roll taken into account.

$$\begin{aligned}\bar{R} = {} & \frac{\rho}{8\pi}\left[\int_{-\pi/2}^{-\alpha 0} + \int_{\pi/2}^{\alpha 0} - \int_{\pi/2}^{3\pi/2}\right]\times \\ & |H(k_1, \alpha)|^2 \frac{k_1(k_1\ \cos\ \alpha - K\ \cos\ \chi)}{\sqrt{1 - 4\Omega\ \cos\ \alpha}} d\alpha \\ & + \frac{\rho}{8\pi}\left[\int_{\alpha 0}^{2\pi-\alpha 0}\right]\times |H(k_2, \alpha)|^2 \frac{k_2(k_2\ \cos\ \alpha - K\ \cos\ \chi)}{\sqrt{1 - 4\Omega\ \cos\ \alpha}} d\alpha \\ & + \frac{\rho}{8\pi}\left[\int_{-\pi/2}^{-\alpha_0'} + \int_{\pi/2}^{\alpha_0'} - \int_{\pi/2}^{3\pi/2}\right]\times \\ & \left|H(k_1', \alpha')\right|^2 \frac{k_1'(k_1'\ \cos\ \alpha' - \frac{1}{2}K\ \cos\ \chi)}{\sqrt{1 - 4\Omega'\ \cos\ \alpha'}} d\alpha' \\ & + \frac{\rho}{8\pi}\left[\int_{\alpha_0'}^{2\pi-\alpha_0'}\right]\times \left|H(k_2', \alpha')\right|^2 \frac{k_2'(k_2'\ \cos\ \alpha' - \frac{1}{2}K\ \cos\ \chi)}{\sqrt{1 - 4\Omega'\ \cos\ \alpha'}} d\alpha' \\ & - \frac{E_3}{\left(\frac{\omega_e}{K}\right)} os\chi \end{aligned} \tag{1}$$

where:

$$\alpha_0 = \begin{cases} 0 & (\Omega \le 1/4) \\ \cos^{-1}\left(\dfrac{1}{4\Omega}\right) & (\Omega > 1/4) \end{cases};\quad \alpha_0' = \begin{cases} 0 & (\Omega' \le 1/4) \\ \cos^{-1}\left(\dfrac{1}{4\Omega'}\right) & (\Omega' > 1/4) \end{cases} \tag{2}$$

U is ship's forward velocity, ω_0 is wave circular frequency, K is wave number, χ is the angle of wave incidence, ρ is the water density and $\chi = \pi$ corresponds to the heading sea. Here we define that the encounter frequency is $\omega_e = \omega_0 - kU\ \cos\ \chi$, the encounter period is T_e, the wavelength is λ and wave number is k for incident wave, diffraction wave and radiation waves due to heave, pitch and surge motions. At the same time, we also define that the frequency is $\omega_{e2}{=}1/2\omega_e$, the period is T_{e2} and wave number is k' for radiation waves due to parametric roll, sway and yaw motions. $H(k,a)$ is Kochin function defined in the reference (Lu et al., 2011b).

The added resistance can be obtained by averaging forces within the duration that is double the encounter period. According to energy dissipation by viscous roll damping force, the follow equations can be obtained:

$$E_3 = \frac{1}{2T_e}\int_0^{2T_e}\left(B_{44\varphi a}\cdot\dot{\phi}_{roll}\right)\dot{\phi}_{roll}dt \tag{3}$$

where ϕ_a is the amplitude of parametric roll, $B_{44}\dot{\phi}$ is the viscous roll damping force, $\dot{\phi}_{roll}$ is the angular velocity of parametric roll. E_3 can be obtained by following formula (Katayama et al., 2010):

$$\begin{aligned} E_3 &= \frac{1}{2T_e}\pi B_{44\phi a}\cdot\phi_a^2\left(\frac{1}{2}\omega_e\right) \\ &= \frac{1}{8}B_{44\phi a}\cdot\phi_a^2\omega_e^2 \end{aligned} \tag{4}$$

Both k_1 wave and k_2 wave are used for incident wave, diffraction wave and radiation waves due to heave, pitch and surge motions.

$$\begin{aligned} k_j &= \frac{K_0\cdot(1 - 2\Omega\ \cos\ \alpha \pm \sqrt{1 - 4\Omega\ \cos\ \alpha})}{2\ \cos^2\ \alpha} \\ & \left(+for\ \ j = 1, - for\ \ j = 2, \Omega = \frac{\omega_e U}{g}, K = \frac{\omega_0^2}{g}, K_0 = \frac{g}{U^2}\right) \end{aligned} \tag{5}$$

Both $k_1{}'$ wave and $k_2{}'$ waves are used for radiation waves due to parametric roll, sway and yaw motions.

$$\begin{aligned} k_j' &= \frac{K_0\cdot(1 - 2\Omega'\ \cos\ \alpha \pm \sqrt{1 - 4\Omega'\ \cos\ \alpha}\ )}{2\ \cos^2\ \alpha} \\ & \left(+ for\ \ j = 1, - for\ \ j = 2, \Omega' = \frac{\omega_{e2}U}{g} = \frac{1}{2}\frac{\omega_e U}{g} = \frac{1}{2}\Omega, K_0 = \frac{g}{U^2}\right) \end{aligned} \tag{6}$$

The Kochin function can be calculated by formula (7), if singularity distributions ($\mu(x)$ and $\sigma(x)$) along the centre line of the ship submerged with a depth of $z(x)$ are properly provided.

$$\begin{aligned} H(k_i, \alpha) = {} & \int_L \sigma(x)e^{-k_i z(x)}e^{ik_i x\ \cos\ \alpha}dx \\ & + \int_L i\mu(x)e^{-k_i' z(x)}k_i'\ \sin\ \alpha e^{ik_i' x\ \cos\ \alpha}dx \end{aligned} \tag{7}$$

Based on the comparisons of calculated added resistance by different methods of source distribution $\sigma(x)$ for the modified Wigley model (Lu et al., 2011b), it can be concluded that Maruo and Ishii (1976) method is most appropriate for the region where parametric roll could appear. Maruo and Ishii's formula can be described with a two-dimensional Kochin function of heave motion which is as follows:

$$\begin{aligned} \sigma(x) = {} & -H_2^+(x)\times\left(i\omega_e - U\frac{\partial}{\partial x}\right)\left(Z_G - x\Theta - \underset{\sim\sim\sim\sim}{\zeta_W}\right) \\ & + H_2^+(x)\times U\frac{\dot{B}(x)}{B(x)}(Z_G - x\Theta - \underset{\sim\sim\sim\sim}{\zeta_W});\quad z = 0 \end{aligned} \tag{8}$$

where $\sigma(x)$ is the source distribution, $Z_G e^{i\omega_e t}$ is the heaving, $\Theta e^{i\omega_e t}$ is the pitching, $\zeta_W e^{i\omega_e t}$ is the wave elevation, $H_2^+(x)$ is the two-dimensional Kochin function in heave, $B(x)$ is the ship breadth at x section and $\dot{B}(x) = \partial B(x)/\partial x$.

For calculating doublet distribution $\mu(x)$, Maruo and Iwase (1980) method is used, which can be described with the two-dimensional Kochin function of sway ($H_1^+(x)$) as follows:

$$\mu(x) = \frac{-1}{2k_e'}H'^+_1(x)\times\left\{\frac{1}{B(x)}\left(\frac{\partial}{\partial t} - V\frac{\partial}{\partial x}\right)[B(x)(Y_G - x\psi + |l_W|\varphi)] - V_W\right\} \tag{9}$$

where, $Y_{G0}e^{i\frac{1}{2}\omega_e t}$ is swaying, $\psi_0 e^{i\frac{1}{2}\omega_e t}$ is yawing, $\varphi_0 e^{i\frac{1}{2}\omega_e t}$ is rolling and V_W is wave particle velocity in y direction.

In this paper, however, only the effect of parametric roll in head seas is investigated during numerical calculation. The doublet distribution $\mu(x)$ can be rewritten as: