A Study on the Effect of Parametric Rolling on Added Resistance in Regular Head Seas

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ABSTRACT

Both parametric rolling and added resistance in head seas are hot topics in ship hydrodynamics. Parametric rolling with half the encounter frequency is not taken into account in the calculation of added resistance in regular head seas. In order to study the correlation between parametric rolling and added resistance, firstly, a formula of added resistance in regular head seas with parametric rolling taken into account based on Maruo theory is developed to investigate the effect of parametric rolling 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 rolling 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 rolling, and the results of experiments also show that heave and pitch motions are distinctly affected by parametric rolling.

Keywords: *Parametric rolling, added resistance, heave, pitch, Maruo theory*

1. INTRODUCTION

The second generation intact stability criteria are under development at the International Maritime Organization (IMO) which covers five stability failure modes including parametric rolling as one of roll restoring variation problems, as a supplement to the existing prescriptive criteria (IMO SDC1, 2014).

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 rolling in following waves were reported (e.g. Munif and Umeda, 2000). In particular, clear experimental records of capsize due to parametric rolling in following waves were published by one of the present authors (Umeda et al., 1995).

In case of head seas, however, prediction of parametric rolling is not so easy because coupling 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 rolling was investigated by many researchers and it was 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 rolling.

Umeda et al (2008) and Umeda&Francescutto (2008) executed numerical simulations of parametric rolling 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) executed numerical simulation of parametric rolling in head seas with added resistance taken into account, in which both the restoring variation and the Kochin function for added resistance are calculated by 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 an 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 longitudinal waves. Hosoda (1973) and Maruo&Iwase (1980) extended these methods to oblique waves with roll, sway and yaw taken into account. Parametric rolling could occur in head seas with half the encounter frequency, and occasionally the amplitude of parametric rolling is more than 40 degrees. All calculation methods of added resistance mentioned above seem not to include wave radiations due to parametric rolling in head seas, and the effect of parametric rolling on added resistance cannot be discussed. Two of the present authors (Lu et al., 2011b)extended Maruo's theory to study the effect of parametric rolling on added resistance in regular head seas, while the effect of parametric rolling on heave and pitch motions was ignored and the experimental studies with and without parametric rolling were not conducted.

Therefore, the authors attempted to use the extended formula based on Maruo's theory for added resistance with parametric rolling taken into account to study the effect of parametric rolling 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 rolling 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 rolling taken into account.

$$\begin{aligned}
\overline{R}= & \frac{\rho}{8\pi}\left[\int_{-\pi/2}^{-\alpha_0}+\int_{\pi/2}^{\alpha_0}-\int_{\pi/2}^{3\pi/2}\right]\times\left|H(k_1,\alpha)\right|^2\frac{k_1(k_1\cos\alpha-K\cos\chi)}{\sqrt{1-4\Omega\cos\alpha}}d\theta \\
& +\frac{\rho}{8\pi}\left[\int_{\alpha_0}^{2\pi-\alpha_0}\right]\times\left|H(k_2,\alpha)\right|^2\frac{k_2(k_2\cos\alpha-K\cos\chi)}{\sqrt{1-4\Omega\cos\alpha}}d\alpha \\
& +\frac{\rho}{8\pi}\left[\int_{-\pi/2}^{-\alpha_0'}+\int_{\pi/2}^{\alpha_0'}-\int_{\pi/2}^{3\pi/2}\right]\times\left|H(k_1',\alpha')\right|^2\frac{k_1'(k_1'\cos\alpha'-\frac{1}{2}K\cos\chi)}{\sqrt{1-4\Omega'\cos\alpha'}}d\theta \qquad (1)\\
& +\frac{\rho}{8\pi}\left[\int_{\alpha_0'}^{2\pi-\alpha_0'}\right]\times\left|H(k_2',\alpha')\right|^2\frac{k_2'(k_2'\cos\alpha'-\frac{1}{2}K\cos\chi)}{\sqrt{1-4\Omega'\cos\alpha'}}d\alpha' \\
& -\frac{E_1}{(\frac{\omega_e}{K})}\cos\chi-\frac{E_2}{(\frac{\omega_e}{K})}\cos\chi-\frac{E_3}{(\frac{\omega_e}{K})}\cos\chi
\end{aligned}$$

where:

$$\alpha_0=\begin{cases}0 & (\Omega\leq 1/4)\\ \cos^{-1}(\frac{1}{4\Omega}) & (\Omega>1/4)\end{cases};\quad \alpha_0'=\begin{cases}0 & (\Omega'\leq 1/4)\\ \cos^{-1}(\frac{1}{4\Omega'}) & (\Omega'>1/4)\end{cases} \qquad (2)$$

U is ship's forward velocity, $\omega_0$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 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}, the wavelength is$\lambda_2$for radiation waves due to parametric roll, sway and yaw motions.

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:

$$\begin{aligned} E_1 &= 0 \\ E_2 &= 0 \\ E_3 &= \int_0^{2T_e} (B_{44\phi_a} \dot{\phi}_{roll}) \dot{\phi}_{roll}\, dt \end{aligned} \tag{3}$$

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

$$E_3 = \pi B_{44\phi_a} \phi_a^2 (\frac{1}{2}\omega_e) \tag{4}$$

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.

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

Both k_1'waveand k_2'wavesare used for radiation wavesdue to parametric roll, sway and yaw motions.

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

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

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

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

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

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's method (Maruo and Iwase,1980)is used, which can be described with the two-dimensional Kochin function of sway($H_1^+(x)$) as follows:

$$\mu(x) = \frac{-1}{2k_e'} H_1^+(x) \times \{\frac{1}{B(x)}(\frac{\partial}{\partial t} - U\frac{\partial}{\partial x})[B(x)(Y_G - x\psi + |l_W|\varphi)] - V_W\} \tag{9}$$

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

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

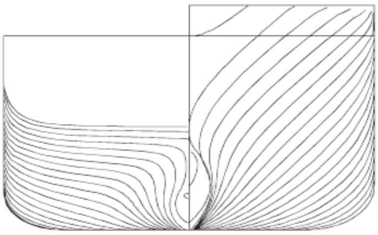
$$\mu(x) = \frac{-1}{2k_e'} H_1^+(x) \times [i(\frac{1}{2}\omega_e)|l_W|\varphi_0 - U\frac{\dot{B}(x)}{B(x)}|l_W|\varphi_0] \tag{10}$$

3. EXPERIMENTS

The partially restrained experiment with a 1/65.5 scaled model of the post Panamax C11 class containership were conducted in the seakeeping basin (length: 69m, breadth: 46m, depth: 4m) of China Ship Scientific Research Center, which is equipped with flap wave makers at the two adjacent sides of the basin.

The partially restrained ship model was towed by the towing carriage in regular head seas and a newly designed equipment was used to measure ship motions including roll, pitch and heave motions and exciting wave moment/force including roll moment, yaw moment, sway force and surge force. Roll and pitch motions were measured by potentiometer sensor. Heave motion was measured by displacement sensor. Roll moment, yaw moment, sway force and surge force were measured by four sensors based on electromotive strain gauge.

The principal particulars and body plan of the C11 class containership are shown in Table1 and Fig.1, respectively. The ship model in partially restrained experiment is shown in Fig.2.



- Figure 1 Lines of C11 containership

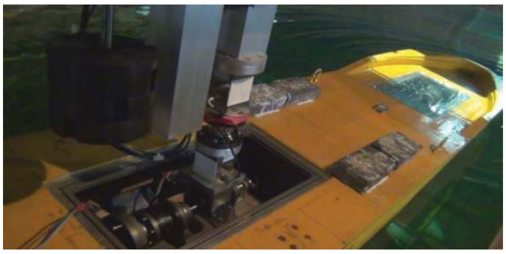
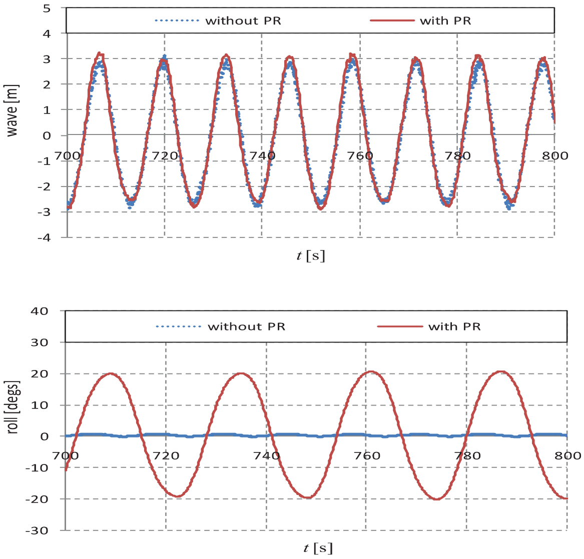


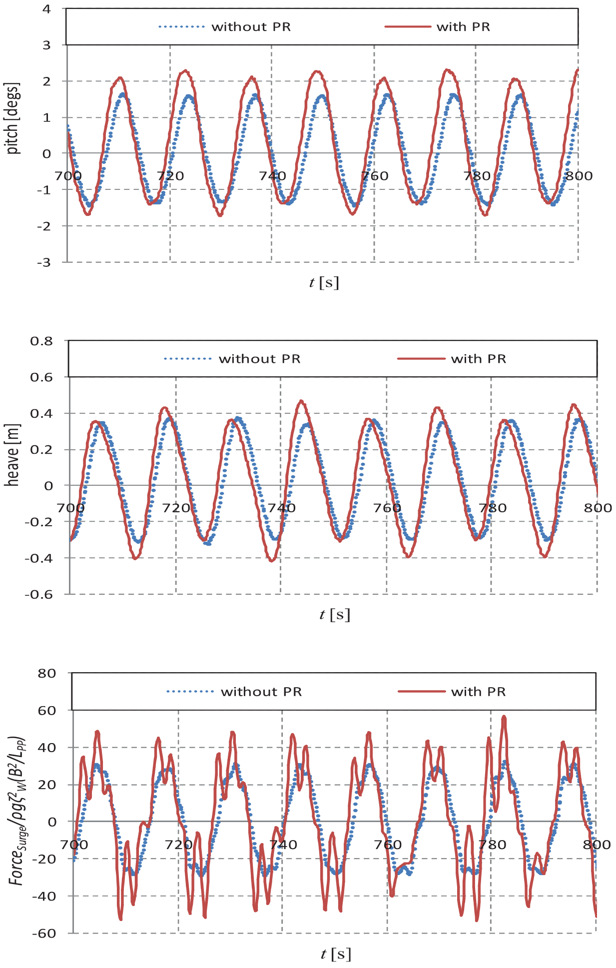
Figure 2The ship model in partially restrained experiment

Table 1 Principal particulars of the C11 containership

Items	Ship	Model
Length:L	262.0m	4.000m
Draft:T	11.5m	0.176m
Breadth:B	40.0m	0.611m
Depth:D	24.45m	0.373m
Displ.:W	67508ton	240.2kg
C_B	0.560	0.560
GM	1.928m	0.029m
T_φ	24.68s	3.05s
K_{YY}	0.24L	0.24L

4. RESULTS AND DISCUSSION





▪ Figure 3 Comparisons of wave, roll, pitch, heave and surge forcein time series between with and without parametric rolling in experiments, with Fn =0.0, H/λ=0.02, λ/Lpp=1.0 and χ=180 degs.

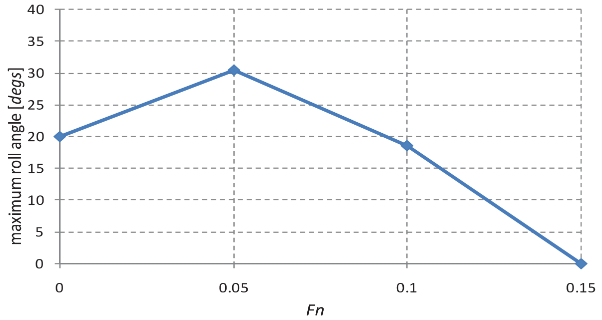
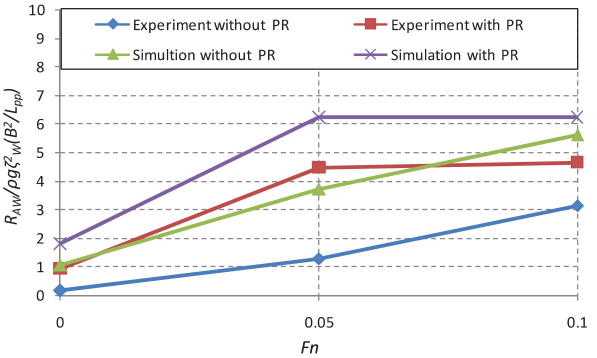


Figure 4 Parametric rolling in experiment as The function of Froude number with λ/L_{pp} =1.0, H/λ=0.02 and χ=180degs.



▪ Figure 5Added resistance with and without parametric rolling in experiments and simulations as the function of the Froude number with λ/L_{pp}=1.0,H/λ=0.02 and χ=180degs.

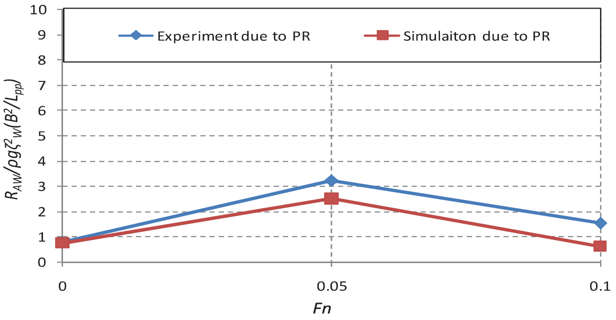
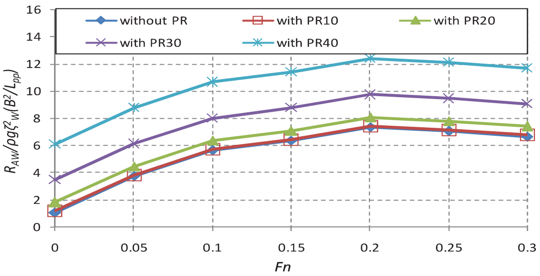
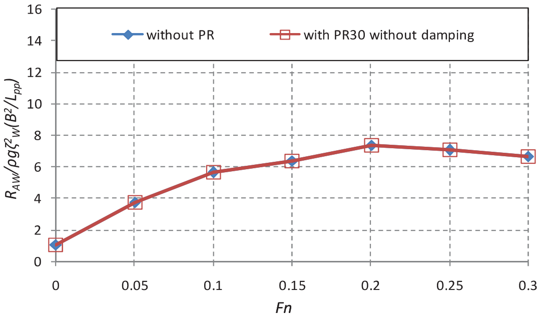


Figure 6The component of added resistance resulted from parametric rolling in experiments and simulations as the function of the Froude number with λ/L_{pp}=1.0,H/λ=0.02 and χ=180degs.



▪ Figure 7 Calculated added resistance with different amplitudes of parametric rolling as the function of the Froude number with λ/L_{pp}=1.0,H/λ=0.02 and χ=180degs.



- Figure 8 Calculated added resistance with parametric rolling and without roll damping force, as the function of the Froude number with λ/L_{pp}=1.0,H/λ=0.02 and χ=180degs.

We compare heave, pitch, roll motions and surge force containing resistance with and without roll motion in experiment. An example of time series is shown in Fig. 3. When parametric rolling occurs with amplitudes of 20 degrees, heave and pitch motions are affected by parametric rolling and their large and small amplitudes alternatively appear. This phenomenon seems like "subharmonic pitch" and "subharmonic heave" (Neves et al., 2009; Lu et al., 2013, 2014). The phase difference of heave and pitch motion are also small changed as shown in Fig.3. This indicates that both the amplitude and phase difference of heave and pitch motions are distinctly affected by parametric rolling. The surge force is also affected when parametric rolling occurs with amplitudes of 20 degrees as shown in Fig.3.Heave and pitch motions are main cause of added resistance in waves. Therefore added resistance in waves could be affected by parametric rolling. Here we only show the experimental results of time series at zero speed, because the towing carriage has mechanical vibrations with forward speed.

Parametric rolling in regular head seas, as a function of the Froude number, was measured by the partially restrained experiment of C11 containership as shown in Fig.4, and the values of parametric rolling in experiments are used during the numerical simulations of added resistance in waves. The added resistance in experiments is obtained by subtracting the resistance in calm water from the averaged surge force. Both the experiment and numerical simulation show that the difference of added resistance with and without parametric rolling is not negligible, as shown in Fig.5. The component of added resistance resulted from parametric rolling in experiments and simulations is shown in Fig. 6. Although the calculated results are general larger than experimental results, the tendency of the effect of parametric rolling on added resistance in waves is the same. Here the viscous roll damping coefficient was estimated by roll decay test of the ship model.

In order to investigate the reason, the added resistance was calculated without parametric rolling and with different amplitudes of parametric rolling, as the function of the Froude number. The results shown in Fig.7 indicate that the effect of parametric rolling on added resistance in regular head seas becomes larger as the amplitude of parametric rolling becomes larger. The calculated added resistance with parametric rolling and without viscous roll damping force, as a function of the Froude number, is shown in Fig.8. The effect of parametric rolling on added resistance in regular head seas within a potential flow theory is very small, and it supports Maruo and Iwase's(1980) conclusion in oblique waves, that is to say, the effect of rolling on added resistance is generally small. This means that the major effect of parametric rolling is viscous roll damping. It is noted here the effect of large parametric rolling on heave and pitch motions in simulations is ignored. Heave and pitch motion are main cause of added resistance in waves. Both the amplitude and phase difference of heave and pitch motions are distinctly affected by parametric rolling as show in Fig.3, which could be one of reasons why the added resistance in experiments is smaller than that in simulations as shown in Fig 6.

5. CONCLUSIONS

As a result of experimental and numerical study on the effect of parametric rolling on added resistance in regular head seas for a containership, the following remarks are noted:

1) An extended formula based on Maruo theory for added resistance in head seas with parametric rolling taken into account can be used to study the effect of parametric rolling on added resistance in regular head seas.

2) The effect of parametric rolling on added resistance in regular head seas mainly is due to viscous roll damping and it becomes larger as the amplitude of parametric rolling becomes larger.

Future research is desirable to validate the effect of heave and pitch motion on added resistance while parametric rolling occurs.

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