Experimental and Numerical Studies on Parametric Roll of a Post-Panamax Container Ship in Irregular Waves

Hirotada Hashimoto, *Osaka University*

Naoya Umeda, *Osaka University*

Akihiko Matsuda, *NRIFE*

Shinya Nakamura, *Osaka University*

ABSTRACT

Firstly free running model experiments of a post-Panamax container ship were conducted in regular waves, long-crested and short-crested irregular waves. As a result, parametric roll in head and bow waves were clearly recorded even in long-crested and short-crested irregular waves. From the experimental results, effect of wave steepness, forward velocity, heading angle, irregularity of waves on parametric roll were systematically examined.

Secondly numerical prediction of parametric roll in long-crested irregular waves was carried out with an uncoupled roll model with restoring variation. The comparison between experimental and numerical results demonstrates that the uncoupled model can explain the experimental results qualitatively but not quantitatively.

Keywords: *Parametric Roll, Free Running Tests, Irregular Waves, Head Waves, Statistical Analysis, Numerical Prediction*

1. INTRODUCTION

Recent accidents of a post-Panamax container ship due to parametric roll in head waves (France et al, 2003) forced the International Maritime Organization (IMO) to start to revise the Intact Stability Code (2002) and the guidance for the master in following and quartering waves (MSC Circ.707, 1995). Although several experimental data were published for parametric roll even in irregular waves (Umeda et al, 1995), only limited outcomes are available for that in head and bow waves.

In this revision work at the IMO, the following questions were now raised to be urgently solved; does the parametric roll in head waves lead not only to cargo damage but also ship capsize, does the danger of parametric roll decrease in irregular waves, especially in short-crested waves, in comparison with ideal regular waves, and how can we avoid and predict parametric roll in realistic head or bow waves? Responding to this situation, free running model experiments mainly focusing on irregular head and bow waves were conducted to directly obtain answers to the above questions. From the experimental results, effect of wave height on parametric roll in regular waves, effect of heading angle and forward velocity on parametric roll in regular waves, effect of irregularity of waves on parametric roll in head waves, effect of heading angle and forward velocity on parametric roll in short-crested irregular waves were systematically examined.

From a practical point of view, free running model experiment is obviously one of the most reliable ways to examine occurrence condition and amplitude of parametric roll; however it is time-consuming and cost-wasting assessment to do model tests with all of the relevant conditions. Therefore we attempted to develop an uncoupled roll model for parametric roll prediction in irregular waves as an alternative option to assess parametric roll danger or to reduce total number of free running model experiment. Regarding parametric roll in irregular waves, how to take the restoring arm variation into account is problem. Because restoring arm and wave steepness has the nonlinear relationship, an ordinary seakeeping theory, that is linear theory, cannot be applied directly. Therefore we apply Grim's effective wave concept (Grim, 1961) to solve the restoring arm variation problem in irregular waves, and compared numerical results with the experimental results.

2. FREE RUNNING MODEL EXPERIMENTS

2.1 Outline of Model Experiment

Model experiments were conducted in the basin of National Research Institute of Fisheries Engineering (length: 60m, width: 25m, depth: 3.2m) with an 80-segmented wave maker. A scaled ship model of a post-Panamax container ship was used here, and her principal particulars and body plan are shown in Table.1 and Figure 1, respectively. The ship model had no deckhouse, but was watertight, and was propelled by an electric motor with a constant revolution control system. The onboard computer realises an autopilot system of the constant gain of 1.0 and stored data of roll, pitch and yaw motions obtained by a fiber-optic gyroscope. In addition, surge and sway velocity were obtained from the data of ship position recorded by an optical tracking sensor fixed to the basin.

In regular wave runs, several sets of propeller revolution number, n_c, wave height, H, wave length, λ, autopilot course, χ_c, were used but the wave length to ship length ratio was fixed to be 1.6. Furthermore the vertical displacement of incident waves at the centre of ship gravity was obtained in consideration of wave phase velocity, ship position and wave height records. In long-crested irregular wave runs, significant wave height $H_{1/3}$ of 0.221m in model scale and mean period T_{01} of 1.3 seconds, which correspond to the wave height and period of regular waves, were used with the ITTC spectrum. In short-crested wave runs, $H_{1/3}$ and T_{01} were the same as the long-crested irregular wave runs, but with cosine to the 2nd or 4th power as the directional distributions function were used. By utilising the single summation method for generating wave signals, uniformity of short-crested waves in space is realised within $\pm$5% error (Sera and Umeda, 2000). In case of irregular wave, model running were repeated so that number of encounter waves is about 150 in average. A photograph of the model runs in short-crested irregular waves is shown in Figure 2 as an example.

Table 1 Principal particulars of the post-Panamax container ship

Items	Ship	Model
Length between perpendiculars: L	283.8m	2.838m
breadth: B	42.8m	0.428m
depth: D	24.0m	0.24m
draught at FP: T_f	14.0m	0.14m
mean draught: T	14.0m	0.14m
draught at AP: T_a	14.0m	0.14m
block coefficient: C_b	0.630	0.630
pitch radius of gyration: K_{yy}/L_{pp}	0.239	0.258
longitudinal position of centre of gravity from amidships: X_{CG}	5.74m aft	0.0574m aft
metacentric height: GM	1.08m	0.0106m
natural roll period: T_ϕ	30.3s	3.20s
natural pitch period: T_θ		0.86s

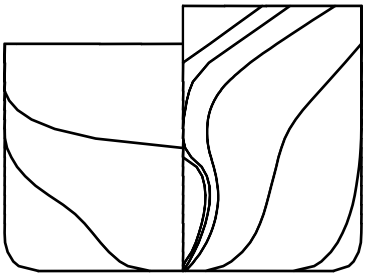

Figure 1 Body plan of the post-Panamax container ship

Figure 2 A photograph of free running model experiment in short-crested head waves

2.2 Experimental Results

Examples of measured time history of head sea parametric roll in regular waves, long-crested irregular waves and short-crested irregular waves are shown in Figures 3-5. Here propeller revolution number is the same and Froude numbers are obtained from measured average speed. $H_{1/3}$ and T_{01} are corresponding to the wave height and period of regular waves. In Figure 3, parametric roll with its steady amplitude of about 18 degrees can be clearly recorded after 10 seconds. In long-crested irregular waves, parametric roll was also observed with the maximum roll angle of about 20 degrees. Even in short-crested waves shown in Figure 5, parametric roll does not disappear and an amplitude of 22 degrees can be found. These demonstrate that wave irregularities or short-crestedness does not exclude danger of parametric roll in head waves.

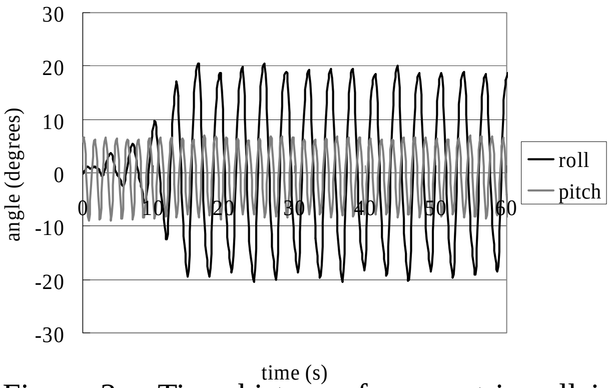

Figure 3 Time history of parametric roll in regular waves (H/λ=1/20.6, λ/L=1.6, χ_c=180 degrees and Fn=0.043)

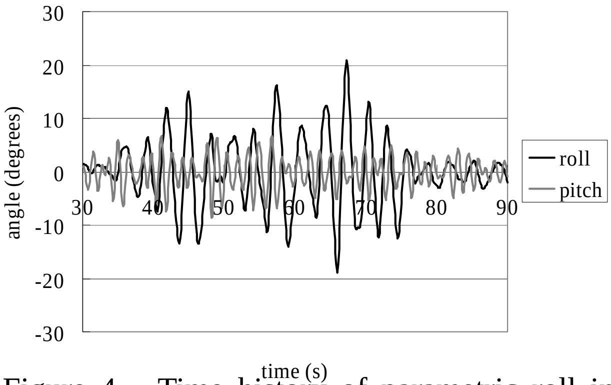

Figure 4 Time history of parametric roll in long-crested irregular waves ($H_{1/3}$=0.221m, T_{01}=1.32s, χ_c=180 degrees and Fn=0.021)

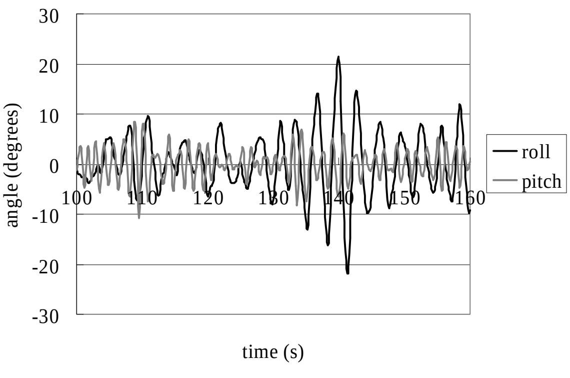

Figure 5 Time history of parametric roll in short-crested irregular waves ($H_{1/3}$=0.221m, T_{01}=1.32s, $\cos^2\theta$ distribution, χ_c=180 degrees and Fn=0.036)

The effect of wave height on parametric roll in regular head waves is shown in Figure 6. Here, wave length to ship length ratio is 1.6 and propeller revolution number was set to realise ship forward velocity satisfying the ratio of 2.0 between encounter frequency and roll natural sfrequency. Parametric roll can be found even in small wave steepness. With increase of wave steepness, parametric roll with its amplitude around 20 degrees was observed at $H/\lambda=0.0176$, and the amplitude does not significantly decrease up to $H/\lambda=0.0528$. Finally parametric roll disappears at $H/\lambda=0.0726$. This can be explained that ship condition deviates from a parametric roll condition with change in mean of restoring moment variation. Because H/λ of 0.072 corresponds to the wave height of 32 m in full scale and the maximum roll angle remains about 23 degrees, it is difficult to find direct relationship between the observed parametric roll and capsizing.

The effects of heading angle and forward velocity on parametric roll in regular waves are shown in Figure 7. Here, the heading angle of 180 degrees means pure head sea condition, and 270 degrees means beam sea condition. The Froude number in the Figure is estimated with the speed loss due to wave taken into account. In head waves, several runs of parametric roll with its maximum roll angle of about 20 degrees was found in smaller Froude number. At the Froude number of 0.1, parametric roll suddenly disappears. When the heading angle becomes larger, except for 270 degrees, the maximum roll angle is smaller than the case of 180 degrees of heading angle, but parametric roll itself does not disappear even in relatively high forward velocity while it does in head waves. This is because the area that satisfies the parametric roll condition shifts to higher forward velocity with increasing heading angle. However, if we focus on severe parametric roll for which the maximum angle is larger than 15 degrees, the danger decreases with increasing heading angle.

The effects of irregularity of incident waves on parametric roll in head waves are shown in Figure 8. Here the maximum amplitudes of parametric rolling in about 75 wave encounters are plotted. In case of smaller forward velocity, roll angles both in long-crested and short-crested irregular waves are slightly smaller than that in regular waves. Here some statistical fluctuation due to non-ergodicity (Belenky, 2004) can be found. When the Froude number is larger than 0.1, however, parametric roll in irregular waves still occurs while no parametric roll occurs in regular waves. This tendency is more conspicuous in the case of short-crested irregular waves.

The effect of heading angle on the maximum roll angle of parametric roll in short-crested irregular waves is shown in Figure 9. Here cosine to the 2nd power was used as the directional distribution function. This figure shows that the ship cannot avoid parametric roll only by changing its course in short-crested irregular waves, and also shows that speed increase is effective in reducing danger of parametric roll at least in the heading angle ranging from 180 degrees to 240 degrees.

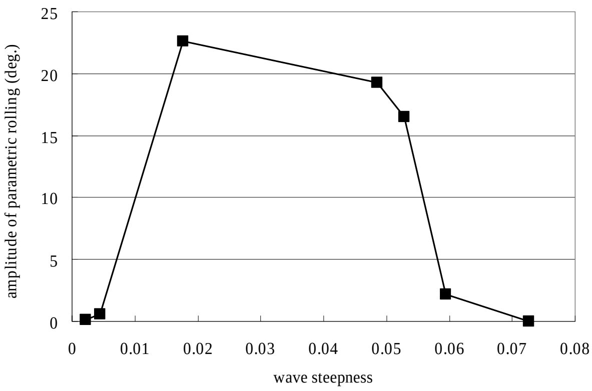

Figure 6 Effect of wave height on parametric roll in regular waves ($\lambda/L=1.6$ and $\chi_c=180$ degrees)

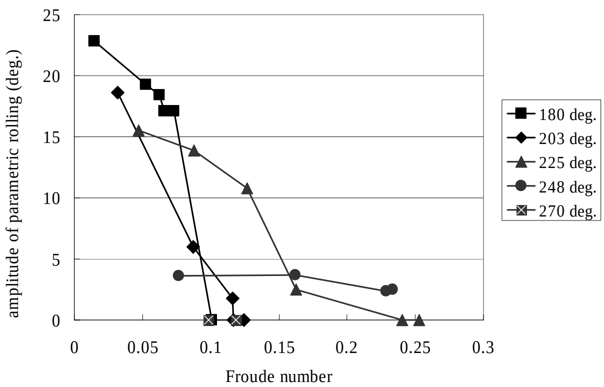

Figure 7 Effect of heading angle and forward velocity on parametric roll in regular waves ($H/\lambda=1/20.6$ and $\lambda/L=1.6$)

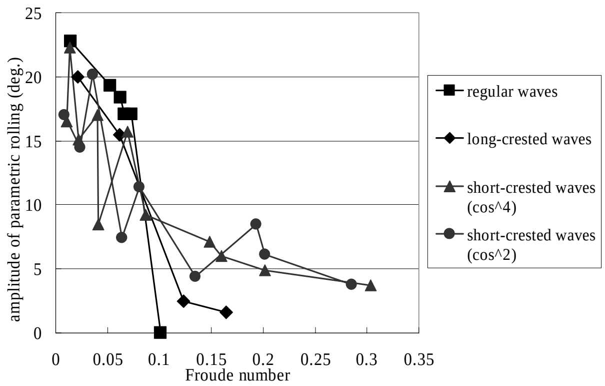

Figure 8 Effect of irregularity of waves on parametric roll in head waves ($H_{1/3}$=0.221m, T_{01}=1.32s and χ_c=180 degrees)

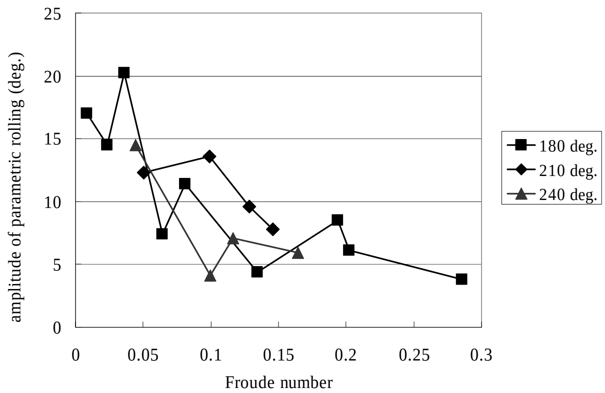

Figure 9 Effect of heading angle on parametric roll in short-crested irregular waves ($H_{1/3}$=0.221m, T_{01}=1.32 s and $\cos^2\theta$ distribution)

2.3 Statistical Analysis

Statistical analysis focusing on instantaneous angle and amplitude of roll and pitch was carried out with recorded time histories. Probability density functions were obtained for both instantaneous angle and amplitude of roll and pitch, and compared with the Gaussian distribution and the Rayleigh distribution, respectively.

Examples of the results in long-crested irregular waves are shown in Figures 10-11. Here the experimental condition is $H_{1/3}$=0.221m, T_{01}=1.32s, autopilot course χ_c=180 degrees. As shown in Figures 10-11, the instantaneous pitch angle agrees with the Gaussian distribution and the pitch amplitude agrees with the Rayleigh distribution. Thus a linear theory can explain experimental results of the pitch motion even with quite high wave height of 22.1 m in full-scale. On the other hand, probability density functions of instantaneous angle and amplitude of roll around 0 degrees are conspicuously large, and do not follow the Gaussian and Rayleigh distributions at all. These results indicate that parametric roll is a strong nonlinear phenomenon. Pitch motion immediately starts whenever a ship meets incident waves while a ship starts to roll only when a ship meets the wave group that exceeds a parametric roll threshold. Therefore probability density around 0 degrees becomes large. For this reason, a conventional seakeeping theory based on a linear or weakly nonlinear assumption cannot be applied to parametric roll problems. Similar results have been reported by Belenky et al. (2003) and Ribeiro e Silva et al. (2005) based on their numerical simulations, however, no publication based on model experiments can be found so far.

Examples of the results in short-crested irregular waves are shown in Figures 12-13. Here the experimental condition is $H_{1/3}$=0.221m, T_{01}=1.32s, autopilot course χ_c=180 degrees and $\cos^2\theta$ distribution. The instantaneous pitch and the pitch amplitude agree well with the Gaussian and Rayleigh distributions, respectively. Instantaneous roll angle and roll amplitude do not agree with the relevant distribution as well as long-crested irregular wave runs; however, the difference becomes smaller to some extent.

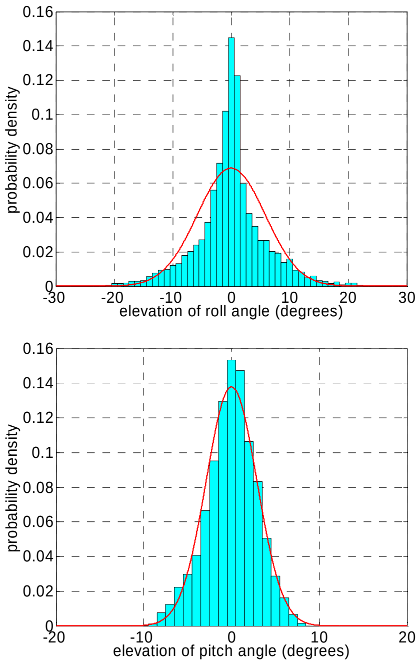

Figure 10 Probability density function of instantaneous roll and pitch angle in long-crested irregular waves for Fn=0.021 (histogram: experiment; dashed line: Gaussian distribution)

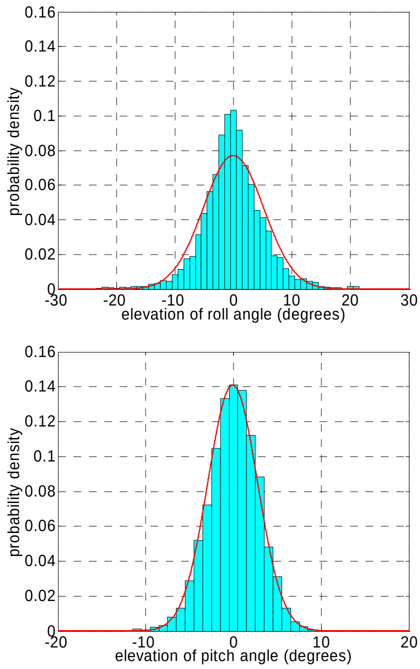

Figure 12 Probability density function of instantaneous roll and pitch angle in short-crested irregular waves for Fn=0.029 (histogram: experiment; dashed line: Gaussian distribution)

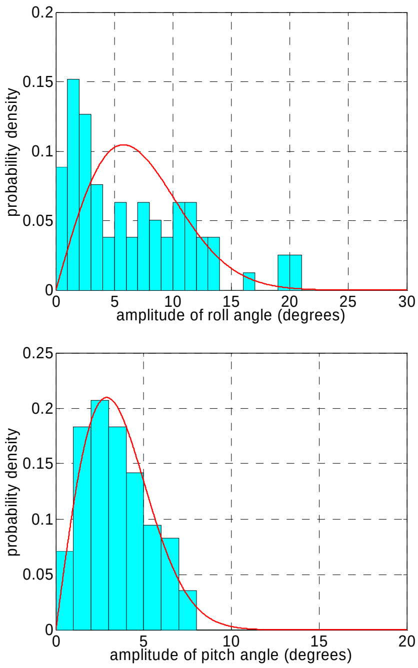

Figure 11 Probability density function of roll and pitch amplitude in long-crested irregular waves for Fn=0.021 (histogram: experiment; dashed line: Rayleigh distribution)

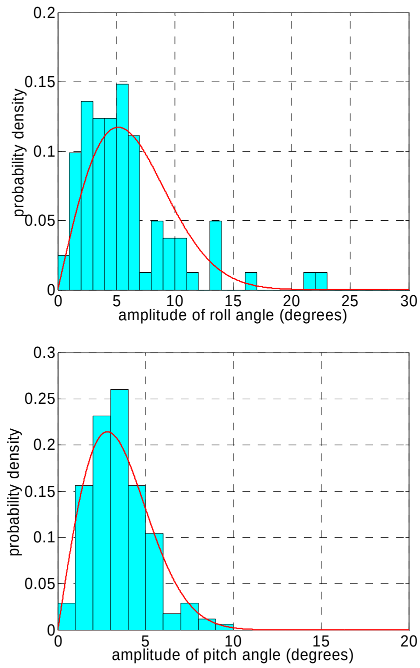

Figure 13 Probability density function of roll and pitch amplitude in short-crested irregular waves for Fn=0.009 (histogram: experiment; dashed line: Rayleigh distribution)

3. NUMERICAL SIMULATION

3.1 Mathematical Model

For simplicity, numerical simulations were carried out only for long-crested irregular waves, and it is assumed that a ship keeps constant forward velocity and constant heading angle of 180 degrees, that is pure head waves. This is because head wave is most dangerous situation for parametric roll occurrence both in regular and irregular waves as we confirmed in the experimental results. Under these assumptions, a mathematical model of ship roll motions can be described as follows:

$$\begin{aligned}(I_{xx}+J_{xx})\ddot{\phi} &= -A\dot{\phi}-C\dot{\phi}^3-WGZ(\phi)\\ &-WGZ_W\left\{\zeta_{eff}(\xi_G,t),\phi\right\}+Mx_\phi(\zeta_{eff}(\xi_G,t))\phi\end{aligned} \tag{1}$$

Here, I_{xx} : inertia moment in roll, J_{xx} : added inertia moment in roll, A, C : linear and cubic damping coefficients, W : ship weight, GZ : restoring arm, GZ_W : restoring arm variation due to wave, ζ_{eff} : effective wave amplitude, ξ_G : relative longitudinal position of the ship to a wave trough, t : time, Mx_ϕ : heel-induced hydrodynamic roll moment.

In the fourth terms of right hand side equation, Grim's effective wave concept is used to take restoring arm variation in irregular waves into account. Grim's effective wave concept is an approximation method of irregular wave profile along the ship to one regular wave called the effective wave. Here length of the effective wave is the same as the ship length between perpendiculars, and its trough or crest is assumed to be on amidships. The effective wave amplitude has linear relationship with the ocean wave elevation, but has nonlinear and non-memory effect on the restoring arm. The last term of the right-hand-side of the equation shows roll-dependent hydrodynamic roll moments that consist of diffraction, radiation and linear lift components, and are obtained by a strip theory with a heel angle taken into account (Umeda et al, 2004). This is because the Froude-Krylov component on its own cannot deal with the speed dependence on the restoring variation, while it could be relatively large in head waves because of high encounter frequency. These hydrodynamic roll moments are assumed to have linear relationship with the wave steepness and are calculated as a function of frequency. Therefore those in irregular waves can be estimated with the linear superposition principle. The roll damping coefficients of A and C are obtained from roll decay model test with no forward velocity.

In numerical calculations, ocean waves are assumed to follow the ITTC spectrum same as in the free running model experiments, and are expressed as a sum of 1000 components of waves with non-uniformly different frequencies and random phases. To compare numerical results with the experimental ones, numerical calculations were carried out for $H_{1/3}$ = 22.1 m, T_{01} = 13.2 s with several Froude numbers in long-crested irregular head waves.

3.2 Numerical Results

Numerical calculations in long-crested irregular waves with the same condition as Figure 4 were carried out and its results are shown in Figure 14. Here the wave elevation is obtained at the ship's center of gravity. In the numerical results, parametric roll with its roll period is twice as long as encounter period can be simulated. The calculated maximum roll angle is about 45 degrees while the measured result is 20 degrees.

Since this discrepancy is large, maximum roll angles of parametric roll are examined for several Froude numbers both in regular and irregular waves. Figures 15-16 show the comparison between experimental results and numerical results obtained with 1) Froude-Krylov component (FK only), 2) Froude-Krylov component and hydrodynamic components (present), 3) experimentally obtained roll restoring moment (direct) (Hashimoto and Umeda, 2004). Here the Froude-Krylov components are calculated by integrating undisturbed wave pressure up to the wave surface with the Smith effect for a ship free in heave and pitch. All of the numerical results do not agree with experimental results except for the case at Froude number of 0.01 in regular waves. As mentioned before, experimentally obtained roll damping coefficients are used throughout. Therefore it is concluded that an uncoupled roll model could be insufficient for predicting parametric roll resonance not only in long-crested irregular waves but also in regular waves. This might be because that a ship tends to change her course from pure head waves to bow waves despite of her rudder effort while parametric roll occurs. Moreover ship surge motion might be not negligibly small because of severe wave steepness or long wave length in the experiment. From this point, a mathematical model taking surge and yaw motions into account could be recommended to predict parametric roll in relatively severe or long waves.

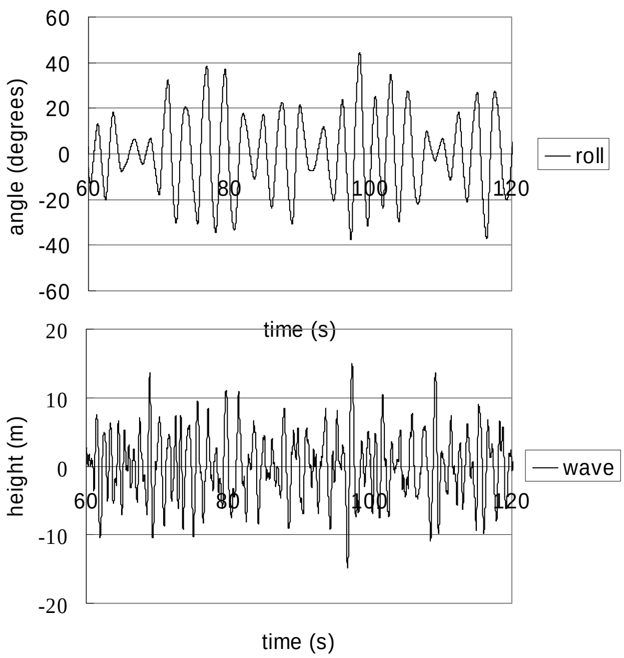

Figure 14 Calculated time series of roll angle and wave elevation in long-crested irregular waves ($H_{1/3}$=0.221m, T_{01}=1.32s, χ_c=180 degrees and Fn=0.02)

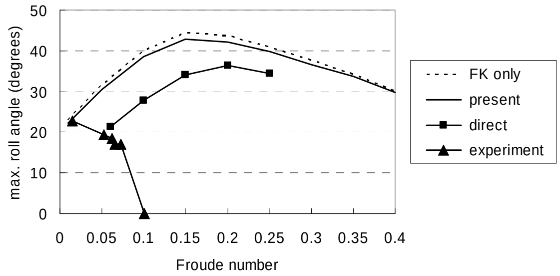

Figure 15 Comparison of maximum roll angle of parametric roll in regular waves with H/λ=1/20.6, λ/L=1.6 and χ_c=180 degrees

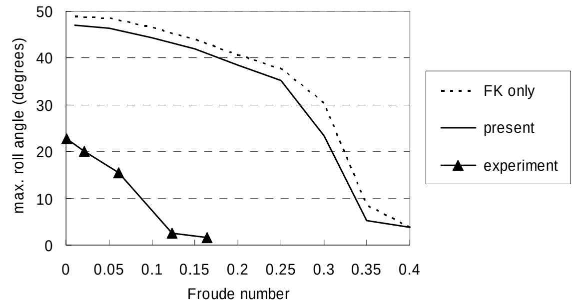

Figure 16 Comparison of maximum roll angle of parametric roll in long-crested irregular waves with $H_{1/3}$=0.221m, T_{01}=1.32s and χ_c=180 degrees

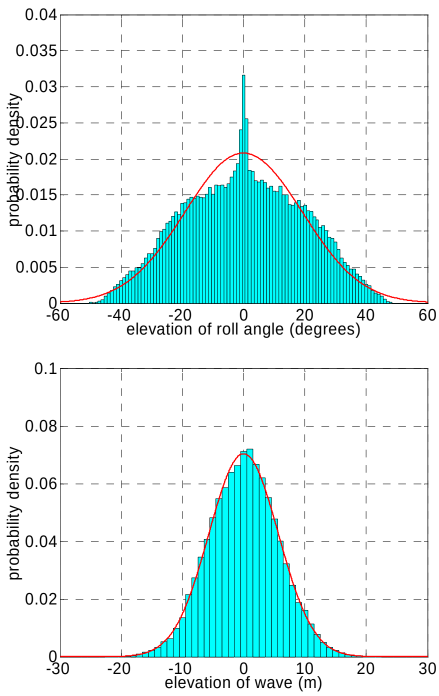

Figure 17 Probability density function of instantaneous elevation of roll angle and wave height in long-crested irregular waves (histogram: calculation; dashed line: Gaussian distribution)

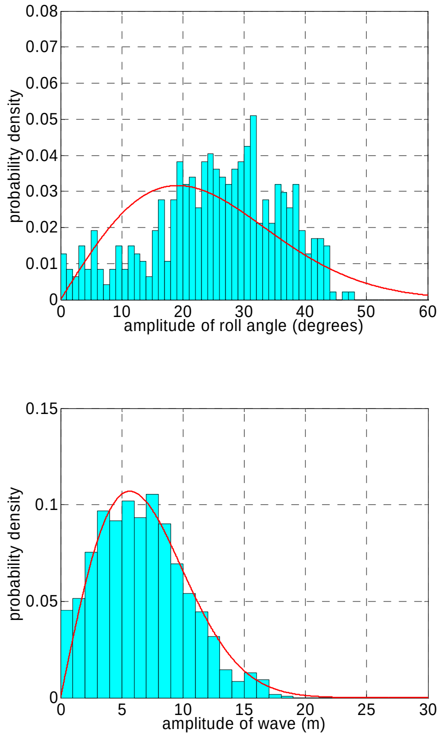

Figure 18 Probability density function of roll and wave amplitude in long-crested irregular waves (histogram: calculation; dashed line: Rayleigh distribution)

Figures 17-18 show the calculated probability density of instantaneous or amplitude of roll angle and wave elevation in long-crested irregular head waves. Although the numerical model reproduces the nonlinearity of parametric roll observed in the experiment, i.e. that the probability density of instantaneous and amplitude of roll angle does not follow the Gaussian and the Rayleigh distributions especially around 0 degrees, its quantitative accuracy is not sufficient and mathematical modelling technique should be improved for more practical purpose.

4. CONCLUSIONS

Capsizing due to parametric roll in head or bow waves was not observed in the experiment for the post-Panamax container ship model with the designed GM value.

The measured maximum roll amplitude of parametric roll does not always increase with wave steepness in regular waves.

It is recommended to avoid ±45degrees of heading angle from head sea condition to prevent severe parametric roll exceeding 15 degrees of roll amplitude in regular waves.

The maximum angle of parametric roll in long-crested irregular waves or short-crested irregular waves is almost as large as the steady amplitude in regular waves.

Maximum roll angle of parametric roll does not depend on heading angle in short-crested irregular bow waves.

Increasing ship forward velocity can be recommended to decrease the parametric roll danger in irregular head and bow waves, as an alternative to decreasing it.

Instantaneous angle and amplitude of parametric roll cannot be explained using the Gaussian and Rayleigh distributions, respectively.

An uncoupled roll model with Grim's effective wave overestimates the occurrence area and its magnitude of parametric roll both in regular and long-crested irregular waves.

Roll-dependent hydrodynamic roll moments due to radiation and diffraction slightly improve the prediction accuracy of parametric roll.

The proposed mathematical model can reproduce the non-Gaussian statistical characteristic of parametric roll as observed in the experiment.

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