Head-Sea Parametric Rolling of a Car Carrier

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ABSTRACT

Recently, a report of head-sea parametric rolling of 50 degrees for a car carrier in the Northern Atlantic was published. To investigate parametric rolling of a car carrier, the authors carried out experimental and numerical study for a latest car carrier in regular and irregular head seas. In the experiment at a towing tank, significant head-sea parametric rolling was observed both in regular and long-crested irregular waves. Numerical simulation using restoring variation with Froude-Krylov, radiation and diffraction components qualitatively explained these experimental outcomes, and its accuracy depends on the precision of restoring variation estimation. In irregular seas, significant non-ergodicity was confirmed both in model experiment and numerical simulation.

KEYWORDS

Parametric Rolling; Car Carrier, Head Seas, Irregular Seas, Restoring Variation, Non-Ergodicity

INTRODUCTION

It has been agreed to set standards for a restoring variation problem including parametric rolling at the International Maritime Organization (IMO) in 2005. In the background of this agreement, there are reports of serious accidents of parametric rolling of a post-Panamax containership and a pure car and truck carrier (PCTC). In particular, there is a definite example of the PCTC: the PCTC Aida suffered head-sea parametric rolling with about 50 degrees of maximum roll angle in the Azores Islands waters in 2003, and she experienced head-sea parametric rolling again in 2004, which was successfully recorded by a sensor (Sweden, 2004).

To investigate these accidents, Hua (2006) conducted the numerical simulation for the Aida based on the Froude-Krylov assumption, and reported that parametric rolling occurs in regular head seas and does not occur in irregular head seas. Finally he concluded that the reason why the Aida suffered parametric rolling is that she had accidentally met with an almost regular wave group. However, this conclusion could invite further discussion.

Therefore, the authors conducted the free running model experiment for a latest PCTC having a similar hull form like the Aida. As a result, significant parametric rolling has been measured both in regular and irregular head seas with the designed GM value. Comparison between an experimental result and a numerical simulation was also conducted, and prediction accuracy of the present mathematical model for parametric rolling prediction is examined. Furthermore, roll restoring variation in head seas, which is an important factor for quantitative prediction of parametric rolling, was measured and compared with the theoretical estimation with dynamic effect on restoring variation taken into account.

SUBJECT SHIP AND MATHEMATICAL MODEL

The principal particulars of the PCTC used for this research is shown in Table 1.

Table 1: Principal particulars

item	value
length: L_{PP}	192.0 m
breadth: B	32.26 m
depth: D	37.0 m
mean draught: T	8.18 m
block coefficient: C_b	0.54
longitudinal position of centre of gravity from a midship: x_{CG}	4.67 m aft
metacentric height: GM	1.25 m
natural roll period: T_ϕ	22.0 s

The mathematical model for parametric rolling prediction in regular head seas is expressed as eq.(1). Although this model is a 1DOF of roll model, heave and pitch motions are taken into account to estimate restoring variation. Restoring moment in waves is calculated as a sum of two components. One is the nonlinear Froude-Krylov component, which is calculated by integrating wave pressure up to wave surface. The other is the dynamic effect, which consists of radiation and diffraction components acting on a heeled asymmetric hull.

As the prediction accuracy of restoring moment could be improved if the dynamic component is included, which was examined in the past research for a post-Panamax containership by the authors (Umeda et al., 2005), we also took into account radiation and diffraction components for the subject car carrier. The dynamic effect is calculated by applying a strip theory to a heeled hull as a linear component with respect to wave height. This effect is considered as an additional effect on GZ by dividing calculated dynamic roll moment with a ship displacement.

$$(I_{xx} + J_{xx})\ddot{\phi} + A\dot{\phi} + B|\dot{\phi}|\dot{\phi} + WGZ(t,\zeta,\theta,\phi,\eta_W) = 0 \quad (1)$$

I_{xx}: inertia of roll moment, J_{xx}: added inertia of roll moment, ϕ: roll angle, A: linear coefficient of roll damping, B: quadratic coefficient of roll damping, W: ship displacement, GZ: righting arm, t: time, ζ: displacement in heave, θ: pitch angle, η_W: wave elevation

The mathematical model for long-crested irregular seas is extended from that for regular seas. In calculation, the instantaneous nonlinear Froude-Krylov component is calculated by taking relative irregular wave elevation in each 2-dimensional section of the hull with transfer functions of heave and pitch motions obtained by a strip method for an upright hull. Dynamic effect component is also calculated as a linear superposition with transfer functions of GZ calculated as radiation and diffraction components. Here dynamic effect is calculated under the assumption that it has the linear relationship with the roll angle. In this research, dynamic effect is obtained for 10 degrees of heel condition. Linear and quadratic damping coefficients are obtained from roll decay test with several different speeds.

HEAD-SEA PARAMETRIC ROLLING IN REGULAR SEAS

Amplitude of Parametric Rolling

The partially restrained free running experiment with a 1/64 scaled model of the car carrier was conducted at the towing tank of Osaka University. A ship model is towed by an elastic rope connected to the bow in regular head seas. Measured steady roll amplitude of parametric rolling for several Froude numbers and wave lengths is shown in Fig.1. Here the wave height is 3.2 m in full scale.

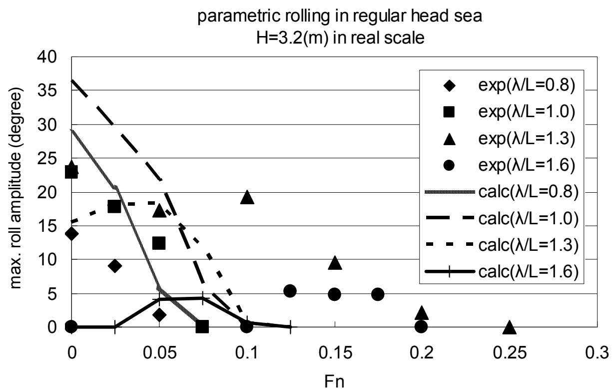

Fig. 1: Maximum roll amplitude of parametric rolling with constant wave height

The parametric rolling amplitude decreases as the wave length increases. This is because the roll restoring variation becomes most significant where the wave length is almost equal to ship length. Moreover, since the wave slope decreases as the wave length increases, restoring variation decreases for a constant wave height.

The Froude number, which satisfies the parametric rolling condition where encounter period is a half of natural roll period under the assumption of linear restoring at the upright condition is shown in Table 2. This Froude number is used in the guidance for the master of the IMO, and it almost corresponds to the experimentally obtained Froude number where parametric rolling amplitude becomes the most significant.

Table 2: Froude number where the encounter period becomes a half of the natural roll period

λ/L	Fn	heading
0.8	0.035	following sea
1.0	0.003	head sea
1.3	0.068	head sea
1.6	0.139	head sea

In the experimental result of $\lambda/L=1.3$, two peaks of the maximum roll amplitude of parametric rolling can be found at Fn=0.0 and Fn=0.1. It was confirmed that two coexisting steady states, e.g. the upright condition and parametric rolling, could be confirmed at Fn=0.0 with different initial disturbances. The time series of roll motion is shown in Fig.2. This is supposed to be a sub-critical bifurcation. Since parametric rolling is a nonlinear phenomenon, its initial value dependency was pointed out and confirmed by analytical solutions and numerical simulation. (Hashimoto and Umeda, 2004) It is interesting that the existence of sub-critical bifurcation has been confirmed by model experiment.

Numerical result can explain the qualitative natures of the experimental result. The roll amplitude decreases as the wave length increases, and the occurrence region shifts to higher speed. However the numerical prediction overestimates the maximum roll amplitude of parametric rolling for each wave lenght. The sub-critical bifurcation observed in the model experiment could not be confirmed through the numerical simulations with various initial roll angles in the same conditions as the experiment.

Fig.3 and Fig.4 show the comparison of the maximum roll amplitude between the experiment and the calculation with constant Froude number of 0.0 and various wave heights for two different wave length to ship length ratios. In the case of $\lambda/L=1.0$, the calculation can simulate qualitative natures of parametric rolling but overestimate the maximum roll amplitude. In the case of $\lambda/L=1.3$, the calculated amplitude is almost 2 times as large as the measured one at $H/\lambda=0.017$. One possible reason of this significant difference is the existence of sub-critical bifurcation.

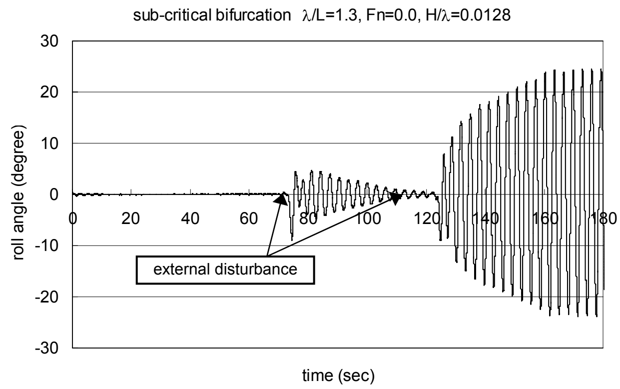

Fig. 2: Experimentally observed sub-critical bifurcation

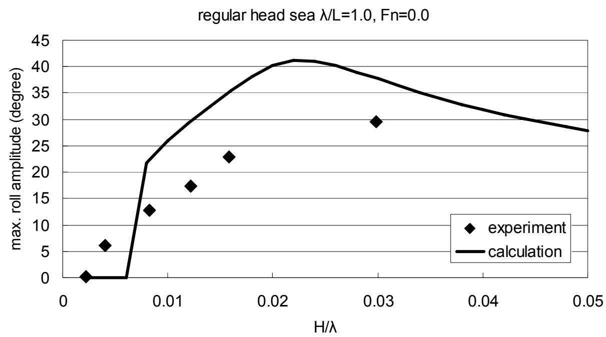

Fig. 3: Roll amplitude of parametric rolling with $\lambda/L=1.0$

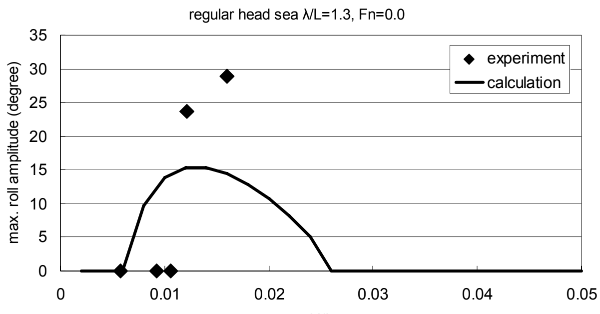

Fig. 4: Roll amplitude of parametric rolling with λ/L=1.3

These comparisons indicate that the present mathematical model can predict head-sea parametric rolling of the car carrier only qualitatively.

Characteristics of restoring variation

Restoring variation in regular head waves, which is important for parametric rolling prediction, was measured by a captive model experiment. In the experiment, ship model is fixed with 10 degrees of heel angle and towed by a towing carriage in regular head waves. Here the model is fixed in surge, sway, yaw and roll and is free in heave and pitch. From the measured roll moment, the restoring variation around the centre of ship gravity is obtained.

Fig.5 shows the comparison of GZ variation in regular head waves with λ/L=1.0, and Fig.6 does with λ/L=1.3. The experimental result indicates that the amplitude of restoring variation decreases as wave length increases for a constant wave height. The numerical estimations are based on following two methods; one takes both Froude-Krylov and dynamic effect components into account and the other does Froude-Krylov moment on its own. Both results qualitatively agree with experimental result, however both estimations overestimate the amplitude of GZ variation to some extent. The tendency of restoring variation that its amplitude decreases as the wave lenght increases is reproduced by the numerical estimation. Although the difference in the amplitude of variation between experiment and calculation with λ/L=1.3 is small compared with λ/L=1.0, its prediction accuracy still remains not in quantitative but in qualitative.

Since agreement of maximum roll amplitude of parametric rolling with λ/L=1.3 in Fig.1 is much better than that with λ/L=1.0 as well as the estimation of roll restoring variation, it might be concluded that the disagreement of restoring variation is one of the reasons why numerical prediction overestimates the parametric rolling danger in regular head seas.

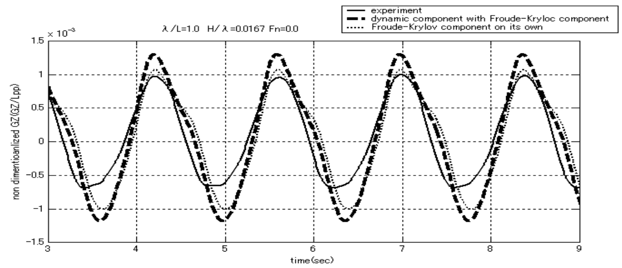

Fig. 5: Restoring variation in regular head seas with λ/L=1.0 and Fn=0.0

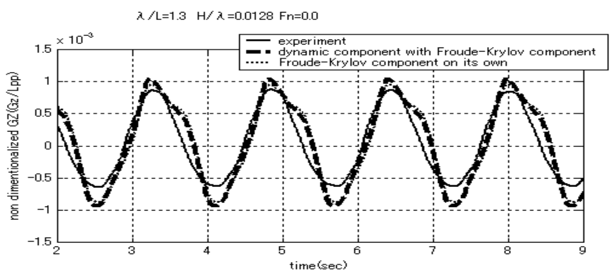

Fig. 6: Restoring variation in regular head seas with λ/L=1.3 and Fn=0.0

HEAD-SEA PARAMETRIC ROLLING IN IRREGULAR SEAS

Maximum Roll Angle of Parametric Rolling

A free running model experiment towed by an elastic rope was carried out in long-crested irregular seas. Following the assumed condition where the PCTC Aida encountered, 5.31m of significant wave height, 9.76 seconds of wave mean period where the peak period corresponds to the wave period of the regular wave whose length is 1.3 times as long as the ship length were used, and ship model was towed with several Froude numbers. Model runs in irregular waves were repeated four to six times with different phase sets of the ingredient waves for each Froude number, and numerical simulation is done for the same time duration as the model runs, about 17 minutes in full scale for one run.

The mathematical models for parametric rolling prediction in irregular seas used here are two methods: one takes the restoring variation calculated with Froude-Krylov component on its own into account, and the other does Froude-Krylov component, radiation and diffraction components. Heave and pitch motions are calculated with transfer functions obtained by a strip method for a non-heeled hull, and they are used in the calculation of Froude-Krylov and dynamic effect components.

Fig.7 shows the measured and calculated maximum roll angles of parametric rolling for each Froude number. In the experiment, significant parametric rolling was observed in irregular waves like the PCTC Aida, and its maximum roll angle exceeds 30 degrees at Fn=0.0. The maximum roll angle of parametric rolling decreases as Froude number increases, and parametric rolling disappears at Fn=0.15. Since the peak period corresponds to the wave period of a regular wave which length is 1.3 times as long as the ship length, Fn=0.07 is obtained as the most relevant speed for parametric rolling occurrence under the linear roll restoring. However most significant parametric rolling was observed at Fn=0.0.

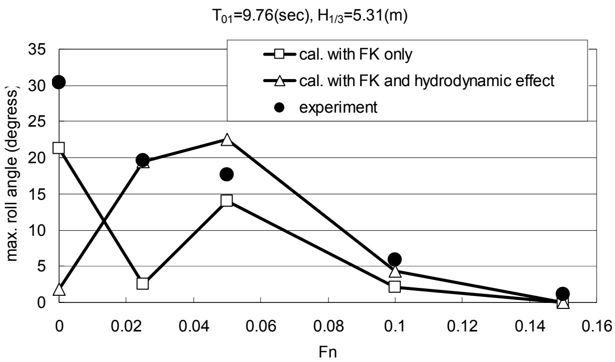

Fig. 7: Maximum roll angle in long-crested irregular head seas

In higher speed region, the numerical simulation can predict the maximum roll angle of parametric rolling with practical accuracy. In lower speed region, however, the calculated results do not agree with the experimental result in maximum roll angle. Moreover, the significant difference among two calculation results is found. Since two numerical calculations have used the same wave data, initial values and coefficients in the mathematical model, we can conclude that this large difference among two calculations is from small difference of estimation of restoring variation.

Characteristics of restoring variation

Restoring variation in long-crested irregular head seas was measured as well as the regular wave case. Here, comparison of time series of heave, pitch and restoring variation, and probability density function of GZ between model experiment and numerical estimation are shown in Figs.8-11. Here Froude number is 0.0. Fig.8 and Fig.9 indicate that heave and pitch motions can be estimated with sufficient accuracy by a strip method without taking heeled condition into account. As shown in Fig.10, the dynamic effect on restoring variation in irregular waves is not as significant as the post post-Panamax containership (Hashimoto et al., 2006). Moreover, it is confirmed that there is almost no difference in restoring variation for the subject PCTC between the experiment and the two calculations.

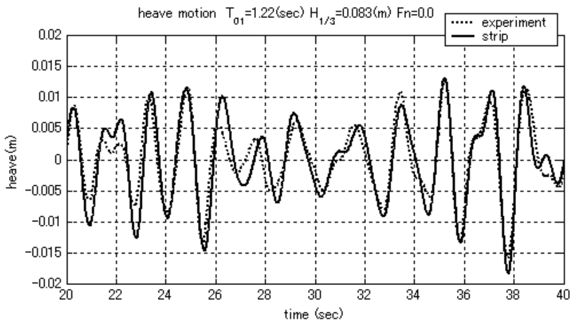

Fig. 8: Comparison of heave motion in irregular seas

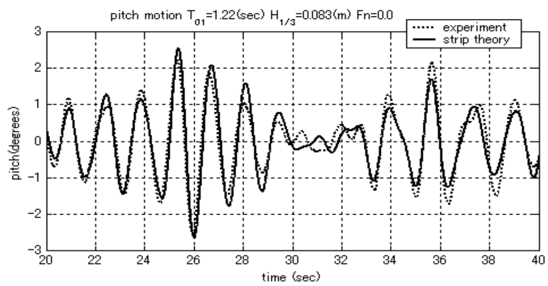

Fig. 9: Comparison of pitch motion in irregular seas

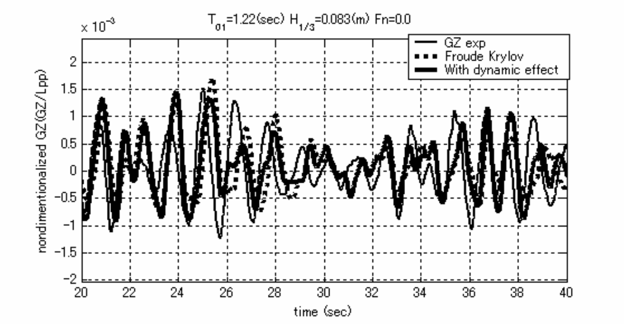

Fig. 10: Comparison of GZ variation in irregular seas

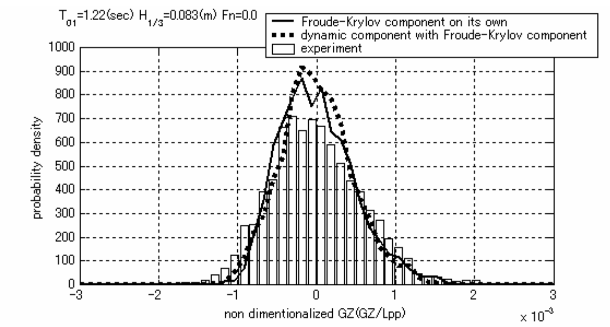

Fig. 11: Comparison of Probability density function of GZ in irregular seas

Since it was confirmed that the estimation of restoring variation used for the numerical simulation of parametric rolling has practical accuracy, it indicates that small difference in restoring variation produces the significant difference of maximum roll angle as shown in Fig.7.

Non-Ergodicity

Fig.12 and Fig.13 show the measured and calculated maximum roll angles of parametric rolling for four different realizations. If the phenomenon of parametric rolling has ergodicity, the maximum values for different realizations tend to a certain value. However there is scatter of maximum roll angles of parametric rolling both in the model experiment and the numerical simulation.

Although Hua (2006) had reported that parametric rolling does not occur in his numerical simulation for the PCTC Aida in irregular waves, non-ergodicity could be one of the reasons why no parametric rolling occurs because he just tested one realization. Considering these facts, it is essential that numerical simulation should be repeated using different random phase sets because of the significant non-ergodicity of parametric rolling.

How to deal with non-ergodicity of parametric rolling in irregular seas is important issue, so that further discussion is needed for appropriately planning experiments and simulations.

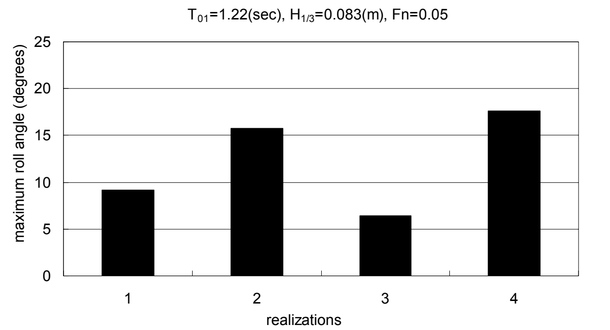

Fig.12: Maximum roll angle for 4 different realizations (experiment)

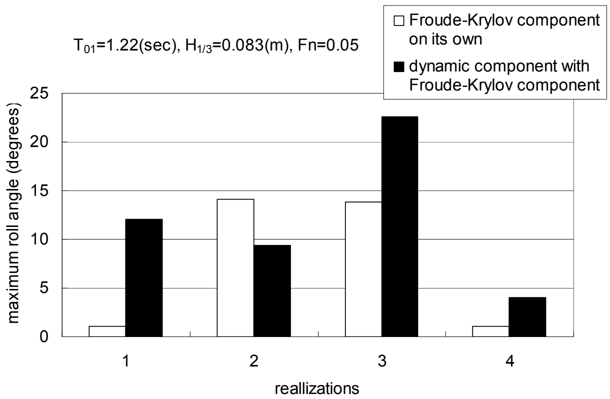

Fig.13: Maximum roll angle for 4 different realizations (calculations)

CONCLUSIONS

1) Free running model experiment of a car carrier was conducted and significant parametric rolling exceeding 20 degrees in regular head seas and 30 degrees in irregular head seas was observed.
2) Sub-critical bifurcation, which is the feature of a nonlinear phenomenon, was observed in the experiment.
3) Numerical simulation could estimate the occurrence region of parametric rolling and its amplitude qualitatively. For more accurate prediction, the improvement of the estimation precision of roll restoring variation is needed.

4) Significant non-ergodicity of parametric rolling in irregular seas has been confirmed both in the experiment and the numerical simulation. It would be important to discuss how to deal with the non-ergodicity from a practical point of view.

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