An examination for the numerical simulation of parametric roll in head and bow seas

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ABSTRACT

Numerical study was carried out using a nonlinear time domain simulation method in accordance with the nonlinear strip method approach. Effects of wave period, wave height and ship speed on the parametric roll were examined through the comparison with the amplitude of roll, which was measured by the free running model experiments in regular and irregular waves.

It is found that the computed 1/10 highest mean of roll by means of the present method with the adequate number of times of simulation gives good agreement with the measured amplitude although the computed maximum amplitude of parametric roll explains experiments merely qualitatively. It was clarified that the roll damping on the parametric roll is significant through the computation of parametric roll using various roll damping.

KEYWORDS

Parametric roll; head and bow seas; nonlinear strip method; maximum and 1/10 highest mean; roll damping; 4 degrees of freedom.

INTRODUCTION

It is well known that the parametric roll is expected to occur when the wave encounter frequency is close to the double of the natural roll frequency of the vessel. Therefore, several approaches, which are mainly focused on the periodic change of the restoring force as the ship advances through the waves, have been investigated to analyze the phenomenon in the last decade years (e.g., Belenky, 2006; Neves, 2006,). As a result, a substantial progress has been achieved to evaluate the parametric roll in regular waves. However, there are some rooms for the improvement of the evaluation of the parametric roll in irregular waves although several studies have been carried out intensively (e.g. Hashimoto, 2006). In addition, several studies (e.g., Taguchi, 2006) investigated the occurrence of the parametric roll not only in the head seas but also in other wave encounter angle. In particular, it is important practically to examine the parametric roll in head and bow seas in terms of cargo damage, which occurs due to the combination of large vertical and horizontal acceleration. Therefore, it is important to examine the parametric roll using the practical model without cumbersome computations not only in the head seas but also in other wave encounter angle.

Based on these backgrounds, numerical study has been carried out using a nonlinear time domain numerical simulation method in accordance with the nonlinear strip method approach.

Firstly, the effects of the number of times and the duration time on the result of numerical simulation were examined by the comprehensive simulation with varying the combination of phase angle of each wave component in each simulation.

Secondly, using the present numerical model, which was narrowed the degrees of freedom down to four, the effect of waves on parametric roll were examined through the comparison with the roll motion, which was measured by the free running model experiments in regular and irregular waves.

Thirdly, the effect of the roll damping on the parametric roll was examined through the comparison of experiments with the numerical results using various roll damping.

COMPUTATIONS

Numerical Model

Ship motions were estimated by the time domain simulation program, developed by the National Maritime Research Institute of Japan (Ogawa, 2005) in accordance with a nonlinear strip method approach (Fujino et al., 1983).

The program, NMRIW, was developed by means of the latest results of a seakeeping and maneuvering study. The NMRIW's numerical model is based on a nonlinear strip theory approach in which forces due to the linear and nonlinear potential flow are combined with maneu-vering forces and viscous drag forces. Generally, it is difficult to compute nonlinear wave loads in bow and quartering seas by means of the conservative time do-main estimation method. Using the present method, wave loads in bow and quartering seas can be estimated rationally.

To describe these hydrodynamic forces rationally, the equation of motion is described in the horizontal body axes coordinate system (Hamamoto et al., 1993). Using the horizontal body axes coordinate system, large rotational angles in severe wave and wind conditions are retained in the equation of motion.

Ship motion components are determined from a set of 6 differential equations of motion with its origin at the center of gravity G. With respect to rotations, a right-handed convention is always used. Equations of motion are solved in the time domain by means of a 4th-order Runge-Kutta scheme.

The Froude-Krylov force, which has considerable effect on the nonlinearity of ship motions, is estimated by the integration of the hydrostatic and hydrodynamic wave pressure along the instantaneous wetted surface of the hull at each time step.

With respect to the sectional wave radiation force and potential value at each time step, the integral equation method is used. Source and doublet are distributed at the origin of each section to avoid the irregular frequency, in accordance with Ohmatsu's method (Ohmatsu, 1975).

In terms of the sectional diffraction force in the present method, it was computed by solving the Helmholtz equation at each time step. The viscous effect of roll damping due to ship hull and bilge keels can be estimated with various empirical formulae.

The propeller thrust is described by means of the propeller characteristic. The hull resistance is a function of an instantaneous speed and draft. The rudder is controlled by the PID control.

The sea surface and wave kinematics are described based on the linear wave theory. The sea surface of irregular waves is described by the linear superposition of regular waves with random phase.

Ship motions estimated by means of this method were verified through the comparison with the many kinds of model tests. Fig. 1 and Fig.2 shows examples of the vertical acceleration of a post-panamax container carrier, which was used in the present study (Ogawa, 2007). The fundamental frequency component, a, is divided by L/g (L : ship length, g : the acceleration of gravity). It is found that wave height has a significant effect on the amplitude of the vertical acceleration. It is also found that the computed amplitude of the vertical acceleration gives good agreement with experiments not only in head seas but also in bow seas.

Fig. 3 shows examples of the roll motion of the post-panamax container carrier, which was used in the present study. The fundamental frequency component, Φ, are divided by wave slope $k\varsigma$ (k: wave number, ς : wave slope). It is also found that the computed amplitude of the roll motion gives good agreement with experiments. It is confirmed that the present method taking account of hydrodynamic forces in each time step can estimate ship motions well when parametric roll does not occur.

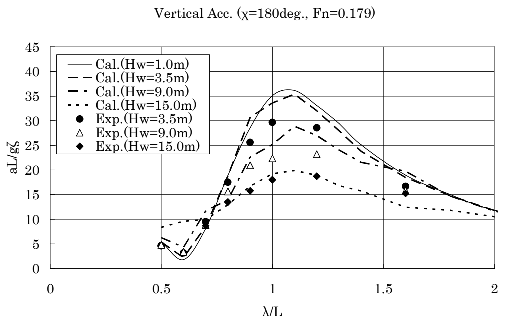

Fig. 1: The response amplitude operator of vertical acceleration at F.P. of a post-panamax container carrier (χ=180deg., Fn=0.179) (Ogawa, 2007)

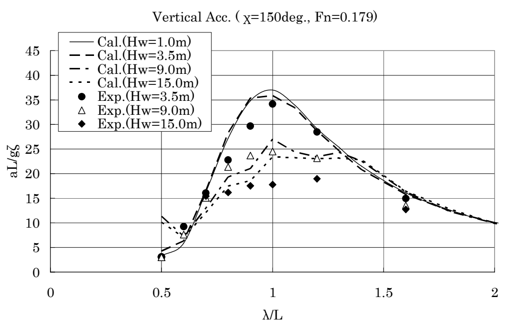

Fig. 2: The response amplitude operator of vertical acceleration at F.P. of a post-panamax container carrier (χ=150deg., Fn=0.179) (Ogawa, 2007)

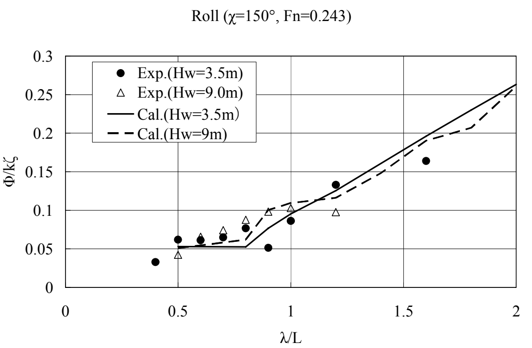

Fig. 3: The response amplitude operator of rolling of a post-panamax container carrier (χ=150deg., Fn=0.243)

Mathematical Model of Roll Motion

In the present study, the degrees of freedom of numerical model was narrowed down to four (sway, heave, roll, pitch) because the main purpose is to examine the parametric roll using the practical model without cumbersome computations not only in the head seas but also in other wave encounter angle. Using this model, the numerical procedure of surge and yaw in larger sea state with slower ship speed were neglected.

On the basis of the assumption, the equation of roll motion can be described as follows:

$$\left(I_{xx}+J_{xx}\right)\ddot{\phi}+a\dot{\phi}+b\dot{\phi}\left|\dot{\phi}\right|+W\left\{GZ_0(\phi)+GZ_w(\phi;t)\right\} = M(t) \qquad (1)$$

Here I_{xx} denotes an inertia moment in roll and J_{xx} denotes an added inertia moment in roll. a and b denote the linear and quadratic damping coefficient. W denotes the displacement. GZ_0 and GZ_w denote the restoring arm and restoring arm variation due to wave. M denotes the heel-induced hydrodynamic roll moment. Roll moment owing to sway, heave and pitch is considered in this term.

In terms of the numerical simulation of the parametric roll in irregular waves, incident wave was realized by the sum of 200 components of waves in accordance with the 1964 ISSC spectrum. To take account of the non-ergodic nature of parametric roll, 20 times simulations with the duration of 2500 seconds of ship scale were carried out in each condition. The combination of phase angle of each wave component was varied in each simulation.

Fig. 4 shows the example of the probability density function of pitch and roll amplitude. The horizontal axis denotes the pitch and roll angle. Dotted lines show the approximation of Gaussian distribution of those computed probability density function. It is found that the probability density function of the computed pitch amplitude of 20 times simulations with the duration of 2500 seconds can be approximated by the Gaussian distribution. However, it is also found that the probability density function of the computed roll amplitude is much different with the Gaussian distribution due to non-ergodic nature of parametric roll although a certain distribution can be approximated.

EXPERIMENTS

Model and Measuring Instruments

A detailed explanation of experiments has been published previously (Taguchi et al., 2006 and 2007). However, the part relevant to this study is repeated here. A series of a free runnning test in waves by means of the model of a post-panamax container carrier was carried out to measure parametric roll.

The tests were conducted at the Square Basin (80 m×80 m×4.5m) of the National Maritime Research Institute of Japan. Table 1 presents the ship's main particulars. Before the test, the model was ballasted to the correct draft, trim and the GM.

Six degree of ship motions were measured by means of optical fiber gyro and gyro accelerometer. Relative water heights at stem, S.S.5 and A.E.. Lateral acceleration beneath the upper deck at S.S. 8 was measured by means of accelerometers.

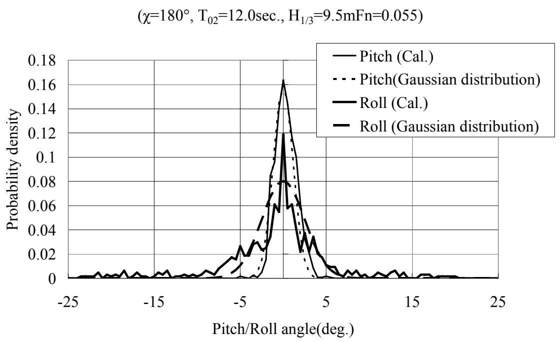

Fig. 4 The probability density function of pitch and roll amplitude (χ=180deg., Fn=0.055, T_{02}=12.0 sec., $H_{1/3}$=9.5m)

Table 1: Main particulars of the container carrier

	Ship	model
Length (L_{pp}) (m)	283.8	3.7
Breadt(B) (m)	42.8	0.558
Draft(d) (m)	14.0	0.183
GM (m)	1.08	0.014
Displacement (m^3)	106970	0.237
Block coefficient (C_b)	0.63	0.63
Natural roll period T_Φ(sec.)	30.3	3.5

Conditions

A series of tests in regular and irregular waves was carried out to allow a comparison with an analytical study. An experiment in regular waves was carried out in head (180 deg.) and bow (165deg., 150deg. and 135deg.) seas. The mean ship speed in waves was varied within a service speed of this post-panamax container carrier (Froude number = 0.239). Experiments were carried out in various wave heights (3.8m to 15.3m). Wave length was also varied in the experi-ments (wave length ratio λ/Lpp = 0.9 to 2.4; λ:wave length).

Tests in irregular waves were also carried out in head (180 deg.) and bow (165deg., 150deg. and 135deg.) seas with various significant wave heights (3.8m to 15.3m). The ISSC spectrum was used for a wave spectrum of irregular waves. The mean wave period, T_{02}, was also varied (9.5sec. to 15.5sec.). The propeller revolution was varied in accordance with the ship speed in the still water (Froude number in the still water, F_{ns} = 0.07 to 0.15) to examine the effect of ship speed on parametric rolling.

NUMERICAL RESULTS

Roll Motion in Regular Waves

Fig. 5 and Fig. 6 give examples of the time history of the parametric roll in head and bow seas, respectively. It is found that the parametric roll occurs with double of the wave encounter period.

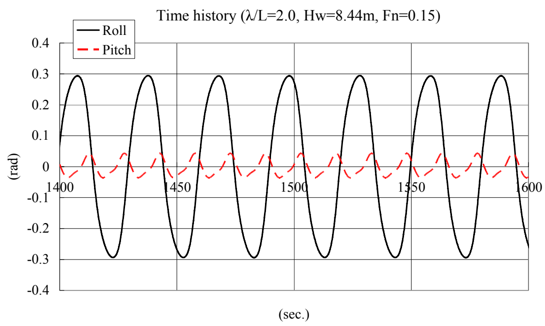

Fig. 5: The time history of roll and pitch in regular waves (χ=180deg, λ/L=2.0, Hw=8.4m, Fn=0.15)

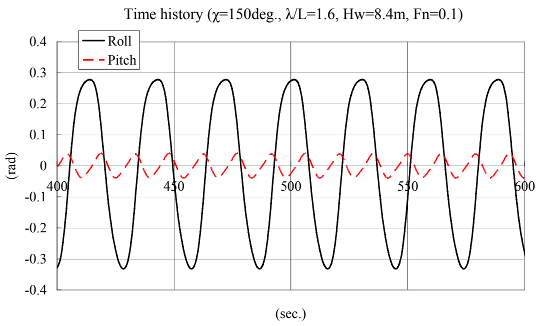

Fig. 6: The time history of roll and pitch in regular waves (χ=150deg, λ/L=1.6, H_w=8.4m, Fn=0.1)

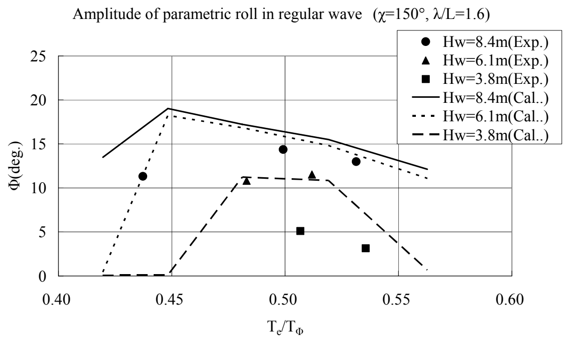

Fig. 8: The relation of a wave encounter period with the amplitude of parametric roll (χ=150deg., λ/L=1.6)

Fig. 7 and Fig. 8 show the amplitude of parametric roll as a function of wave encounter period. The horizontal axis is the ratio of the wave encounter period, T_e, to the natural roll period, T_Φ. It is found that computed range, in which parametric rolling resonance occurs, gives good agreement with measured range. It is verified that the computed amplitude of parametric roll by means of the present method gives good agreement with experiments although there are some discrepancies in the small sea states of bow seas.

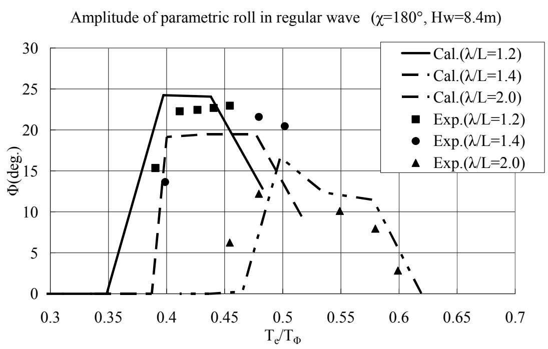

Fig.7: The relation of a wave encounter period with the amplitude of parametric roll (χ=180deg., H_w=8.4m)

Effect of Wave Period on Roll Motion in Irregular Waves

Fig. 9 gives examples of the time history of the parametric roll in bow irregular waves. It is found that the parametric roll occurs with double of the period of pitch.

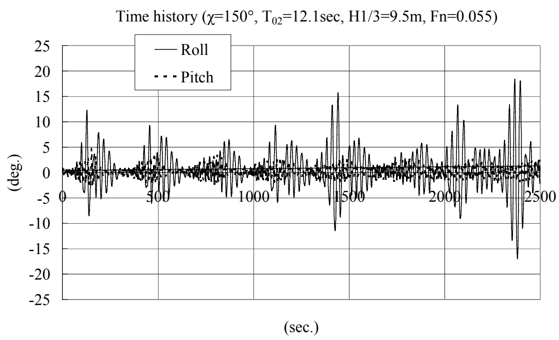

Fig. 9: The time history of roll and pitch in irregular waves (χ=150deg, T_{02}=12.0sec, $H_{1/3}$=9.5m, Fn=0.055)

Fig. 10 and Fig. 11 show the maximum and 1/10 highest mean of amplitude of roll as a function of mean wave period, T_{02}, in head and bow seas. In experiments, the parametric roll occurred except waves of the mean wave period of 9.5sec. It is verified that the computed parametric roll occurred in the same condition as experiments. It is found that computed 1/10 highest mean of roll gives good agreement with experiments. It is also found that the computed maximum amplitude qualitatively agrees with experiments in terms of mean wave period although there is certain discrepancy between the computed maximum amplitude and experiments.

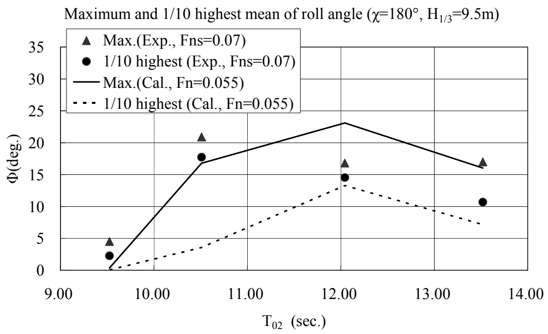

Fig. 10: The effect of mean wave period on roll in irregular waves (χ=180deg., $H_{1/3}$=9.5m)

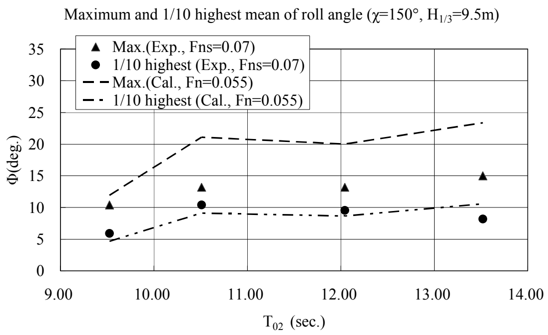

Fig. 11: The effect of mean wave period on roll in irregular waves (χ=150deg., $H_{1/3}$=9.5m)

Effect of Wave Height on Roll Motion in Irregular Waves

Fig. 12 and Fig. 13 show the maximum and 1/10 highest mean of amplitude of roll as a function of significant wave height, $H_{1/3}$, in head and bow seas. In experiments, the parametric roll occurred except waves of the significant wave height of 3.8m. It is verified that the computed parametric roll occurred with the same significant wave height as experiments. It is found that computed 1/10 highest mean of roll gives good agreement with experiments. It is also found that the computed maximum amplitude qualitatively agrees with experiments in terms of wave height although there is certain discrepancy between the computed maximum amplitude and experiments.

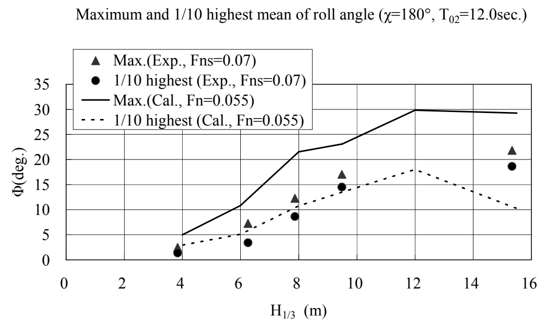

Fig. 12: The effect of significant wave height on rolling in irregular waves (χ=180deg., T_{02}=12.0sec.)

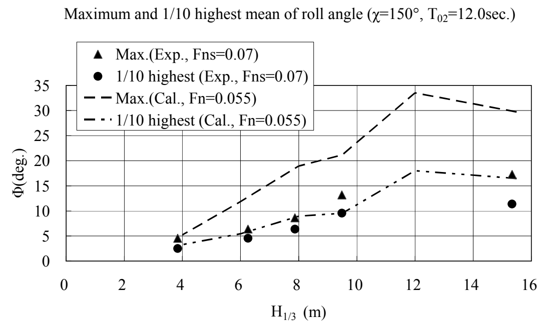

Fig. 13: The effect of significant wave height on rolling in irregular waves (χ=150deg., T_{02}=12.0sec.)

Effect of Wave Direction on Roll Motion in Irregular Waves

Fig. 14 and Fig. 15 show the maximum and 1/10 highest mean of amplitude of roll as a function of wave direction, χ. In experiments, the parametric roll occurred except waves of χ=135deg. However, it is found that the computed parametric roll occurred except waves in bow seas (χ=135deg.) with Fn=0.1. It is found that computed 1/10 highest mean of roll gives good agreement with experiments. It is also found that the computed maximum amplitude qualitatively agrees with experiments in terms of wave direction although there is certain discrepancy between the computed maximum amplitude and experiments.

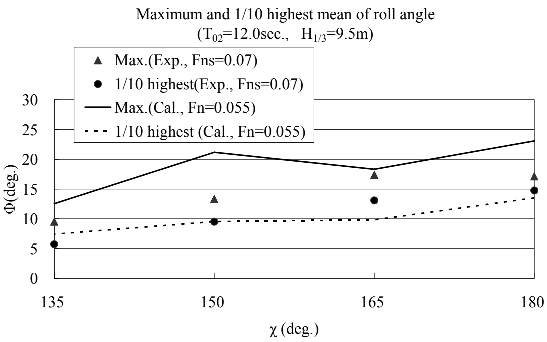

Fig. 14: The effect of wave direction on rolling in irregular waves (Fn=0.055, T_{02}=12.0sec., $H_{1/3}$=9.5m)

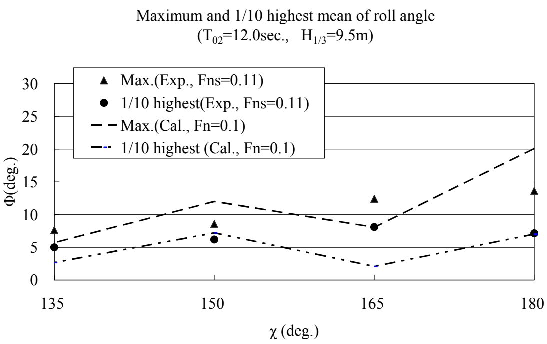

Fig. 15: The effect of wave direction on rolling in irregular waves (Fn=0.1, T_{02}=12.0sec. $H_{1/3}$=9.5m)

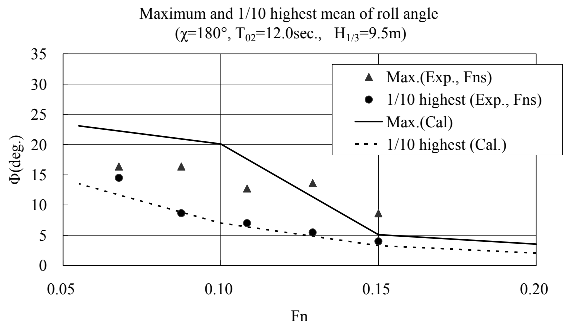

Fig. 16: The effect of ship speed on rolling in irregular waves (χ=180deg., T_{02}=12.0sec., $H_{1/3}$=9.5m)

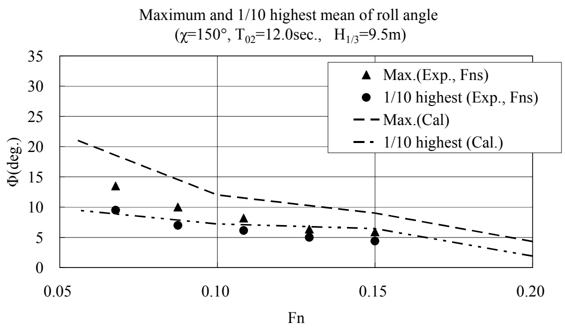

Fig. 17: The effect of ship speed on rolling in irregular waves (χ=150deg., T_{02}=12.0sec., $H_{1/3}$=9.5m)

Effect of Ship Speed on Roll Motion in Irregular Waves

Fig. 16 and Fig. 17 show the maximum and 1/10 highest mean of amplitude of roll as a function of Froude number in head and bow seas. In experiments, parametric roll occurred in all conditions shown in Fig.16 and Fig.17. It is verified that the computed parametric roll also occurred in the same conditions as experiments. It is found that computed 1/10 highest mean of roll gives good agreement with experiments. It is also found that the computed maximum amplitude qualitatively agrees with experiments in terms of ship speed although there is certain discrepancy between the computed maximum amplitude and experiments.

Effect of Ship Speed on Roll Damping in Irregular Waves

To examine the effect of roll damping on the parametric roll, the computation by means of the roll damping increased by 10% was carried out. In this computation, both the linear and the quadratic damping coefficients were increased by 10%. Fig. 18 shows the maximum and 1/10 highest mean of amplitude of roll as a function of significant wave height, $H_{1/3}$, in head seas. This figure corresponds to the Fig.12. It is found that the roll damping has much effect on the roll amplitude. It is also found that the computed parametric roll by means of the increased roll damping gives agreement with the measured maximum amplitude.

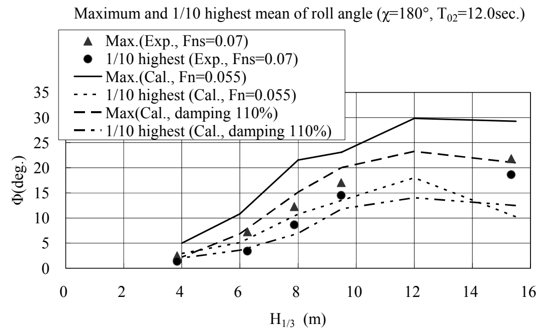

Fig. 18: The effect of roll damping on parametric roll in irregular waves (χ=180deg., T_{02}=12.0sec.)

CONCLUSIONS

Numerical study was carried out using a nonlinear time domain simulation method of 4 degrees of freedom. Effects of wave period, wave height and ship speed on the amplitude of parametric roll were examined. The effect of roll damping was also examined. Conclusions are as follows:

1) Computed amplitude of parametric roll by means of the present method gives good agreement with the measured amplitude in regular waves.

2) The present method explains the parametric roll in terms of wave period, wave height and ship speed.

3) The computed 1/10 highest mean of roll gives good agreement with experiments. However, there is certain discrepancy between the computed maximum amplitude and the experiment although the present computation explains experiments qualitatively.

4) The probability density function of the computed roll amplitude is much different with the Gaussian distribution due to non-ergodic nature of parametric roll although the probability density function of the computed pitch amplitude can be approximated by the Gaussian distribution.

5) The roll damping has much effect on the roll amplitude. The computed parametric roll by means of the increased roll damping gives agreement with experiments.

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