A study on Quantitative Prediction of Parametric Roll in Regular Waves

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ABSTRACT

To investigate the influence of roll damping estimation methods on parametric roll prediction, a forced roll test was conducted to measure roll damping for large roll amplitude up to 30 degrees. Then, the 3DOF (degrees of freedom) numerical model based on a nonlinear strip theory was developed and numerical simulations in the time domain with roll damping estimated by a forced roll model test, a roll decay model test and the Ikeda's semi-empirical prediction method were conducted. By comparing these numerical results with an experimental result, the influence of different estimation methods for roll damping on parametric roll prediction was examined for developing reliable performance-based new Intact Stability criteria.

KEYWORDS

Parametric Roll; Roll Damping; Forced Roll Test; Roll Decay Test; Ikeda's Prediction Method.

INTRODUCTION

Since parametric roll is well known as one of the most dangerous phenomena which could lead to serious accidents due to significant roll, a new Intact Stability code, which is under development at IMO (International Maritime Organization), is required to cover this phenomenon. Although a lot of numerical models for parametric roll prediction have been proposed so far, roll damping for large amplitude and influence of roll damping estimation methods on parametric roll prediction have not been investigated enough.

Based on this situation, a forced roll model test for a containership was conducted for measuring roll damping up to 30 degrees of roll amplitude where the nonlinearity could appear remarkably. Then roll damping obtained by the forced roll model test was compared with those by a conventional roll decay model test and the Ikeda's semi-empirical prediction method [Ikeda, 2004] to discuss the accuracy of each method for roll damping estimation.

For a numerical study on the influence of estimation methods for roll damping on parametric roll prediction, it is preferable to utilize a reliable numerical simulation model which can quantitatively predict large amplitude of parametric roll. For this purpose, we developed a coupled 3DOF (degrees of freedom) of heave-roll-pitch model based on a nonlinear strip theory, which considers time-dependent hydrodynamic forces for instantaneous submerged hull at each time step. To validate this numerical model, we conducted a model experiment to measure roll restoring variation, which is a major cause of parametric roll, with constant heel angles up to 30 degrees.

Finally a model experiment was conducted to measure occurrence region and roll amplitude of parametric roll in regular head seas. By comparing this experimental result with numerical results with roll damping estimated from the forced roll model test, the roll decay model test and the Ikeda's prediction method, we examined the influence of roll damping estimation methods on parametric roll prediction.

MATHEMATICAL MODEL

The coupled 3DOF mathematical model based on a nonlinear strip theory was developed for quantitative prediction of parametric roll. In this model, the nonlinear Froude-Krylov forces are calculated by integrating wave pressure up to wave surface. Dynamic components, i.e. radiation and diffraction forces are calculated for an instantaneous submerged hull by considering a time-dependent roll angle. Two-dimensional hydrodynamic forces are calculated by solving the boundary integral equation for the velocity potential. Diffraction forces are calculated by the STF method [Salvesen et al., 1970]. Hydrodynamic forces for heave and diffraction modes are calculated with encounter frequency and those for sway and roll modes are done with half the encounter frequency assuming principal parametric rolling. In a calculation of the radiation forces, so called the end term effect is included because a hydrodynamic lift effect on roll moment cannot be neglected when a ship has advance speed. Mathematical model of the 3DOF coupled ship motion is shown in Eqs.(1)-(3).

$$\begin{aligned}&(m+A_{33}(\phi))\ddot{\zeta}+B_{33}(\phi)\dot{\zeta}+A_{34}(\phi)\ddot{\phi}\\&+B_{34}(\phi)\dot{\phi}+A_{35}(\phi)\ddot{\theta}+B_{35}(\phi)\dot{\theta}\\&=F_3^{FK+B}(\xi_G/\lambda,\zeta,\phi,\theta)+F_3^{DF}(\phi)\end{aligned} \tag{1}$$

$$\begin{aligned}&(I_{xx}+A_{44}(\phi))\ddot{\phi}+N(\dot{\phi})+A_{43}(\phi)\ddot{\zeta}\\&+B_{43}(\phi)\dot{\zeta}+A_{45}(\phi)\ddot{\theta}+B_{45}(\phi)\dot{\theta}\\&=F_4^{FK+B}(\xi_G/\lambda,\zeta,\phi,\theta)+F_4^{DF}(\phi)\end{aligned} \tag{2}$$

$$\begin{aligned}&(I_{yy}+A_{55}(\phi))\ddot{\theta}+B_{55}(\phi)\dot{\theta}+A_{53}(\phi)\ddot{\zeta}\\&+B_{53}(\phi)\dot{\zeta}+A_{54}(\phi)\ddot{\phi}+B_{54}(\phi)\dot{\phi}\\&=F_5^{FK+B}(\xi_G/\lambda,\zeta,\phi,\theta)+F_5^{DF}(\phi)\end{aligned} \tag{3}$$

FORCED/FIXED ROLL TEST

To accurately measure roll restoring variation and roll damping for large angle/amplitude, which are dominant factors of parametric roll prediction, a new measurement system for forced/fixed roll test was newly developed. Roll moment around centre of ship gravity can be directly added by an electric motor and measured by a load cell located on the roll axis. [Hirayama and Takezawa, 1982] In the forced oscillation test, heave and pitch motions are allowed. Guaranteed operational range of this measurement system is -30 to 30 degrees of roll angle/amplitude, and 0.1 to 2.0 Hz of rotational frequency. Schematic view of the experimental setup is shown in Fig.1. Subject ship is a 6600TEU post-Panamax containership and its 1/100 scaled ship model was used for the experiment. Principal particulars and body plan of this ship are shown in Table 1 and Fig.2, respectively.

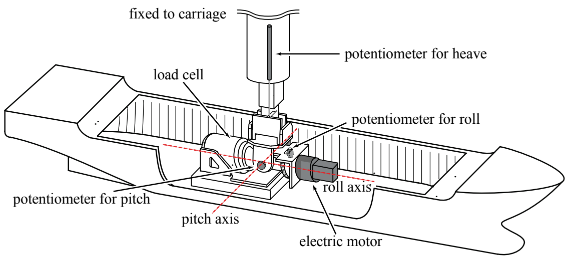

Fig.1 Schematic view of the experimental setup

Table 1 Principal particulars of the subject ship

Item	Value
Length between perpendiculars : L	283.8m
breadth : B	42.8m
depth : D	24.4m
mean draught : T	14.0m
block coefficient : C_b	0.629
metacentric height : GM	1.06m
natural roll period : T_ϕ	30.3s

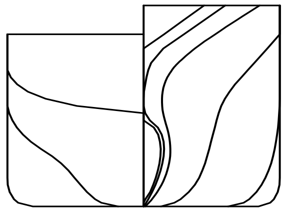

Fig.2 Body plan of the subject ship

Roll Restoring Variation

Although roll restoring variation is a most important factor for parametric roll prediction, the number of researches to investigate roll restoring variation in head waves is limited. As to experimental investigation on roll restoring variation for large roll angle with forward velocity, there have been only a few researches so far. Therefore, we conducted a model experiment for measuring roll restoring variation in regular head seas with large constant heel angle, ϕ_c, up to 30 degrees for several Froude numbers. In the experiment, heave and pitch motions were in free and roll restoring moment around centre of ship gravity was measured by a load cell. Incident wave conditions are; wavelength to ship length ratio, λ/L, of 1.0 and wave steepness, H/λ, of 0.03.

The comparison of roll restoring variation between the model experiment and numerical calculations with the 1DOF of roll model [Hashimoto et al., 2006] and the developed 3DOF model are shown in Figs. 3-5. Here the relative position of the ship gravitational centre to a wave trough, ξ_G, is normalised with the wave length, λ; so that ξ_G/λ=0.0 and 1.0 means a wave trough, $0<\xi_G/\lambda<0.5$ is a wave down-slope, 0.5 is a wave crest, and $0.5<\xi_G/\lambda<1.0$ is a wave up-slope. The 1DOF model underestimates the amplitude of roll restoring variation particularly when a ship has forward velocity. On the other hand, the estimation accuracy of roll restoring variation is improved by the 3DOF model, in other words, becomes closer to the experimental result. It is concluded that the 3DOF model can estimate the roll restoring variation with practical accuracy for wide range of heel angle and ship advance speed relevant to parametric roll.

To investigate the major reason why the estimation accuracy is improved by the 3DOF model, the calculated heave and pitch motions with different heel angles were compared with the experimental result as shown in Fig.6. From the experimental result, the influence of heel angle on a heave motion is so large that it cannot be neglected for quantitative prediction. The 3DOF model can take account of this trend. This result indicates that incorporating the effect of heel angle on a heave motion could improve the estimation accuracy of roll restoring variation.

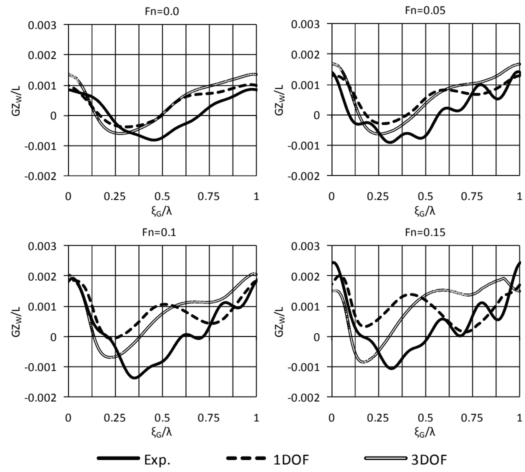

Fig.3 Comparison of roll restoring variation with λ/L=1.0, H/λ=0.03 and ϕ_c=10 degrees

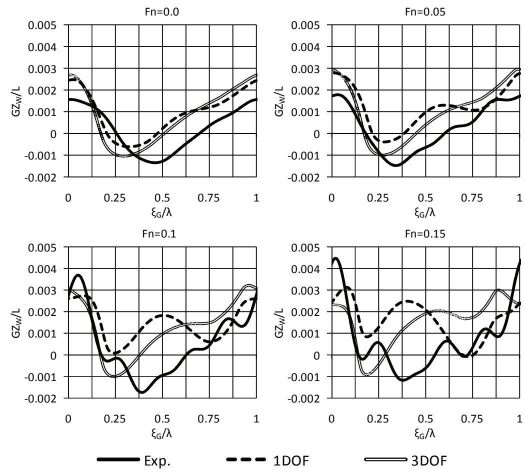

Fig.4 Comparison of roll restoring variation with λ/L=1.0, H/λ=0.03 and ϕ_c =20 degrees

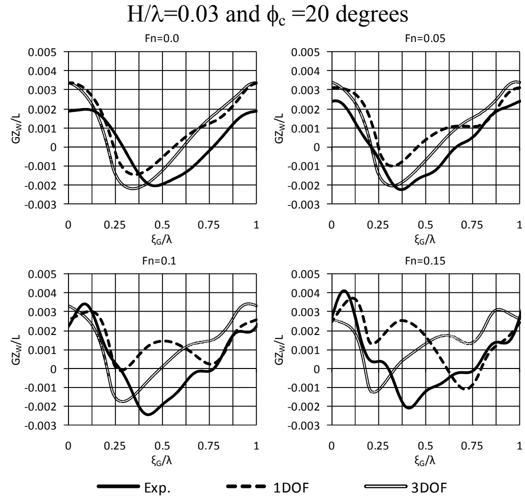

Fig.5 Comparison of roll restoring variation with λ/L=1.0, H/λ=0.03 and ϕ_c =30 degrees

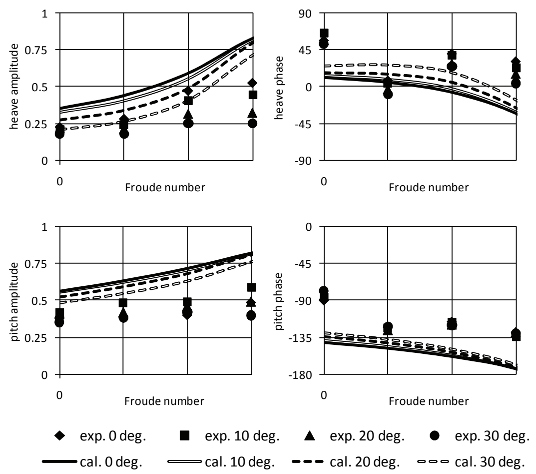

Fig.6 Comparison of heave and pitch motions at ϕ_c=0, 10, 20, 30 degrees

Roll Damping

Since roll damping significantly affects on roll amplitude and occurrence region of parametric roll, accurate estimation of roll damping is crucial for quantitative prediction of parametric roll. In most researches of numerical prediction of parametric roll, a roll decay test or the Ikeda's semi-empirical prediction method are used for roll damping estimation. However their accuracy and applicability to the prediction of large amplitude of parametric roll has not been investigated sufficiently. Therefore we conducted a forced roll model test to measure roll damping with large roll amplitude up to 30 degrees with/without forward velocity. In the current experiment, heave and pitch motions were allowed because vertical motion could affect on measured roll damping particularly for large roll amplitude test, which Hirayama and Takezawa (1982) were not.

Normalised roll damping coefficients estimated by means of a forced roll test, a roll decay test and the Ikeda's prediction method are shown in Fig.7. Roll damping estimated from the roll decay test is significantly overestimated for small roll angle and is slightly underestimated for large roll angle. Furthermore, its accuracy becomes worse when the Froude number becomes large. This might be because the roll damping with the roll decay test is determined not for a steady rolling but also for transiently decaying rolling. Estimated roll damping by the Ikeda's prediction method is significantly overestimated as compared to the result of forced roll test in all roll amplitudes and Froude numbers nevertheless the Ikeda's prediction method was developed for a steady roll motion. Further discussion on the Ikeda's prediction method is described in the latter chapter.

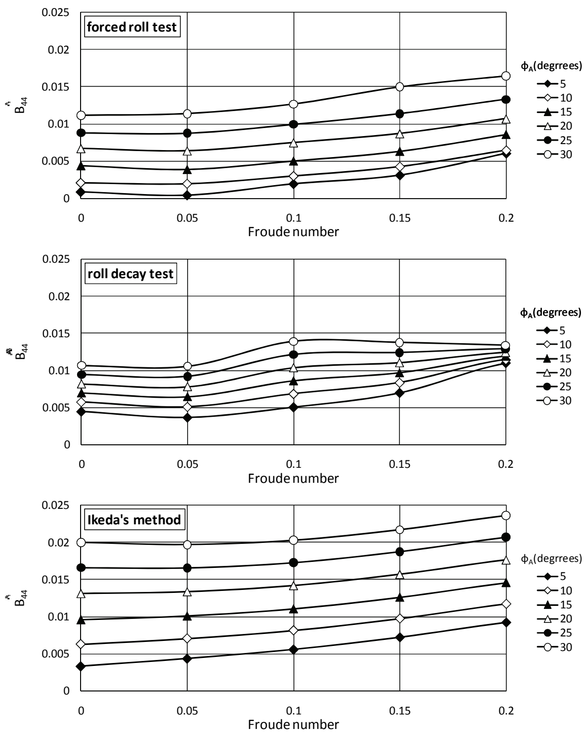

Fig.7 Roll damping coefficients estimated by a forced roll motion test, a roll decay test and the Ikeda's method

PARAMETRIC ROLL PREDICTION

Model experiment was conducted to obtain the validation data for the numerical simulation model and discussion on the influence of estimation accuracy of roll damping on parametric roll prediction. Model experiment was done for λ/L=0.6, 0.8, 1.0, 1.2 and 1.4, constant wave height H=0.085m and Fn=0.0, 0.05, 0.1, 0.15 and 0.2. Numerical results with the 3DOF model utilizing the roll damping estimated from a forced roll test, a roll decay test and the Ikeda's prediction method were compared with the experimental result as shown in Fig.8. Since instantaneous roll amplitude is required for estimating roll damping in the time-domain simulation, temporal roll amplitude, ϕ_a, is approximated with roll angle and roll angular velocity as shown in the Eq.(4).

$$\phi_a = \sqrt{\phi^2 + \left(2\dot{\phi} / \omega_e\right)^2} \tag{4}$$

Numerical result with the roll damping estimated from a forced roll model test agrees well with experimental result of parametric roll for wide range of wave length and Froude number. The comparison demonstrates that using the roll damping estimated from a roll decay model test significantly overestimates parametric roll in certain conditions and it underestimates parametric roll if the Ikeda's prediction method is applied for roll damping estimation.

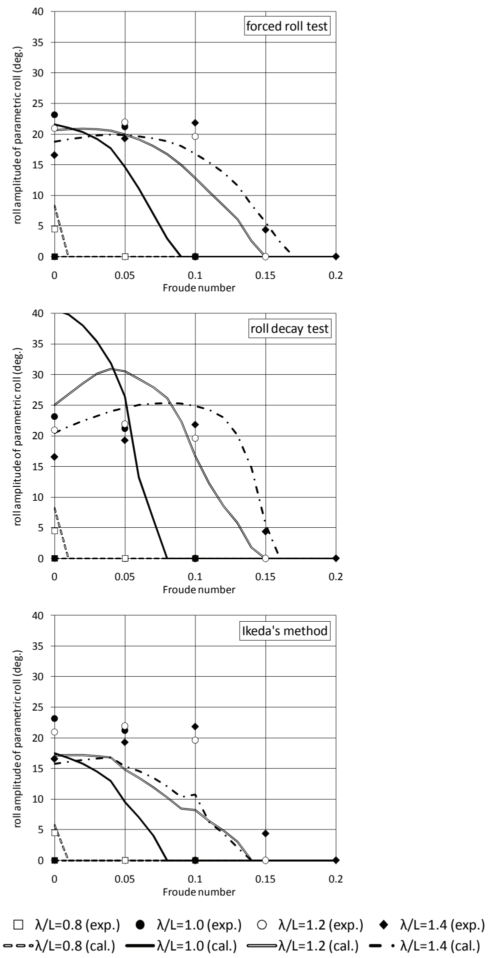

Fig.8 Numerical results of parametric roll with the roll damping estimated from a forced roll test, a roll decay test and the Ikeda's method with H=0.0851 m

C11 CONTAINERSHIP

The similar investigation was executed for a C11 post-Panamax containership modified by MARIN. (Levadou and van't Veer, 2006) Principal particulars and body plan are shown in Fig.9 and Table 2, respectively.

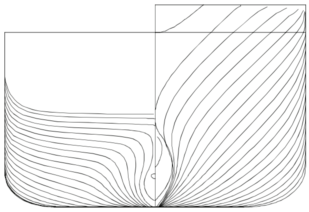

Fig.9 Body plan of the C11 containership

Table 2 Principal particulars of the C11 containership

Item	Value
Length between perpendiculars : L	262.0m
breadth : B	40.0m
depth : D	24.45m
mean draught : T	11.5m
block coefficient : C_b	0.56
metacentric height : GM	1.965m
natural roll period : T_ϕ	25.1s

Roll Damping

Estimated roll damping for the C11 containership by a roll decay test and the Ikeda's semi-empirical prediction method are shown in Fig.10. There are significant differences between the two estimation methods, and the trend of the differences is the same as the 6600 TEU containership.

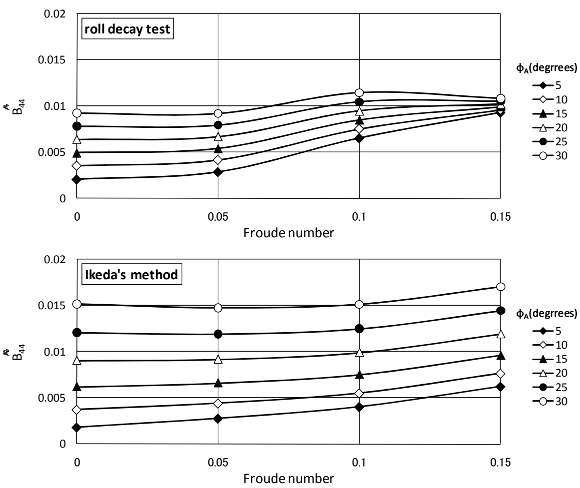

Fig.10 Roll damping coefficients estimated by a roll decay test and the Ikeda's method for the C11 containership

Parametric Roll Prediction

Comparisons of roll amplitude of parametric roll in regular head seas between the model experiment [Sogawa et al., 2010] and the numerical simulations with the roll damping estimated by the roll decay test and the Ikeda's prediction method are shown in Fig.11. Numerical result with the roll damping by the roll decay test almost agrees with the model experiment for all wave steepness and Froude numbers. By contrast, the numerical result with the roll damping by the Ikeda's semi-empirical prediction method significantly underestimates the model experiment because of its overestimation of roll damping as shown in Fig.10. Since the amplitude of roll restoring variation increases its nonlinearity with a roll angle, the difference of estimation methods of roll damping could significantly affect on parametric roll prediction and could result in completely different amplitude. Therefore more attention to the estimation methods of roll damping should be paid for quantitative validation of numerical simulation of parametric roll.

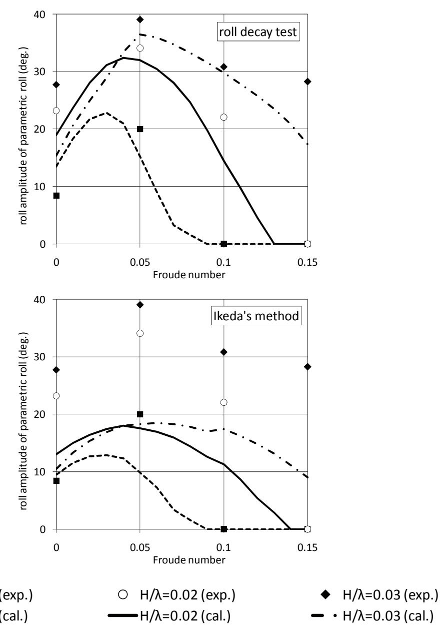

Fig.11 Numerical results of parametric roll with the roll damping estimated from a roll decay test and the Ikeda's method for the C11 containership with λ/L=1.0

DISCUSSION ON IKEDA'S METHOD

For the estimation of roll damping by the Ikeda's semi-empirical prediction method, commercial software was used in this study. Since approximation of the each transverse section is performed automatically in the software, estimation accuracy of roll damping could depend on this approximation accuracy itself. Therefore we recalculated the roll damping coefficient both for the 6600 TEU and C11 containerships by imputing the exact position of the bilge keels for every transverse section by hand. As shown in Fig.12, the calculated result of roll damping for the 6600 TEU containership drastically changes and almost agrees with the experimental result of a forced roll model test except for small roll amplitude. On the other hand, the result for the C11 containership does not change very much even if the exact position of the bilge keels in each section is given, and the significant difference still remains between the roll damping estimated by a roll decay test and that by the Ikeda's prediction method. Further investigation, such as a forced roll motion test for the C11 containership and the similar examination for other types of ships, is required for further discussion.

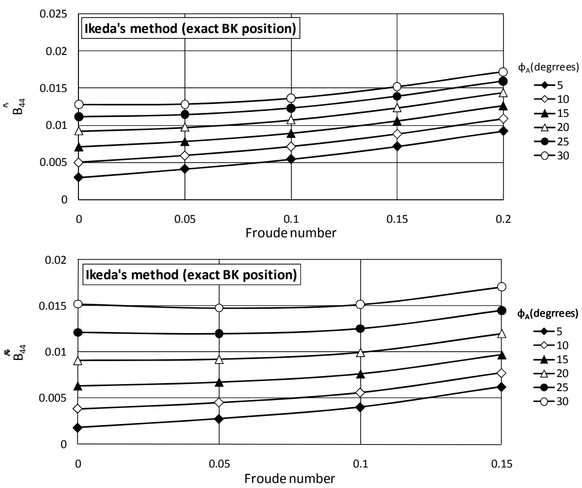

Fig.12 Estimated roll damping by the Ikeda's method with exact bilge keel position for the 6600TEU containership (upper) and the C11 containership (lower)

CONCLUSIONS

Numerical investigation on the influence of roll damping estimation methods on parametric roll prediction was conducted. As a result, the estimation methods of roll damping significantly affect on the numerical prediction of parametric roll for the two containerships used here. Further investigations and discussions on roll damping matters are desirable to develop reasonable performance-based intact stability criteria on parametric rolling.

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NOMENCLATURE

A_{ij}	Added mass/added moment of inertia
B_{ij}	Damping coefficient
F_i^{DF}	Diffraction force
F_i^{FK+B}	Froude-Krylov force and buoyancy
F_n	Froude number
H	Wave height
I_{xx}	Moment of inertia in roll
m	Ship mass
N	Roll damping coefficient
ϕ	Roll angle
ϕ_a	Roll amplitude
λ	Wave length
θ	Pitch angle
ω_e	Encounter frequency
ζ	Heave displacement