A Study on Roll Damping Estimation for Non Periodic Motion

Toru Katayama

Graduate school of engineering, Osaka Prefecture University

Jun Umeda

Graduate school of engineering, Osaka Prefecture University

Hirotada Hashimoto

Graduate school of engineering, Osaka University

Burak Yıldız

Faculty of Naval Architecture and Maritime, Yildiz Technical University

ABSTRACT

Ikeda's estimation method is well-known as a prediction method of the roll damping. It is developed with theoretical and experimental backgrounds for periodical roll motion. However, it is difficult to apply it to estimation of transitional and non-periodical roll motion problems (i.e. roll motion and parametric rolling in irregular waves, broaching to capsize etc). In this study, an estimation method of bilge-keel component of non-periodic roll damping for time domain is investigated. Firstly, an estimation method for bilge-keel component of roll damping for time-domain is proposed. This method is based on Ikeda`s prediction method, the drag coefficients are based on an empirical formula of flat plate. Secondly, the estimated results are compared with measured results by irregular forced rolling test. Finally, parametric rolling in irregular waves is calculated by using the estimation method of bilge-keel component in time-domain. The difference of calculated roll motions by using the proposed method and Ikeda's original method is shown.

KEYWORDS

bilge-keel component, Keulegan-Carpenter number, drag coefficient, transitional motion, time-domain simulation

INTRODUCTION

It is important to evaluate stability of vessel (especially roll motion) in order to sail safely. For accurate prediction of stability, it is significant to estimate hydrodynamic forces acting on ship with accuracy. However, it is not easy to estimate roll damping, which includes significant viscous effects. It is well known that there is a prediction method of roll damping proposed by Ikeda's et al.(1976) (1977) (1978). It is developed with theoretical and experimental backgrounds for periodical motion. However, it is difficult to apply it to estimation of transitional and non-periodical roll motion problems (i.e. roll motion and parametric rolling in irregular waves, broaching to capsize etc). An approximate transformation is necessary in order to apply it to non-periodic rolling in time domain simulation. The purpose of this study is to propose an estimation method of bilge-keel component of roll damping for time domain simulation. Finally, parametric rolling in irregular wave is calculated by using the estimation method of bilge-keel component in time-domain. The effects of the estimation method on occurrence of parametric rolling are shown.

BILGE-KEEL COMPONENT OF ROLL DAMPING FOR TIME DOMAIN SIMULATON

Ikeda's method and change of the method

Bilge-keel component of roll damping is composed of normal force component on bilge-keels and hull surface pressure component. The normal force component is calculated by Eq.(1) using a drag coefficient of flat plate expressed by Eq.(2). The hull surface pressure component is calculated by Eq.(3). The coefficient C_P in Eq.(3) is divided into the pressure coefficient C_P^+ on front face of bilge-keels and the pressure coefficient C_P^- on back face of bilge-keels. And the pressure coefficient C_P^- is calculated by Eq.(4) using C_D expressed by Eq.(2). The hull surface pressure component can be obtained from the integration which is shown in Fig.1. Length of negative pressure region S_0, depends on the Keulegan-Carpenter number, and it is calculated by Eq.(5),

$$M_{BKN} = \frac{1}{2}\rho\left(2\, l_{BK}\; b_{BK}\right) C_D l^2\; \dot{\phi}\left|\dot{\phi}\right|\, l f^{\,2} \qquad (1)$$

$$C_D = 22.5\left(\frac{b_{\mathrm{BK}}}{\pi\, l \phi_{\mathrm{a}}}\right)\frac{1}{f} + 2.4 \qquad (2)$$

$$M_{BKH} = \frac{1}{2}\rho\, l^2 f^{\,2}\; \dot{\phi}\left|\dot{\phi}\right| \int_G C_p \cdot l_p\, dG \qquad (3)$$

$$C_{\mathrm{p}}^- = C_P^+ - C_D = 1.2 - C_D \qquad (4)$$

$$S_0 / b_{\mathrm{BK}} = 0.3\left(\frac{\pi l \phi_{\mathrm{a}}}{b_{\mathrm{BK}}}\right) f + 1.95 \qquad (5)$$

where l_{BK} and b_{BK} is the length and breadth of the bilge-keel and l is the distance from the roll axis to the tip of the bilge-keel. ϕ_a is roll amplitude. f is a correction factor to take account of the increment of flow velocity at the bilge.

There are two problems to apply Ikeda's original method to roll damping calculation in time domain. The first one is that the drag coefficient acting on the bilge-keel is drag coefficient of flat plate in steady oscillation and it is constant for one swing (from stop to stop). It is observed that drag coefficient of flat plate in steady oscillation is different from value for time-domain according to the previous study (Katayama et al.,(2010)). The other is the memory effects. It was pointed out that the vortexes created by previous swings affect roll damping in time domain.

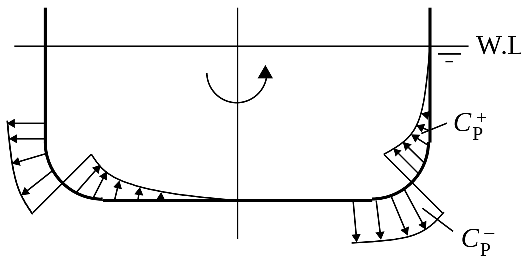

Fig.1 Assumed pressure distribution on the hull surface created by bilge-keels.

Estimation method of Roll Damping of non-periodic motion

The empirical formula of the drag coefficient of flat plate in time domain is used to solve the problems.

Under one-way acceleration, the drag coefficient C_{Dacc} of flat plate for time-domain can be obtained as follows,

$$\frac{C_{Dacc}}{C_{D0}} = \begin{pmatrix} 14.3e^{-1.80Kc_d} + 4.41e^{-0.37Kc_d} + \\ -10.4e^{-1.03Kc_d} - 0.30e^{-0.17Kc_d} + 1.0 \end{pmatrix} \times\left(0.908 + \frac{1.2}{1+1.01^{Kc_d}}\right) \qquad (6)$$

$$(0 < Kc_d \le 250)$$

$$Kc = Kc_d = \frac{2\pi \cdot y}{D_P} \qquad (7)$$

where C_{D0} is the drag coefficient under uniform flow. K_C number for Eq.(6) is obtained from Eq.(7). y in Eq.(7) is a moving distance from the starting position.

The drag coefficient under steady oscillation is obtained from Eq.(8). K_C number for Eq.(8) is obtained from Eq.(9),

$$\frac{C_{Dperi}}{C_{D0}} = (20.0e^{-1.23Kc_a} + 2.86e^{-0.174Kc_a} + 1.0) \times \left(0.908 + \frac{1.2}{1+1.01^{Kc_a}}\right) \quad (8)$$
$$(0 < Kc_a \le 250)$$

$$Kc = Kc_a = \frac{2\pi \cdot y_a}{D_P} \quad (9)$$

where y_A is amplitude of steady oscillation.

In the previous paper (Katayama et al. (2010)), it is confirmed that the drag coefficient in each swing of steady oscillation is gradually increasing, and after the 4th swing the drag coefficient becomes constant. These characteristics are also expressed by an empirical formula in the paper. In order to apply it to time domain estimation of drag coefficient, the following equation is proposed,

$$\frac{C_{Daccn}}{C_{D0}} = \frac{C_{Dacc}}{C_{D0}} \times \left\{1 + \left(\frac{C_{Dperi}}{C_{D1}} - 1\right) \times \frac{n-1}{3}\right\} \quad (10)$$

where n is the number of swing (n = 1,2,3 and 4). In Eq.(10), it is assumed that the drag coefficient in first swing is C_{Dacc} and the drag coefficient that is increased from the 1st swing to the 4th swing according to the ratio of C_{Dperi} and C_{D1} is C_{Daccn}. The drag coefficient of flat plate for 1st swing in steady oscillation is C_{D1} and obtained by following equation. K_C number for Eq.(11) is obtained from Eq.(9),

$$\frac{C_{D1}}{C_{D0}} = \left\{\begin{matrix} 5.42e^{-0.23Kc} + 13.2e^{-1.25Kc} - \\ 1.96e^{-0.21Kc} - 8.72e^{-0.78Kc} + 1.0 \end{matrix}\right\} \times \left(0.908 + \frac{1.2}{1+1.01^{Kc}}\right) \quad (11)$$
$$(0 < Kc \le 250)$$

C_D in Eq.(2) is replaced with drag coefficient in time-domain to estimate bilge-keel component in time-domain. Considering the increment of flow velocity at the bilge, drag coefficient of bilge-keel is obtained from Eq.(12) with replacing Eq.(8) and Eq.(14) with replacing Eq.(6). K_C number in Eq.(12) is obtained by using Eq.(13). K_C number in Eq.(14) is obtained from Eq.(15),

$$\frac{C_{Dperi}}{C_{D0}} = \left(20.0e^{-1.23f\cdot Kc} + 2.86e^{-0.174f\cdot Kc} + 1.0\right) \times \left(0.908 + \frac{1.2}{1+1.01^{f\cdot Kc}}\right) \quad (12)$$

$$Kc = Kc_a = \frac{\pi\, l\, \phi_a}{b_{BK}} \quad (13)$$

$$\frac{C_{Dacc}}{C_{D0}} = \left(\begin{matrix} 14.3e^{-1.80f\cdot Kc_d} + 4.41e^{-0.37f\cdot Kc_d} + \\ -10.4e^{-1.03f\cdot Kc_d} - 0.30e^{-0.17f\cdot Kc_d} + 1.0 \end{matrix}\right) \times \left(0.908 + \frac{1.2}{1+1.01^{f\cdot Kc_d}}\right) \quad (14)$$

$$Kc = Kc_d = \frac{\pi\, l\, \phi}{2b_{BK}} \quad (15)$$

where ϕ is a moving distance from the starting position where angular velocity of roll is zero.

Considering the memory effects on bilge-keel component, the drag coefficient for 1st swing is expressed as Eq.(16) with K_C number in Eq.(13). The drag coefficient for each swing can be obtained by substituting the drag coefficient in Eq.(12),(14) and (16) for Eq.(10).

$$\frac{C_{D1}}{C_{D0}} = \left(\begin{matrix} 5.42e^{-0.23f\cdot Kc} + 13.2e^{-1.25f\cdot Kc} + \\ -1.96e^{-0.21f\cdot Kc} - 8.72e^{-0.78f\cdot Kc} + 1.0 \end{matrix}\right) \times \left(0.908 + \frac{1.2}{1+1.01^{f\cdot Kc}}\right) \quad (16)$$

COMPARISON OF ESTIMATED AND MEASURED RESULTS

Measurement method of Roll Damping

Roll damping of bilge-keel component acting on the two dimension model with bilge-keel are measured. The principal particulars of two dimensional model are shown in Table1.

Estimated results are compared with measured results in irregular forced rolling.

Table 1 Principal particulars of two dimensional model.

Length	0.8m
Breath	0.237m
Draught	0.096m
Height of Roll axis	0.096m
Bilge-keel	0.01m×0.8m
C_B	0.977

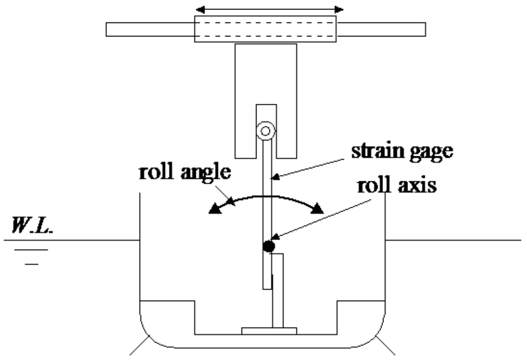

Fig.2 Schematic view of forced rolling device.

The model is fixed by a forced rolling device (shown in Fig.2), and it is forced rolling. Roll angle and damping moment are measured. Roll damping is obtained from subtracting the inertia moment and restoring moment from the measured moment. Eddy component accounts for small percentage of roll damping and can be ignored. Frictional component is obtained by following equation.

$$M_F = \frac{1}{2}\rho S_f r_f^{\,3} C_F \quad \dot{\phi}|\dot{\phi}| \tag{17}$$

In estimation of the coefficient of friction, Reynolds number in time-domain is used, whose characteristic length is moving distance from the starting position where angular velocity of roll is zero. Three estimation methods of bilge-keel component are compared. The drag coefficient in the formulas is different for each method. The first one uses the drag coefficient, which changes in every time step, depends on Kc_d number expressed by Eq.(15). The second one uses the drag coefficient considering memory effect on the bilge-keel component by Eq.(10). The third one uses the constant drag coefficient depends on Kc number expressed by Eq.(13).

Irregular motion test

Fig.3 shows comparison of the measured and the three estimated results in time-domain. The upper, middle and bottom figure of Fig.3 show the roll angles, the roll damping, and the drag coefficient in time-domain, respectively. The result of the second method shows the value of roll damping becomes maximum before the velocity become maximum.

In the case, the results show that estimated results of the method considering memory effect on the bilge-keel component are best agreement with measured result in the three methods.

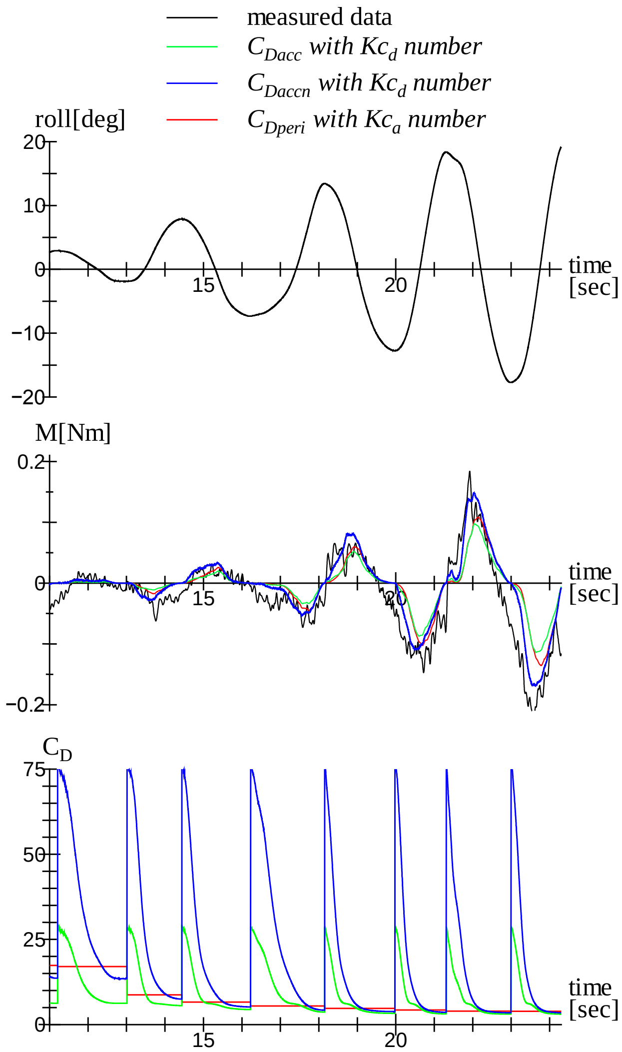

Fig.3 Results of irregular motion test.

TIME DOMAIN SIMULATION USING PROPOSED METHOD

Parametric rolling in irregular waves is calculated to investigate the effects of the proposed method.

The sample ship and calculation method

Fig.8 and Table 2 shows body plan and principal particulars of the sample ship.

The numerical simulation model (Hashimoto and Umeda, 2010) is used for calculations. In the simulation, roll damping component is estimated by two methods. The first one is a simplified method using Ikeda's original method which is used originally in the numerical simulation, and the other one is the proposed method in this study, which includes the estimation method for bilge-keel component by using the drag coefficient considering memory effects in time-domain.

In the simplified method, roll damping is estimated at changed roll amplitudes systematically in roll natural period by Ikeda's original method. And roll damping in the simulation is calculated by interpolation of the results. The roll amplitude is calculated by Eq.(18) with the roll angle and the roll angular velocity in each time step.

$$\phi_a = \sqrt{\phi^2 + \left(\frac{2\dot{\phi}}{\omega_e}\right)^2} \qquad (18)$$

The simulation is carried out at F_n =0.083 in irregular head waves whose significant wave height is 6.0m. The spectrum of irregular wave is the ITTC spectrum expressed by Eq.(19).

$$S(\omega) = 0.0081 \times \frac{g^2}{\omega^5} \exp\left(\frac{-3.11}{H_{1/3}^2 \times \omega^4}\right) \qquad (19)$$

To make irregular waves, the spectrum whose range of wave period is T_e/T_ϕ=0.45~0.65 is divided into 60, and a sine wave of each frequency component is superposed. In addition, the phase difference of each frequency component is given as random number.

Roll motions and roll damping in time histories are compared between two methods and the effect of the difference of estimation methods on prediction of the parametric rolling.

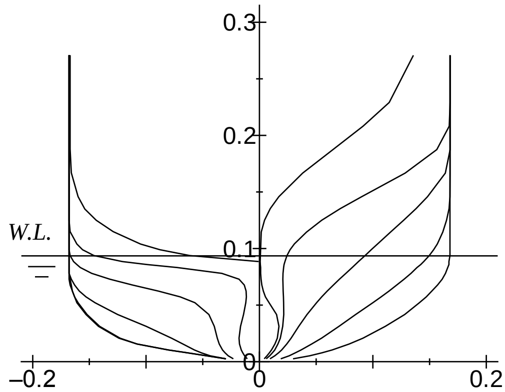

Fig.8 Body plan of the sample ship.

Table 2 Principal particulars of the subject ship and wave condition in the time domain simulation.

Length between perpendiculars: L_{PP}	192m
Breath: B	32.26m
Depth: D	26m
draught: d	9.0m
Height of gravity: KG	17.0m
Metacentric height: GM	1.89m
Natural roll period: T_ϕ	18.42s
Displacement: W	27205ton
Breadth of bilge-keels	0.7m
Position of bilge-keels	s.s. 3.34-s.s. 5.59
Wave spectrum	ITTC spectrum
Significant wave height: $H_{1/3}$	6.0m

Simulated results

Fig.9 shows comparison between the two calculated roll motions in time-domain. In the result of the proposed method, periodic motion occurs. On the other hand, in the result of the simplified method, periodic motion does not occur. It is confirmed that parametric rolling occurs more easily in the proposed method than in simplified method. Fig.10 shows histogram of roll angles for two methods. The results show that frequency of amplitudes over 5 degrees in the proposed method is higher than that in the simplified method. Therefore, it is confirmed that roll amplitudes of the proposed method become larger than the simplified method.

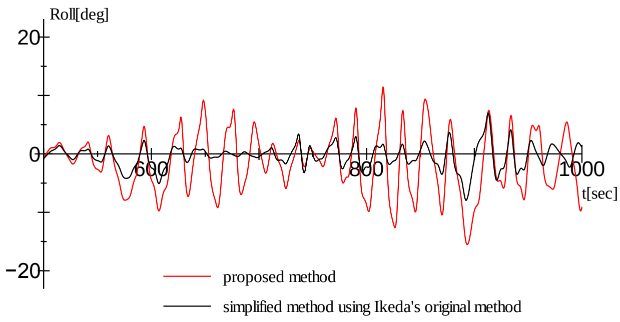

Fig.9 Time history of simulated roll motions.

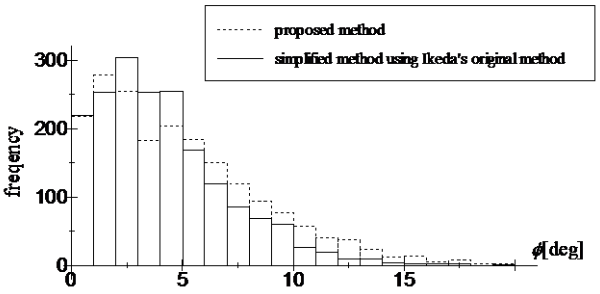

Fig.10 Histogram of roll amplitude

CONCLUSIONS

In this paper, an estimation method of bilge-keel component of roll damping in time-domain is proposed based on an empirical formula of drag coefficient of flat plate. The bilge-keel component acting on the two dimension model with bilge-keels is measured, and compared with the estimated result. The estimated result shows better agreement with the measured one.

The estimation method is applied for a time domain simulation of parametric rolling in irregular head waves (Hashimoto and Umeda, 2010). And it is confirmed that roll amplitudes become larger easily, because the estimated roll damping is slightly smaller than the simplified method which is used originally in the simulation.

REFERENCES

Hashimoto, H. and Umeda, N., "A Study on Quantitative Prediction of Parametric Roll in Regular Waves", Proceedings of the 11th International Ship Stability Workshop, Stability Workshop, 2010, pp.295-301

Katayama T., Yoshioka Y., and Kakinoki T., "A Study on Bilge-keel component of Roll Damping for Time Domain Simulation", Proceedings of the 12th International Ship Stability Workshop, 2011,

Katayama T., Yoshioka Y., Kakinoki T. and Ikeda Y., "Some Topics for Estimation of Bilge-keel Component of Roll Damping", *Proceedings of the 11th International Ship Stability Workshop*, 2010, pp.225-230.

Ikeda Y., Himeno Y. and Tanaka N., "On Roll Damping Force of ship - Effects of Friction of Hull and Normal Force of Bilge Keels-", *Journal of Kansai Society of Naval Architects, Japan*, Vol. 161, 1976, pp.41-49.

Ikeda Y., Komatsu K., Himeno Y. and Tanaka N., "On Roll Damping Force of Ship -Effects of Hull Surface Pressure Created by Bilge Keels", *Journal of Kansai Society of Naval Architects, Japan*, Vol. 165, 1977, pp.31-40.

Ikeda Y., Osa K. and Tanaka N. : Viscous Forces Acting on irregularly Oscillating Circular Cylinders and Flat Plate, Proceedings of 6th International Symposium on Offshore Mechanics & Arctic Engineering, Vol.1, 1987.