A Study on Roll Damping Time Domain Estimation for Non Periodic Motion

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ABSTRACT

In this study, the memory effects of bilge keel component of roll damping in irregular rolling are investigated by numerically. First, in order to validate the results of numerical simulation, a forced irregular roll motion test is carried out, and the characteristics of the memory effects are also confirmed. Second, the mechanism of the memory effects is made clear by the numerical simulation. Finally, based on the simulation results, the roll damping time domain estimation, which is proposed by Katayama et al. (2013) based on the prediction method proposed by Ikeda et al. (1978), is improved.

Keywords: *Roll damping, Memory effects, Transient Effects, Previous Amplitude Effects, Time domain estimation, Non periodic motion*

1. INTRODUCTION

In order to guarantee the safety of vessels, it is important to estimate roll damping accurately. It is well known that there is a prediction method of the roll damping proposed by Ikeda et al. (1978). However, it is indicated by the previous studies that there are some problems in Ikeda's method. Ikeda's method is developed with theoretical and experimental backgrounds for periodical roll motion. Therefore, it is difficult to apply it to a time domain simulation of transitional and irregular roll motions.

In the previous studies (Ikeda et al., 1988, Katayama et al., 2010), it is pointed out that the memory effects of roll damping are necessary to consider for time domain simulations of non-periodical roll motions. Ikeda et al. (1988) show through experiments that the drag coefficient on flat plate increased in the first few oscillations when the flat plate is started rest (it is called the transient effects in this paper). An additional valuable observation reports from the experiments by Ikeda et al. (1988) is that the memory effects remain important in irregular motion. When an oscillation has a larger amplitude than the oscillation after it, then the drag coefficient is larger than at a steady oscillation amplitude (it is called the memory effects in this paper). Katayama et al. (2010) investigate the effects of transient motion on the drag force of a flat plate. In the region of KC < 250, the drag coefficient for acceleration in one direction is larger than the drag coefficient for acceleration in a uniform flow and smaller than that in a steady oscillatory flow. Moreover, in a transient condition under forced oscillation, the drag coefficients from the first to the third oscillation are smaller than that in a steady oscillatory flow. Katayama et al. (2013) propose a time domain estimation method which is an improved Ikeda's method of bilge-keel component of roll damping based on the results of Katayama et al. (2010). However the improved method include only the transient effects and it is required to include the memory effects.

In this study, the bilge-keel component of roll damping for non-periodic motion is focused. The memory effects is investigated by numerically. First, a forced roll motion test with irregular motion is carried out, and the characteristics of the memory effects are confirmed and the numerical simulation is validated. Second, the mechanism of the memory effects is made clear by the numerical simulation. Finally, based on the CFD results, the roll damping time domain prediction method, which is proposed by Katayama et al. (2013) including the transient effects based on Ikeda's method (1978), is improved.

2. FORCED IRREGULAR ROLL MOTION TEST

2.1 Model and Measurement

In order to investigate the memory effects and take some validation data for the numerical simulation, forced roll motion measurements are carried out at the towing tank of Osaka Prefecture University (length 70m, breadth 3m, depth 1.5m).

Table 1 and Figure 1 show a body plan and principal particulars of a two dimensional model. The model is attached to end plate in order to remove three dimensional effects.

The model is given forced roll moment by the forced irregular roll motion device shown as figure 2, and it is putted on the centre line of the model. The device has three axis of rotation and three rods attached weights are rotated in the horizontal plane at different periods. In the measurement, roll motion and rotating positions of rods are measured in sampling frequency 100Hz.

Table 2 shows the conditions in the measurement. The measurements at systematically changed forced roll periods and drafts are carried out. In order to reduce wave making component, forced roll period is more than 1.2sec.

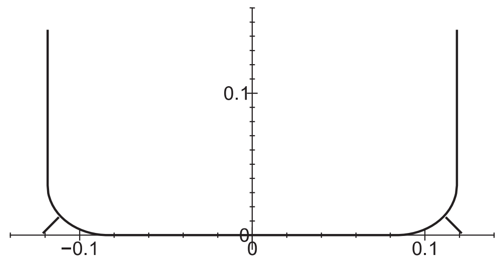


Figure 1 Section of the two dimensional model.

Table 1 Principal particulars of the two dimensional model.

L_{PP} [m]	0.80
B[m]	0.235
D[m]	0.145
Bilge radius[deg]	0.035
Bilge keel[m×m]	0.01×0.80

Figure 2 Forced irregular roll motion device.

Table 2 Conditions in the measurement.

height of roll axis [mm]	96
draft [mm]	96, 80, 72, 57
forced roll period [sec]	1.60-1.28, 1.80-1.44
device from roll axis [mm]	119
A mass of weight [g]	150
attached position of weight from centre of rotation[mm]	50

2.2 CFD Calculation

In the tank test, it is difficult to visualize flow around hull and divide the measured hydrodynamic forces into the each component, which are the normal component and the hull surface pressure component of the bilge keel component. In this study, bilge keel component calculated by CFD (Fluent) is divide into the each component and the memory effects on the each component is investigated.

In the calculation, the two dimensional model is given the roll motion expressed by Eq. (1), and roll moment acting on hull is calculated.

$$\phi(t) = \phi_{a1} f_1(t) \sin\omega_1 t + \phi_{a2} f_2(t) \sin\omega_2 t$$

$$f_i(t) = \begin{cases} \frac{1}{2}\sin\left(\frac{1}{4}\frac{\pi}{T_i}t - \frac{1}{2}\pi\right) + \frac{1}{2} & (for, t \le 4T_i) \\ 1 & (for, t > 4T_i) \end{cases} \tag{1}$$

Eq.(1) can almost express the measured roll motion in the forced irregular roll motion test in the limited cases, which is small amplitude irregular motion caused by two rods. Table 3 shows the calculation conditions and settings.

Table3 Calculation conditions.

Numerical solver	implicit unsteady first order
Viscous model	*k-ε* model
Solution algorithm	SIMPLE
Multiphase model	VOF, Geo-reconstructed
Gradient	Least Squares Cell Based
Discretization scheme	Second order Upwind
Interpolation scheme	PRESTO!
Draft[mm]	96
Forced roll period[sec] and amplitude[deg]	2.00-1.2sec and 8.0-5.0deg 1.20-0.67sec and 5.0-5.0deg 1.80-2.00sec and 10.0-8.0deg 1.60-2.00sec and 8.0-6.0deg 1.40-1.8sec and 8.0-6.0deg 1.60-1.28sec (measured) 1.80-1.44sec (measured)

2.3 Analysis of Roll Damping

The roll motion in the measurement and the calculation is expressed as Eq. (2).

$$A_{44}\ddot{\phi}(t) + B_{44}\dot{\phi}(t)\left|\dot{\phi}(t)\right| + C_{44}\phi(t) = M_E \tag{2}$$

Where the first term of left side of the equation is moment of inertia including added moment of inertia, the second term is the roll damping moment, the third term is the restoring moment and M_E is forced roll moment. It should be noted that A_{44}, B_{44} and C_{44} are not constant value for each time step.

In the measurement, the forced roll moment is given by the forced irregular roll motion device. The given moment can be calculated as follow. Figure 3 shows schematic view and coordinate system.

$$\begin{aligned} x &= r\cos\omega t \\ y &= r\sin\omega t\cos\phi + h\sin\phi \\ z &= h\cos\phi - r\sin\omega t\sin\phi \end{aligned} \tag{3}$$

Kinetic energy and potential energy of weights caused by rotation of weights and roll motion of hull are expressed as Eq. (4) and (5).

$$T = \frac{1}{2}m\{r^2\omega^2 + \left(h^2 + r^2\sin^2\omega t\right)\dot{\phi}^2 + 2hr\omega\dot{\phi}\cos\omega t\} \tag{4}$$

$$U = mg\left(h\cos\phi - r\sin\omega t\sin\phi\right) \tag{5}$$

The forced roll moment caused by weights can be obtained from applying Lagrange equation of motion to these energy.

$$\begin{aligned} m_{Ei} &= -mr^2\sin^2\omega t\ddot{\phi} \\ &- 2mr^2\omega_i\dot{\phi}\sin\omega_i t\cos\omega_i t \\ &+ mg\left(h\sin\phi + r\sin\omega_i t\cos\phi\right) \\ &+ mr\omega_i^2 h\sin\omega_i t \end{aligned} \tag{6}$$

C_{44} in Eq.(2) is obtained by the calculated *Gz* curve corresponding to the roll angle. The roll angle removed noises by low-pass filter (10Hz) from the measured ones is used in Eq.(2). And roll angular velocity and acceleration obtained from differentiating numerically the filtered roll angle are used in Eq.(2). A_{44} and B_{44} in Eq. (2) are obtained to satisfy the Eq. (2). In concrete terms, the coefficients (A_{44} and B_{44}) at certain time t are decided by using least square method to time history data (data number n) from the starting position where angular velocity of roll is zero to a certain time. Roll damping is obtained in time domain due to decide the coefficients (A_{44} and B_{44}) changed in time step while increasing data number n.

On the other hand, in the calculation, the roll motion expressed by Eq. (1) is given, and the roll moment acting on hull M_E is calculated. The roll damping is obtained from the same way as the above-mentioned method.

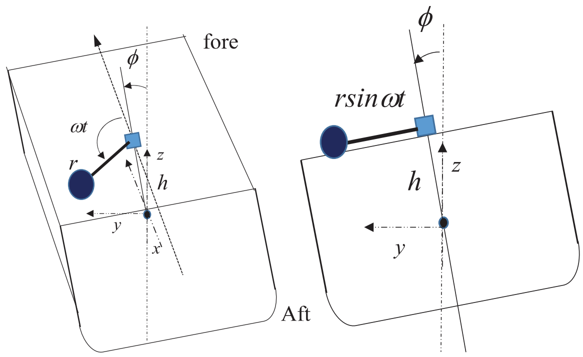


Figure 3 Schematic view of forced irregular motion test.

3. MEMORY EFFECTS

3.1 Comparison of Measured and Calculated results

An example of the comparison between measured and calculated roll damping is shown in Figure 4. The upper and bottom figures of Figure 4 show the time histories of roll angle and roll damping, respectively. The calculated result is good agreement with that of the measured result. It is confirm that roll damping under irregular motion can be calculated accurately by CFD.

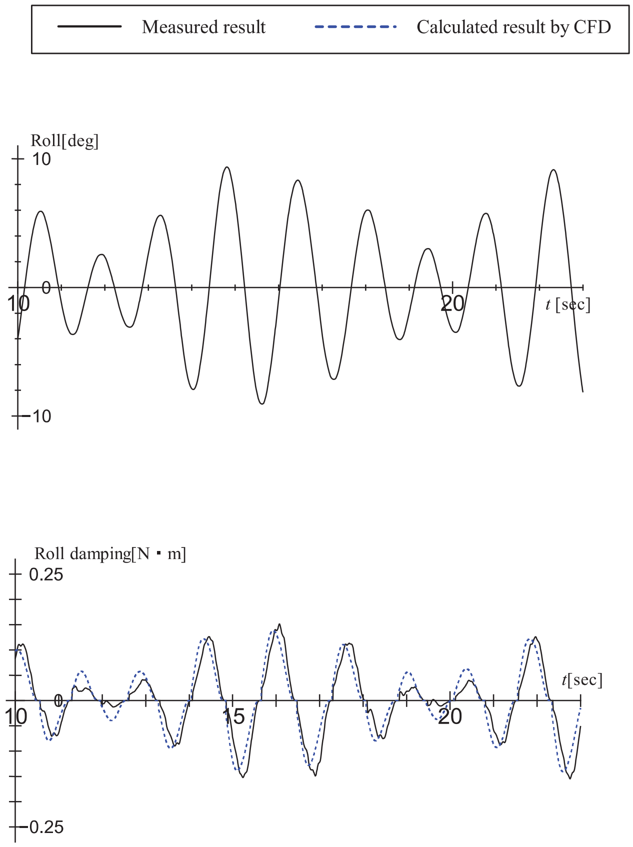


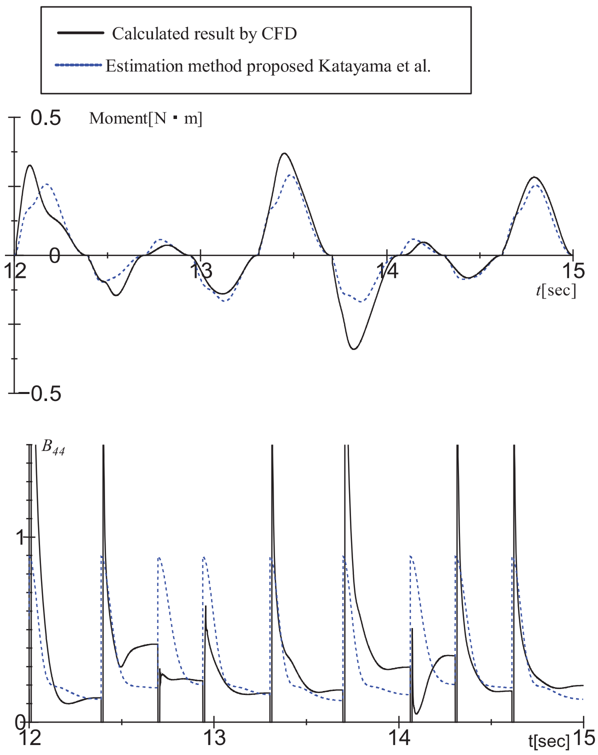
Figure 4 Comparison of measured and calculated roll damping.

3.2 Memory Effects on Normal Force Component

It is confirm that the vortex created by previous swing affects drag force acting on flat plate in present swing by Katayama et al. (2010) and it is assumed that bilge keel component may be affected by the memory effects.

In this section, bilge keel component calculated by CFD is divide into normal force component and hull surface pressure component and the memory effects on normal force component is investigated. Normal force component is the moment due to drag force acting on bilge keel. And the result by CFD is compared with the result estimated by the time domain estimation proposed by Katayama (2013).

An example of the comparison between calculated and estimated roll damping is shown in Figure 5. The upper, middle and bottom figure of Figure 5 show time history of roll damping, time history of roll damping coefficient and *Kc* number for half cycle, respectively. When *Kc* number of the previous swing is larger than *Kc* number of the present swing, the calculated damping coefficient is larger than the estimated result. On the other hand, when *Kc* number of the previous swing is smaller than *Kc* number of the present swing, the calculated damping coefficient is good agreement with the estimated result. Therefore, when *Kc* number of the previous swing is larger than *Kc* number of the present swing, the memory effects must be considered in estimation method of normal force component.



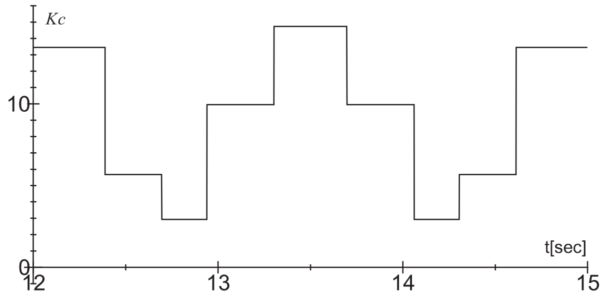


Figure 5 Previous amplitude effects on normal force component shown by comparison between the calculated result of CFD and the estimated result by the estimation method proposed by Katayama et al., (2014).

3.3 Memory Effects on Hull Surface Pressure Component

An example of roll damping coefficients of hull surface pressure component in time domain is shown in Figure 6. It is confirmed that the values are different even if *Kc* number of the present swing is the same. When *Kc* number of the previous swing is larger than *Kc* number of the present swing, the damping coefficient is larger. Therefore, it is also need to consider the memory effects on hull surface pressure component.

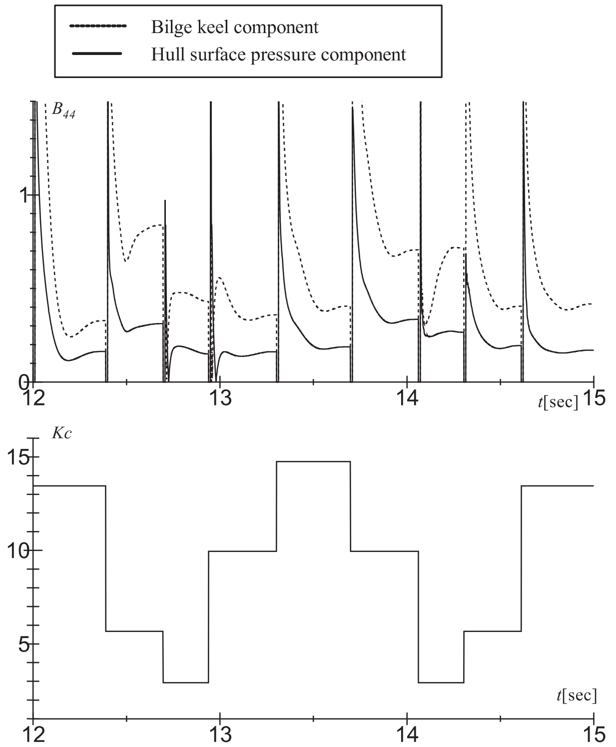
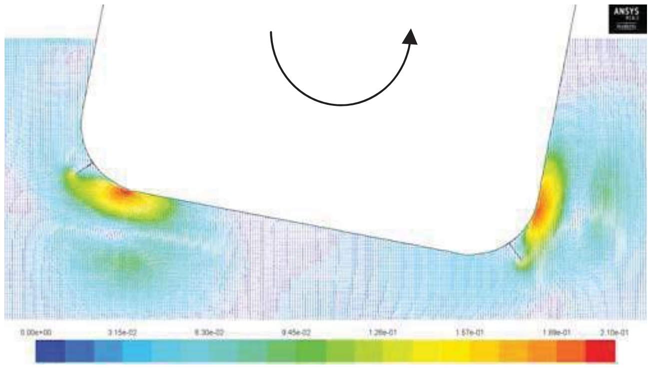


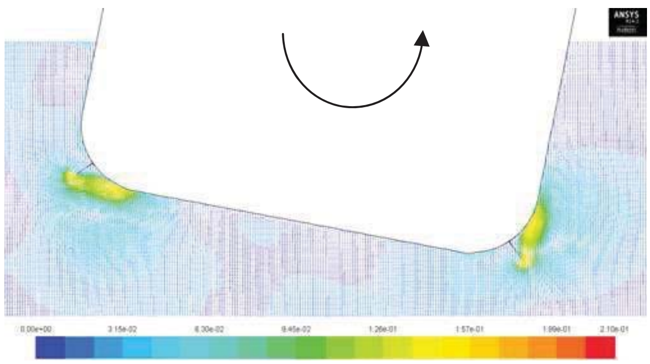
Figure 6 Memory effect for hull surface pressure component calculated by CFD.

3.4 Visualization of Flow around Hull

Flow field around hull is visualized in order to understand the mechanism of the memory effects. Figure 7 shows the velocity vectors around hull at the starting position of swing, and the direction of motion velocity of hull. The scales of these colour contour and arrow figures are the same and these show velocity magnitude. From figure 7(a) and (b), it is found that the fluid in front of bilge keels is given velocity due to the vortexes developed by the previous swing. The fluid velocity in front of bilge keel in the Figure 7 (a) is faster than that in the Figure 7 (b), because Kc number of previous swing of (a) is larger than Kc number of previous swing of (b) and the vortexes developed by previous swing of (a) are larger than that developed by the previous swing of (b). The moment due to the bilge keel is increased by increase of the relative velocity of the fluid in front of bilge keel. Therefore, the memory effects depends on Kc number in previous swing and in present swing.



(a) *Kc* number of previous swing is 19.61



(b) *Kc* number of previous swing is 9.35

Figure 7 Calculated velocity vectors around hull starting position of swing for various *Kc* numbers of previous swing.

4. ROLL DAMPING TIMEDOMAIN ESTIMATION

4.1 Time domain Estimation Considering Memory effects

It is confirmed that the memory effects must be considered in time domain estimation of bilge keel component and the memory effects depends on Kc number in previous swing and in present swing. Therefore, the estimation method considering Kc number in previous swing and in present swing is proposed.

The normal force component is calculated by Eq.(7) using a drag coefficient of flat plate under one direction accelerating expressed by Eq.(11) (Katayama et al. (2010)). The hull surface pressure component is calculated by Eq.(8). The coefficient C_P in Eq.(8) 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.(9) using CD expressed by Eq.(2). The hull surface pressure component can be obtained from the integration which is shown in Figure 8. Length of negative pressure region S_0, depends on the Kc number, and it is defined by Eq.(12).

$$M_{BKN} = \frac{1}{2}\rho l_{BK}\, b_{BK}\, mC_D l^2\, \dot{\phi}|\dot{\phi}|\, l\, f^2 \tag{7}$$

$$M_{BKH} = \frac{1}{2}\rho\, l^2 f^2\, \dot{\phi}|\dot{\phi}|\, \int_G C_p \cdot l_p dG \tag{8}$$

$$C_P^- = C_P^+ - mC_D = 1.2 - mC_D \tag{9}$$

$$S_0 / b_{\mathrm{BK}} = 0.3\left(\frac{\pi l \phi}{b_{\mathrm{BK}}}\right) f + 1.95 \tag{10}$$

$$C_D = \begin{pmatrix} 14.3e^{-1.80Kc_d} + 4.41e^{-0.37Kc_d} + \\ -10.4e^{-1.03Kc_d} - 0.30e^{-0.17Kc_d} + 1.0 \end{pmatrix} \times \left(0.908 + \frac{1.2}{1+1.01^{Kc_d}}\right) \times 2.1 \tag{11}$$

$(0 < Kc_d \leq 250)$

$$Kc = Kc_d = \frac{\pi l \phi}{b_{BK}} \tag{12}$$

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. f is a correction factor to take account of the increment of flow velocity at the bilge. m is a memory effect factor. The memory effects on normal force component is considered by the memory effect factor in Eq.(7) and the memory effects on hull surface pressure component is considered by the coefficient C_P^- in Eq.(9).

In order to investigate the memory effects factor, the ratio of roll damping coefficients estimated by using Eq. (11) to the coefficients of normal force component at the velocity is maximum are obtained. When Kc number of the previous swing is smaller than Kc number of the present swing, it is assumed that the memory effects factor equal 1.0.

Figure 9 shows the memory effects factor vs. difference of Kc number between previous swing and in present swing. In order to decide the memory effects factor, a fitting curve is obtained from the results. The memory effects factor is expressed as the following equation.

$$m = 0.0129(Kc_{previous} - Kc_{present})^2 + 0.0647(Kc_{previous} - Kc_{present}) + 1$$

(12)

$$Kc_{previ} - Kc_{present} > 0$$

Where $Kc_{prev.}$ is Kc number in previous swing and Kc_a is Kc number in present swing.

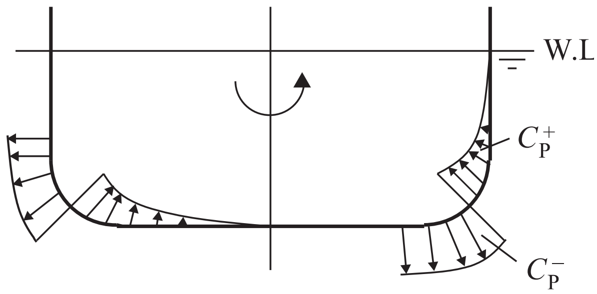


Figure 8 Assumed pressure distribution on the hull surface created by bilge-keels.

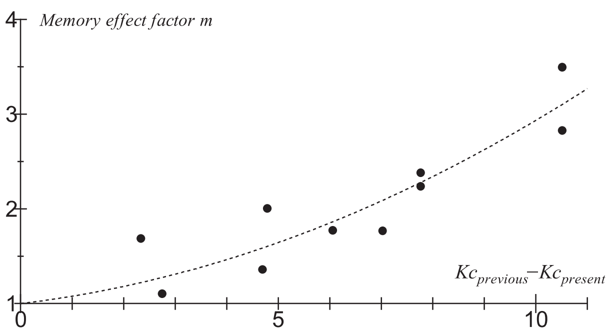


Figure 9 The memory effects factor vs. difference of Kc number between previous swing and in present swing.

4.2 Comparison with Measured Result

Figure 10 shows the result estimated by the proposed method and the result calculated by CFD and the measured result. In the case, the results show that the estimated result is good agreement with the measured and the calculated results. It is confirmed that roll damping can be estimated in time domain by using the method considering the memory effects.

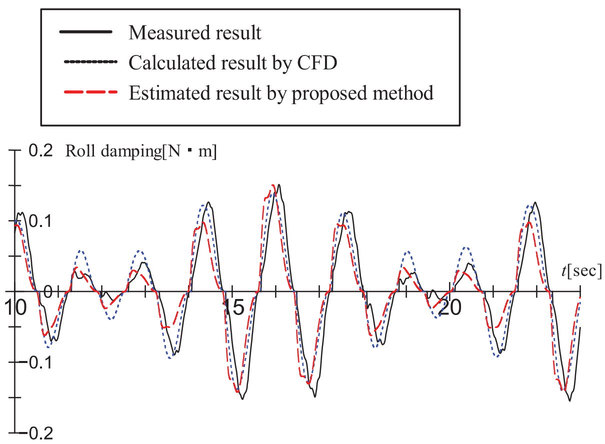


Figure 10 Comparison of estimated and calculated and measured result

5. NUMERICAL SIMULATION USING PROPOSED METHOD

5.1 The Subject Ship and Calculation method

By utilizing the numerical simulation model (H. Hashimoto et al., 2010), the effects of rolling in irregular waves is calculated to investigate the effects of the proposed method.

Fig.11 and Table 4 shows body plan and principal particulars of the subject ship.

In order to investigate effects of different roll damping estimation methods, 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 (the following section it is called the previous method) 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 roll damping coefficient considering the memory effects in time-domain.

In the previous 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.(13) with the roll angle and the roll angular velocity in each time step.

$$\phi_a = \sqrt{\phi^2 + \left(\frac{2\dot{\phi}}{\omega_e}\right)^2} \qquad (13)$$

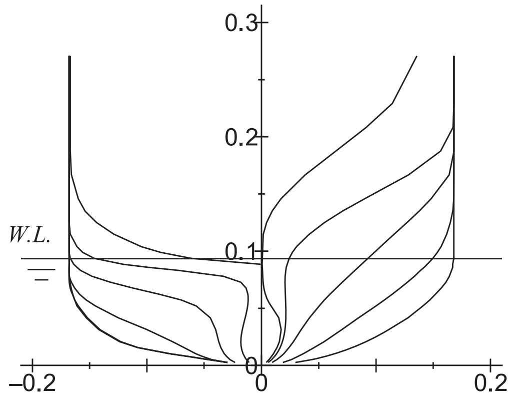


Figure 11 Body plan of the subject ship.

Table 4 Principal particulars of the subject ship.

L_{PP}	192.0 m
B	32.26 m
d	9.0 m
Speed	7knot
Height of gravity: KG	17.0 m
Metacentric height: GM	1.89 m
Natural roll period: T_ϕ	18.42 sec
Displacement: W	27205 ton
Breadth of bilge-keels	0.7 m
Position of bilge-keels	s.s. 3.34-s.s. 5.59

The simulation is carried out at F_n =0.083 in irregular head waves whose significant wave height is 6.0m for 120 minutes (real time scale). The spectrum of irregular wave is the ITTC spectrum expressed by Eq.(14).

$$S(\omega) = 0.0081 \times \frac{g^2}{\omega^5} \exp\left(\frac{-3.11}{H_{1/3}^2 \times \omega^4} \right) \quad (14)$$

The making irregular waves is same and roll motions in time histories are compared between two methods and the effect of the difference of estimation methods on prediction of the parametric rolling.

5.2 Results of Simulations

Figure 12 shows an example of the comparison between the two calculated roll motions in time. The bottom of figure 10 shows the wave elevation at the midship. In this figure, the ratios of mean encounter wave period to the roll natural period ($\overline{T_e} / T_\phi$) at T_1, T_2 and T_3 are also shown. From this figure, it is found that periodic rolling does not occur at T_2. In the result calculated by simplified method using Ikeda's original method, periodic rolling occurs at T_1. On the other hand, in the result calculated by proposed method, periodic rolling does not occur at T_1. In the two results, it is found that periodic rolling occurs at T_3. However, in the result calculated by the simplified method, roll amplitudes become large rapidly.

Therefore, it is confirmed that parametric rolling occurs more easily in simplified method than in the proposed method.

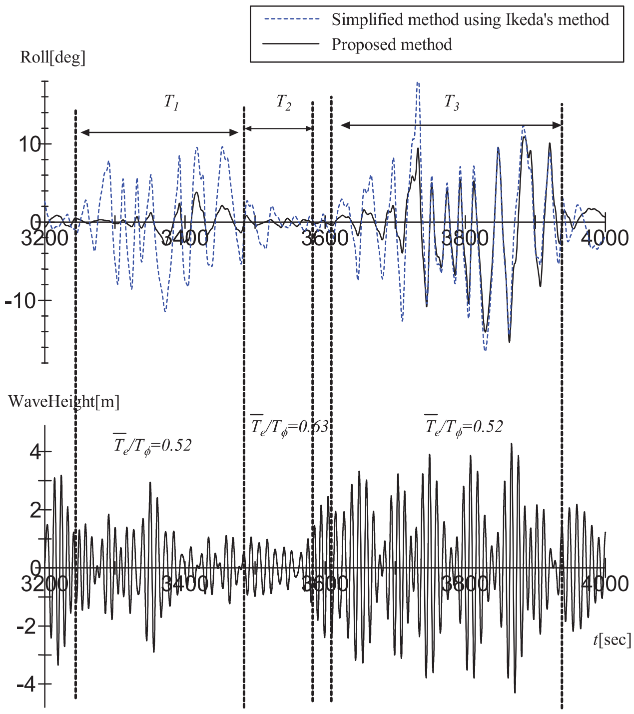


Figure 12 Calculation time history of roll angle and wave height in long crested head irregular waves.

6. CONCLUSIONS

In this study, the memory effects on roll damping is investigated by numerically. The following conclusions are obtained.

In order to take validation data for CFD, forced roll motion test with irregular motion is carried out and the analysis for the test. It is confirm that the proposed analysis can be applied roll damping under irregular motion and roll damping can be calculated accurately by CFD.

Bilge keel component is divide into normal force component and hull surface pressure component by using CFD and the memory effects is investigated. The memory effects depends on Kc number in previous swing and in present swing. Moreover, in order to clarify the mechanism of the memory effects, the flow filed around hull is investigated numerically. The relative fluid velocity in front of bilge keels is increased by the vortexes developed by the previous swing. If Kc number of previous swing is larger, the vortexes developed by previous swing are larger. The moment due to the bilge keel is increased by increase of the relative velocity of the fluid in front of bilge keel.

The estimation method considering the memory effects is proposed. The result estimated by the proposed method is compared with the result calculated by CFD and measured in forced irregular motion test and roll damping can be estimated in time domain by using the method considering the memory effects.

The proposed estimation method is applied for a time domain simulation of parametric rolling in irregular head waves. It is confirmed that parametric rolling occurs more easily in previous method than in the proposed method.

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