# Some Topics for Estimation of Bilge-keel Component of Roll Damping

Toru Katayama, Yuuki Yoshioka, Takahiro Kakinoki, and Yoshiho Ikeda
Graduate school of Engineering, Osaka Prefecture University

## ABSTRACT

In this paper, two topics of roll damping estimation problems are introduced. In these topics, bilge-keel component of roll damping is focused, because the component is generally most part of viscous roll damping. First topic is the bilge-keel component of roll damping under shallow draft and large amplitude roll motion, and a prediction model of the draft effects for Ikeda's prediction method is proposed. Second topic is the bilge-keel component of roll damping under transitional rolling, and a prediction method of roll damping for transitional rolling is proposed.

## KEYWORDS

bilge-keel component, parametric rolling, relative draft, low Keulegan-Carpenter number, drag coefficient, transitional motion

## INTRODUCTION

In order to guarantee the safety of vessels, it is very important to understand the characteristics of roll motion and to estimate roll motion adequately. However, it is very complicated to calculate it because of difficulty of roll damping prediction due to significant viscous effects depending on vortex shedding.

It is well known that there is a prediction method of roll damping proposed by Ikeda et al. (1976)(1977)(1978). However, some estimation problems are indicated in the previous studies (Tanaka et al., (1981)(1982), (Ikeda et al.,(1994), Hashimoto et al.,(2008)(2009)) .

In this paper, two topics of roll damping estimation problems are introduced and bilge-keel component of roll damping is focused mainly, because the component is generally the largest part of total roll damping. In the first topics, the effects of shallow draft are investigated. A forced rolling test is carried out. And a simplified prediction method of the effects is proposed. In the second topics, the effects of transitional motion are investigated. First, under transitional motion, the characteristic of drag coefficient of flat plate in the region of low *Kc* number is experimentally measured. Second, using the forced oscillation device, the characteristic of drag coefficient of flat plate under transitional condition in periodic motion is measured. Finally, based on the results of these experiments, a prediction method based on Ikeda's method is proposed.

## EFFECTS OF SHALLOW DRAFT

### *Forced Rolling Test*

In the previous study by Tanaka et al. (1981), it is pointed out that bilge-keel component decreases when the draft is shallow. However, no formulation is proposed. Then, in this study, a forced rolling test is carried out by using two-dimensional model, and the characteristics of the effects of shallow draft on bilge-keel component is investigated to propose an empirical formula.

Table 1 shows the principal particulars of the model with bilge keel. Fig. 1 shows some parameters for explaining experimental conditions. The measurements at systematically changed roll amplitudes, roll periods, drafts and height of roll axis (the center of rolling) are carried out. Bilge-keel component is obtained from subtraction measured data of hull without bilge keel from measured data of hull with bilge keel at the same condition.

Table 1 Principle particulars of two-dimensional model.

| | |
|---|---|
| length: $L$ | 0.80m |
| breadth: $B$ | 0.237m |
| depth: $d$ | 0.14465m |
| block coefficient: $C_B$ | 0.8m |
| bilge radius | 0.035m |
| lenght × breadth | 0.01m × 0.80m |

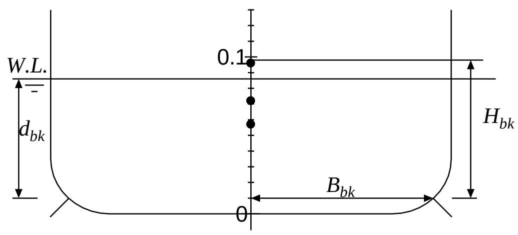


Fig. 1: Cross section of two-dimensional model.

***Empirical Formula***

Figs. 2-4 show the ratio of the predicted results by the measured ones. Horizontal axis shows $d_{bk}$ / $B_{bk}$. Each figure shows the results of different $H_{bk}$ / $B_{bk}$. Where $d_{bk}$, $B_{bk}$ and $H_{bk}$ are shown in Fig.1. Measured results are indicated by different marks for different roll amplitude. The maximum roll amplitudes is different for each height of roll axis and they are 17.71, 18.57, 21.0 degrees respectively.

Fig. 2 shows that the ratio increases linearly with increase of draft. For different roll amplitudes, the tendency is almost same quantitatively. Fig. 3 shows that the ratio is almost same for different roll amplitudes. And the ratio increases linearly and its inclination is higher than Fig. 2. Fig. 4 shows that the similar tendency as Fig. 2. And its inclination is the highest of all. If draft is deep enough, the estimation results can be agree with the measured results. It means that the ratio does not exceed 1.0 with increase of draft. Moreover, above-mentioned characteristics are not almost affected by roll period.

A fitting curve is obtained from the measured data. Correction factor's formula (1) is expressed as following equation.

$$
\begin{aligned}
C_{bk} = & \left(3.615\frac{H_{bk}}{B_{bk}} - 1.227\right)\frac{d_{bk}}{B_{bk}} \\
& + \left\{3.29\left(\frac{H_{bk}}{B_{bk}}\right)^2 - 5.35\frac{H_{bk}}{B_{bk}} + 1.98\right\}\phi_a^2 \\
& + \left\{2.48\left(\frac{H_{bk}}{B_{bk}}\right)^2 + 1.90\frac{H_{bk}}{B_{bk}} - 11.6\right\}\phi_a \quad (1) \\
& + \left\{2.77\left(\frac{H_{bk}}{B_{bk}}\right)^2 - 3.27\frac{H_{bk}}{B_{bk}} + 1.14\right\} \\
& \leq 1.0
\end{aligned}
$$

where $\phi_a$ is in radian. Bilge-keel component is obtained by multiplying correction factor by bilge-keel component of Ikeda's roll damping prediction method.

***Calculated Results***

For a post panamax container ship (Hashimoto et al.,(2008)(2009)), roll damping is calculated by Ikeda's method with the correction factor. When parametric rolling occurs at high wave height in head waves, large relative draft change is caused. In the roll damping calculation, the relative draft of each cross section at the moment, where roll is upright, is used. Fig. 5 shows the calculated results. Total roll damping decreases 6% at roll amplitude $\phi_a$ = 8.59deg, 11% at $\phi_a$ = 14.38deg, and 19% at $\phi_a$ = 20 deg, for the results without considering the relative draft change. Shallow draft due to draft change in waves affects on bilge-keel component significantly.

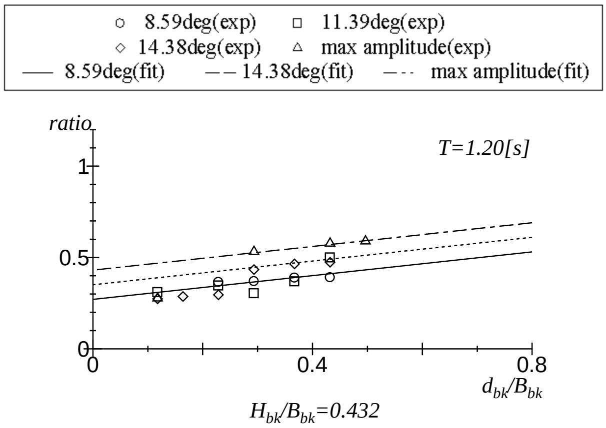


Fig. 2: Ratio of experiment of bilge-keel damping component to prediction at height of roll axis $KG$=57mm.

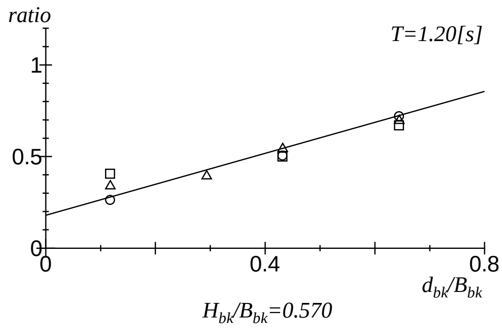


Fig. 3: Ratio of experiment of bilge-keel damping component to prediction at height of roll axis $KG$=72mm.

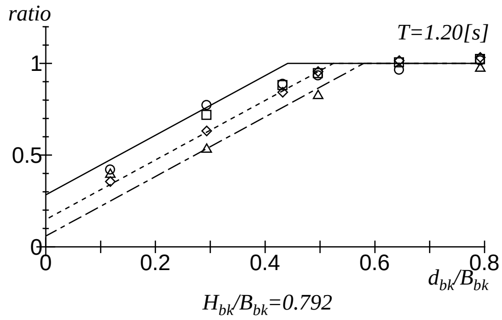


Fig. 4: Ratio of experiment of bilge-keel damping component to prediction at height of roll axis $KG$=96mm.

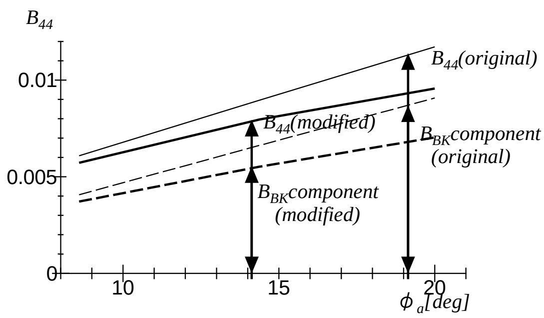


Fig. 5: Prediction result of roll damping including relative draft effects.

## EFFECTS OF TRANSITIONAL AND NON-PERIODIC ROLLING

### *Drag Coefficient in Uniform Flow*

First, drag coefficient of a flat plate, which is assumed as bilge keels, in uniform flow is measured. A strut and a flat plate are fixed by a load cell (shown in Fig. 6), and it is towed at constant forward speed. Towing speeds are from $U$ = 0.1 to 1.0m/s at 0.1 m/s space. Drag force acting on a flat plate $D$ is obtained from deducting measured drag without the flat plate. Drag coefficient is calculated with the following equation.

$$C_D = \frac{D}{0.5\rho SU^2} \tag{2}$$

where $D$, $\rho$, $S$ and $U$ denote drag force, density of fluid, area of flat plate and towing speed. In order to avoid low $Kc$ number effects, measured data in the region $Kc$ > 100 are used in the analysis of drag force. $Kc$ number is expressed as follows,

$$Kc = \frac{2\pi\ x}{D_P} \tag{3}$$

where $x$ and $D_P$ denote forward distance and height of a flat plate shown in Fig. 6 ($L_P/D_P$ = 11).

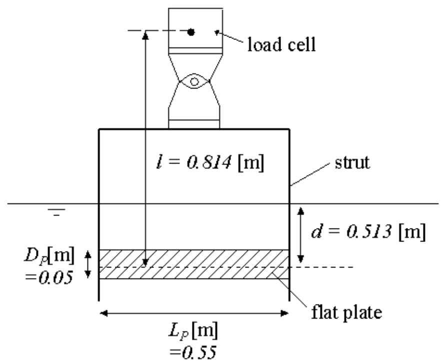


Fig. 6: Schematic view of the experimental device.

Fig. 7 shows the results. Drag coefficient of a flat plate ($L_P \gg D_P$) measured by Hoerner (1993) is also shown in Fig. 7. In order to remove low Reynolds number effects on drag force, drag force of a tapered flat plate is also measured. From this figure, it is confirmed that drag coefficients of a tapered flat plate is constant for change in forward speed, even if it is lower than Hoerner's results. In this study, a tapered flat plate is used.

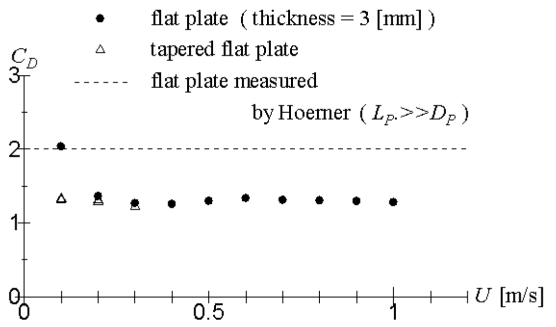


Fig. 7: Drag coefficients of flat plates in uniform flow.

***Drag Coefficient in Oscillatory Flow***

It is known that drag coefficients on oscillating flat plate at low $Kc$ number ($Kc$ < 10) is significantly changed by a slight change of $Kc$ number (Tanaka et al.,(1980), Kudo et al.,(1980)). $Kc$ number of oscillating flat plate is expressed as follows,

$$Kc = \frac{2\pi\ y_A}{D_P} \tag{4}$$

where $y_A$ is amplitude of oscillation. However, the experimental results at low $Kc$ number ($Kc$ < 3) is not found because of difficulty of measurement. Then, drag force of a flat plate at low $Kc$ number is carefully measured.

The experimental device shown in Fig. 6 is oscillated and hydrodynamic force and forced motion are measured. Drag force, which is proportional to motion velocity, is obtained from these data. Drag coefficient is calculated with the following equation.

$$C_{Dperi} = \frac{F_P}{0.5\rho S(y_A\ \omega)^2} \tag{5}$$

where, $\omega$ is circular frequency of forced oscillation, and $F_P$ is drag force acting on a flat plate. $F_P$ is obtained from deducting drag force without flat plate.

Fig. 8 shows the results. Drag coefficient is about 20 at $Kc$ = 0.5, and decreases with increase of $Kc$ number, and becomes the value in uniform flow at about $Kc$=250. As the results, a fitting curve of drag coefficient Eq. (6) is determined, and it is shown in Fig.8 as a dotted line.

$$\frac{C_{Dperi}}{C_{D0}} = (20.0e^{-1.23Kc} + 2.86e^{-0.174Kc} + 1) \times \left(0.908 + \frac{1.2}{1+1.01^{Kc}}\right) \tag{6}$$
$$(0 < Kc \le 250)$$

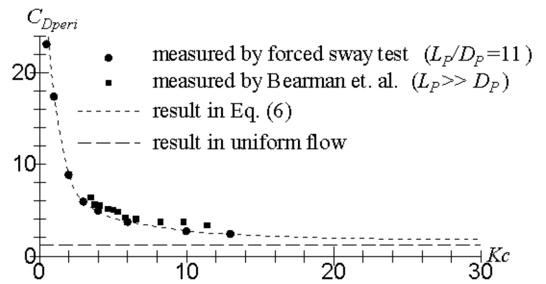


Fig. 8: Drag coefficients of flat plates in oscillatory flow.

***Drag Coefficient under One Direction Accelerating***

Experimental device shown in Fig. 5 is towed horizontally by a method of free fall of a weight shown in Fig. 9. In order to obtain drag force acting on a flat plate, two measurements with and without flat plate are carried out, and these data are analysed by deducting inertia components, respectively. Drag coefficients in the both cases are obtained and fitting curve (7) and (8) are determined respectively.

$$\frac{C_{D(S+P)acc}}{C_{D0}} = \begin{pmatrix} 4.76e^{-0.279Kc} \\ +20.6e^{-2.06Kc} + 1.168 \end{pmatrix} \times \left(0.908 + \frac{1.2}{1+1.01^{Kc}}\right) \quad (7)$$

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

$$\frac{C_{DSacc}}{C_{D0}} = (17.0e^{-1.89Kc} + 2.72e^{-0.50Kc} + 0.168) \times \left(0.908 + \frac{1.2}{1+1.01^{Kc}}\right) \quad (8)$$

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

where $Kc$ number obtained from Eq. (3). From Eqs. (7) and (8), drag coefficient of a flat plate at one direction accelerating is calculated with the following equation and the results are shown in Fig. 10.

$$\frac{C_{Dacc}}{C_{D0}} = \frac{C_{D(S+P)acc}}{C_{D0}} - \frac{C_{DSacc}}{C_{D0}} \quad (9)$$

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

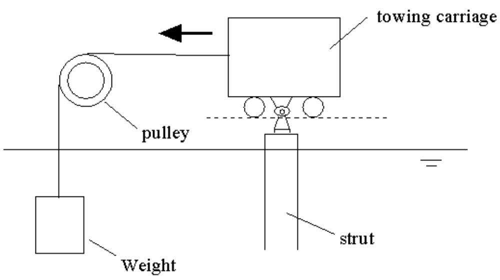


Fig. 9: Schematic view of experiment towed by free fall of a weight.

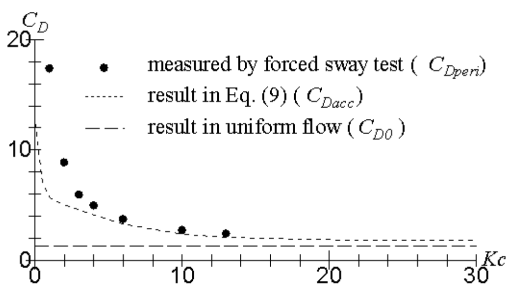


Fig. 10: Comparison of drag coefficients of a flat plate by forced sway test and by direction accelerating test.

***Drag Coefficient under Transitional Condition in Oscillatory Flow***

In this section, using the forced oscillating device, measurements of forces acting on a flat plate in each swing from rest is carried out.

Figs. 11 and 12 show the results. Drag coefficient is gradually increasing from the first swing to the fourth swing. After the fourth swing, drag coefficient becomes constant. From the results, the formula of drag coefficients including the number of swing from rest is decided as the following equation.

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

where $n$ is the number of swing ( $n$ = 1, 2, 3 and 4), and $Kc$ number obtained from Eq. (4).

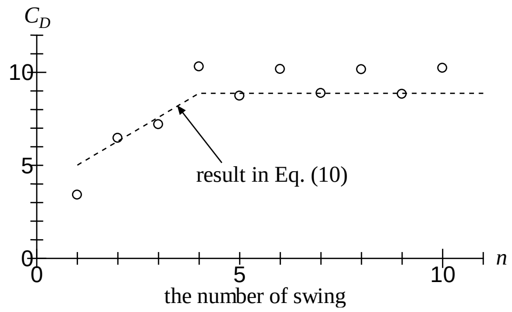


Fig. 11: Drag coefficient of flat plate vs. the number of swing at $Kc$ = 2.0.

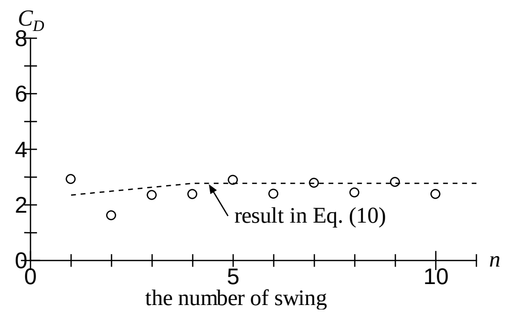


Fig. 12: Drag coefficient of flat plate vs. the number of swing at $Kc$=10.0

## CONCLUSION

In this paper, two topics of roll damping estimation problems are introduced.

In the first topics, the effects of shallow draft are investigated. Bilge-keel component of roll damping by Ikeda's prediction method is overestimated for lower roll axis and shallow draft. Based on the measured results, an empirical formula to the bilge-keel component is proposed.

In the second topics, the effects of transitional motion are investigated. In the region at *Kc* <250, drag coefficient of a flat plate under one direction accelerating is larger than that in uniform flow and smaller than that in steady oscillatory flow. Moreover, in transitional condition under forced oscillation, the drag coefficients from 1st swing to 3rd swing are smaller than that in steady oscillatory flow. These facts may indicate that the characteristics of drag coefficient affect transitional and non-periodic rolling. Based on the results, an empirical formula to the bilge-keel component by Ikeda's prediction method is presented.

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