Numerical Estimation and Validation of Shallow Draft Effect on Roll Damping

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Abstract: It is difficult to calculate roll damping of ships theoretically due to the effects of viscosity. Therefore, Computational Fluid Dynamics (CFD) has become a powerful tool for the prediction of roll damping recently. For ship roll damping, the bilge keel component accounts for the greatest part of the total roll damping. However, bilge keels are most effective when they are fully submerged and the contribution of bilge keel to the total roll damping decrease when the draft is shallow. In this paper, the flow around a forced rolling two dimensional body is analyzed to see the shallow draft effect on roll damping by using CFD code Fluent. In order to validate the CFD calculations, the results are compared with both the forced roll test results that were carried out by Katayama et al. (2010) [1] and Ikeda's estimation method. This study seeks to assess if the CFD code can correctly predict roll damping coefficients of a rolling vessel.

Key words: Roll damping, bilge keel, shallow draft, computational fluid dynamics

1. Introduction

The roll response of a ship is an important consideration in its design. Roll motion limits ship operability, affects crew performance and ship habitability and affects dynamic stability and it can lead to ship capsize. Roll motion is one of the most critical responses of a ship in waves. The roll motion of a ship can be determined by analyzing various kinds of moments acting on the ship, virtual and actual mass moments of inertia, roll damping moment, restoring moment, wave excitation and other moments caused by other modes of ship motion. Among them, the roll damping moment has been considered to be the most important term that should be correctly predicted.

Damping of roll motion strongly depends on viscous effects so that it is really significant to calculate damping forces correctly. Prediction of roll damping by using potential flow theories is hard due to viscous effects. Therefore, Computational fluid dynamics (CFD) have become an important tool for the estimation of roll damping. Many researchers have recently studied about prediction and validation of roll damping by using CFD. Jaouen et al. (2011) verified and validated MARIN's URANS code ReFRESCO for roll damping of 2D hull sections by comparing with the damping coefficients measured by Ikeda et al. (1978) [2]. Bonfiglio et al. (2011) by using the developed CFD code base on the open source libraries of OpenFOAM and Henning (2011) by using FLUENT evaluated the hydrodynamic damping and added mass coefficients of 2D ship-like hull sections in the case of forced oscillations [3][4]. Bangun et al. (2010) calculated the hydrodynamic damping and added mass coefficients of a 2-D rectangular sections with bilge keels and compared the predictions with measured results by Yago et al. (2008) [5]. Paap (2005) investigated verification of CFD calculations with forced roll test results for a circular cylinder with various types of bilge keels and a free surface [6]. Bassler (2013) analyses the hydrodynamics of large amplitude ship roll motion as components of the added inertia and damping based on the results of forced roll test and CFD. It is shown that the effects of the hull geometry, bilge keel geometry, deck edge and the free surface all affect the hydrodynamic components during large amplitude roll motions [7].

Large amplitude roll motions have the same effect on bilge keel with shallow draft. Bilge keel come closer to the free surface in both case.

Bilge keels have been used on ships to increase damping and reduce the roll motion. Bilge keel component is the biggest part of total roll damping so that it should be calculated accurately. There are some factors that affect the contribution of bilge keel to total roll damping. One of these factors is shallow draft effect. In the previous study by Tanaka et al. (1981), it is pointed out that bilge-keel component decreases when the draft is shallow [8].

In this study, the effect of shallow draft on roll damping is investigated by using a commercial CFD code and the CFD results validated with the experiment results of Katayama et al. (2010). The simulations are carried out for three different center of gravity (KG) and several draft values for each KG. Also the roll damping coefficients are calculated by using Ikeda's estimation method and it is observed that Ikeda's method does not consider shallow draft effect.

2. Theoretical Formulation

2.1 Definitions

The roll motion of the 2D hull section is forced around the z axis, perpendicular to the hull section. The description of the symbols used in this study is given in Table 1.

Table 1 Nomenclature

B	Breadth of the hull (m)
d	Draft of the hull (m)
g	Gravitational acceleration (m^2/s)
T	Roll period (s)
ρ	Density of water (kg/m^3)
ϕ_0	Roll Amplitude (rad)
ω	Roll angular frequency (rad/s)
$B_{\phi\phi}$	Damping coefficient (-)

2.2 Roll Damping Analysis

As many numerical simulations that indicate a body motion, a gradual start of the motion is needed in order to avoid strong transient flows at the earlier time-steps of the calculation. It can take considerable number iterations to get rid of those initial peaks. The final motion of the hull will be a pure sine:

$$\emptyset(\mathrm{t}) = \emptyset_0 \sin \omega t \qquad (2)$$

A start-up function is defined that slowly increases the amplitude from zero to the final value for the first 4 periods, the frequency will be constant during the whole computation. The start-up function f(t) is defined by

$$\mathrm{f(t)} = \begin{cases} \frac{1}{2} sin\left(\frac{1}{4}.\frac{\pi}{T}.t - \frac{1}{2}\pi\right) + \frac{1}{2}, for\ t < 4T \\ 1 \qquad , for\ t > 4T \end{cases} \qquad (3)$$

The function that indicates the prescribed motion, f(t), is written with C^{++} programming language and fluent calls this function as an user defined function (UDF). UDF gives the rotational velocity as function of time and Fluent reads these values to force the body to harmonic oscillation, see in Fig.1.

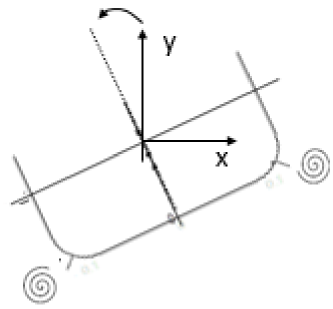

Fig. 1 – Description of the forced roll model

The roll angle $\emptyset(\mathrm{t})$ is now defined by

$$\emptyset(\mathrm{t}) = \mathrm{f(t)}\emptyset_0 \sin \omega t \qquad (4)$$

The uncoupled equation of motion to describe the forced roll motion may be written as

$$a_{\emptyset\emptyset}\emptyset'' + B(\emptyset, \emptyset') + C(\emptyset) = M_E(t) \quad (5)$$

where $a_{\emptyset\emptyset}$ is the added mass for roll motion, $B(\emptyset, \emptyset')$ is the damping moment, $C(\emptyset)$ is the restoring moment and $M_E(t)$ is the time history of the computed moments and it is fitted with

$$M_E(t) = M_0 sin(\omega t + \varepsilon) \quad (6)$$

by applying the Fourier analysis, M_0 is the amplitude of the roll moment and ε indicates the phase angle between the prescribed roll angle and the roll moment. Time history of the computed moments are acquired via experiments and CFD simulations, then M_0 and ε can be calculated with Fourier transformation between time history of moments and roll angle. The final step is calculation of roll damping coefficient which can be expressed as follow:

$$B_{\emptyset\emptyset} = \frac{M_0 sin(\varepsilon)}{\emptyset_0 \omega} \quad (7)$$

To be able to compare these results with other research projects damping terms will be presented dimensionless. Dimension analyses give the following dimensionless representations of the damping coefficient.

$$\hat{B} = \frac{B}{\rho \nabla B_{WL}^2} \sqrt{\frac{B_{WL}}{2g}} \quad (1)$$

3. Forced Roll Experiments

In this study, the results of forced rolling test that is carried out by using two-dimensional model to observe the effects of shallow draft on roll damping is used to validate the CFD results.

Table 2 shows the principal particulars of the model with bilge keel. Fig. 2 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 2 Principle particulars of two-dimensional model

length: L	0.80m
breadth: B	0.237m
depth: D	0.14465m
block coefficient: C_B	0.8
bilge radius	0.035m
length X breadth	0.01m x 0.80m

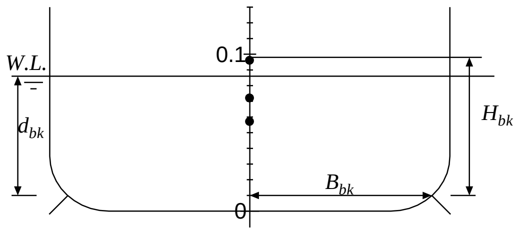

Fig. 2 – Cross section of two-dimensional model

4. Numerical Settings

CFD package Fluent is used for calculations, based on the specifications, should be able to perform 2D computations on a rolling midsection of a ship. It can include any kind of prescribed roll motion, radiation of waves, far field wave damping, grid refinement around the bilge keel, turbulence modeling and it can record the forces and moments on the body.

Fluent, viscous flow code, can be used for unsteady analyses. It is used to simulate incompressible flow around the rolling 2D section and it uses the finite-volume approach. This is based on control volume technique which all transport equations (mass and momentum equations) are solved numerically. The finite volume type solution method also calculates the equations for turbulence model and volume fraction of water-air. In this study, the segregated iterative solution method which is based on SIMPLE algorithm is preferred instead of coupled solution methods (Fluent Handbook). First order implicit scheme is used for time integration. To calculate the free surface effect a volume of fluid method (VOF) is applied. The k-ε-standard turbulence is used for all calculations.

The integral value of the energy dissipation during the forced roll motion can be calculated based on the flow simulation results. In the past, two groups of RANSE-simulation methods for estimating roll damping have been applied: one which uses a fixed roll axis as well as a sliding interface, and one which uses grid motion or deformation technique to simulate the free motion without an interface [9]. In this study 2D midsection is fixed to x axis and cylindrical mesh zone rotated around the roll axis. There is an interface between stationary zone and rigid moving zone which avoids cell-deforming issue, see Fig. 3.

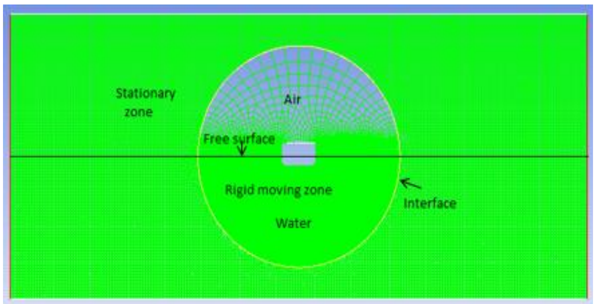

Fig. 3 – The geometry and computational mesh

Both experiment and CFD simulations are carried out for variable KG and draft values, also Ikeda's estimation method is used for calculations, see in Table 3.

Table 3 Principle particulars of experiments and simulations

KG	T	ϕ	d	CFD	Exp.	Ikeda
0.096	1.2	8.59	0.095	O	O	O
0.096	1.2	8.59	0.08	O	O	O
0.096	1.2	8.59	0.072	O	X	O
0.096	1.2	8.59	0.06	O	O	O
0.096	1.2	8.59	0.05	O	O	O
0.096	1.2	8.59	0.042	O	O	O
0.096	1.2	8.59	0.035	O	X	O
0.096	1.2	8.59	0.025	O	X	O
0.072	1.2	8.59	0.095	O	X	O
0.072	1.2	8.59	0.08	O	O	O
0.072	1.2	8.59	0.072	O	X	O
0.072	1.2	8.59	0.06	O	X	O
0.072	1.2	8.59	0.05	O	O	O
0.072	1.2	8.59	0.042	O	O	O
0.072	1.2	8.59	0.035	O	X	O
0.072	1.2	8.59	0.03	O	X	O
0.072	1.2	8.59	0.025	O	X	O
0.072	1.2	8.59	0.023	O	O	O
0.057	1.2	8.59	0.057	O	O	O
0.057	1.2	8.59	0.05	O	O	O
0.057	1.2	8.59	0.042	O	O	O
0.057	1.2	8.59	0.035	O	O	O
0.057	1.2	8.59	0.025	O	X	O
0.057	1.2	8.59	0.023	O	X	O

(O = Done, X = Not done)

5. Calculations and Validations

CFD computations have been carried out for 2D midsection for different draft values and results have been validated with both experiment results and Ikeda's estimation method.

Fig. 4 shows the harmonic oscillation of the body that slowly increases the amplitude from zero to the final value for the first 4 periods. Moments on hull and bilge keels have been calculated by using CFD for this movement of body. It is observed that when the draft decreases, total roll damping decreases because free surface effect increases for shallow draft. Fig. 5 shows the time history of calculated moment on bilge keels. It is observed that when the draft becomes shallow. The moment on bilge keels decrease.

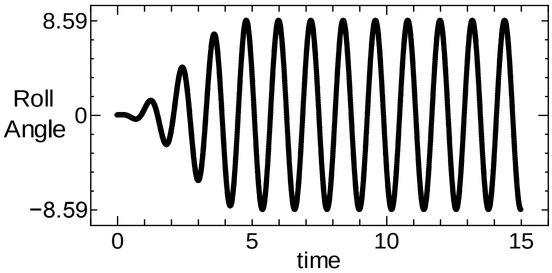

Fig. 4 – Time history of roll motion

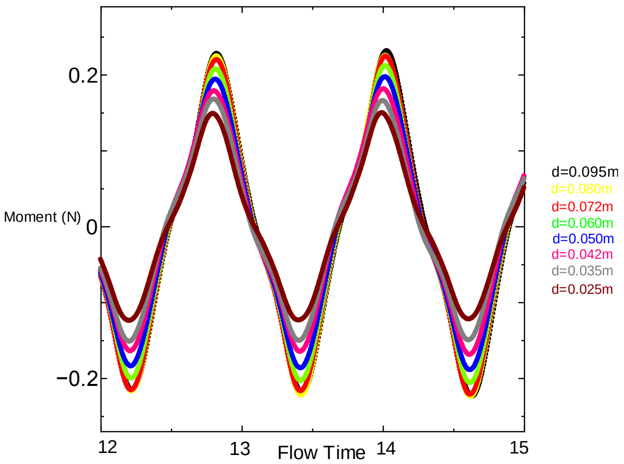

Fig. 5 – Time history of bilge-keel moment for different drafts

Comparison between CFD results and experiments and also Ikeda's method for different KG values are shown in Fig, 6-7 and 8. As it is shown in figures, CFD results show good agreement with experiment results. Non dimensional roll damping coefficients are shown for each draft values in figures. When the draft decreases, the difference between CFD results and Ikeda's estimation method increases, especially for Fig. 6 and 7. The reason of this difference is that Ikeda's method does not consider shallow draft effect.

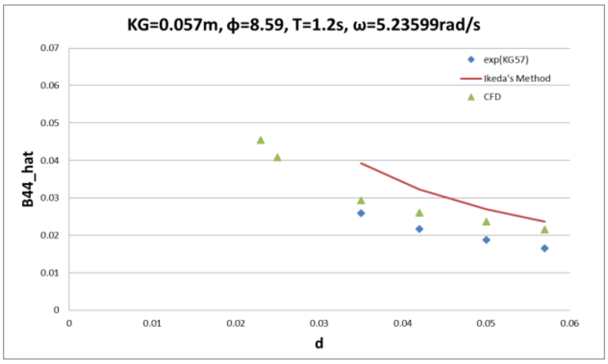

Fig.6 – Dimensionless roll damping coefficient (KG=0.057)

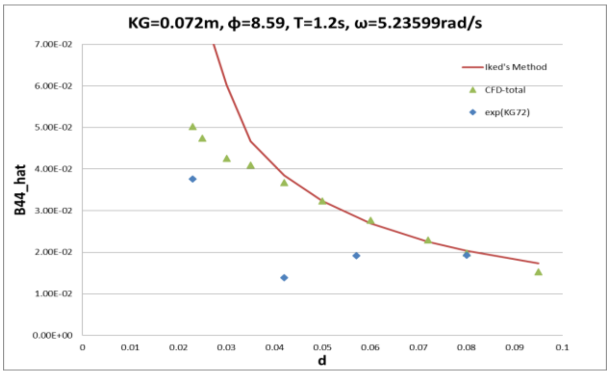

Fig. 7 – Dimensionless roll damping coefficient (KG=0.072)

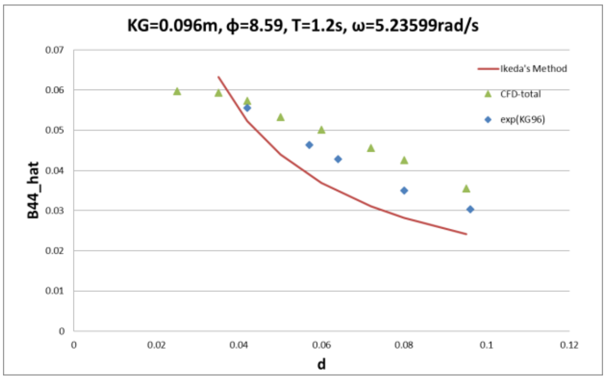

Fig. 8 – Dimensionless roll damping coefficient (KG=0.096)

6. Conclusions

In this paper CFD code Fluent has been used for the estimation of effect of shallow draft on roll-damping. The unsteady flow around a forced rolling 2D midsection with bilge keels is computed. Extensive numerical sensitivity studies are carried out and the viscous-damping coefficient is computed for various draft values. The numerical results of Fluent are compared to experimental values and Ikeda's estimation method. It is found out that CFD can be used for accurate prediction of roll damping coefficient.

Calculations for shallow draft show that the roll damping moment decreases when the draft becomes shallow. It is because of that the bilge keel comes closer to the free surface when the ship rolled. This free surface effect decrease the total roll damping coefficient. Ikeda's estimation method does not consider this effect. However, CFD calculates this effect and results show good agreement with model tests.

There are a lot of options that directly affect the CFD results, especially mesh quality. In this study, medium mesh quality is used for calculations due to computational time. As a future work calculations will be carried out for a high quality mesh to have better results.

CFD is a practical and fast way to estimate ship roll damping but without validation CFD results are not essential. Therefore, as a first step of estimation of roll damping, experiment results needs to be provided to validate CFD results. After that we can develop a more accurate model to describe and predict roll motions in severe wave environments.

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