Effect of Vortex Shedding and Free Surface Interaction on Roll Damping Due to Large Amplitude Roll Motion

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ABSTRACT

Among all ship motions, roll motion is the most important response of a ship to calculate, because large amplitude roll motions may lead to capsize, cargo shift, loss of deck cargo and other undesirable consequences. However, the accuracy of the calculated results by using linear potential flow theory, such as strip method, for roll motion lag behind the other degrees of freedom. This is because; viscosity plays an important role in roll, especially near resonance. Computational methods based on potential flow theory do not capture these viscous effects such as effective creation of vortices in the boundary layer, flow separation at appendages and vortex shedding. The vortex shedding is the main physical phenomena involved in the viscous damping of the roll motion and it affects the flow velocity around the body that may lead to pressure increase or decrease. In this study, roll damping of a forced rolling hull with bilge keel for large amplitude roll motion with free surface is calculated by using Unsteady Reynolds-averaged Navier–Stokes (URANS) solver. The generated vorticity contours around the hull and bilge keel is observed and it is showed that vortices shed from the bilge keel are proportional to amplitude of roll motion. In the case of large roll amplitude motion, the vortex shedding from the bilge keel interacts with free surface and this interaction leads to decrease on the roll damping. The results are compared with Ikeda's estimation method.

Keywords:*Roll damping, bilge keel, large amplitude, URANS, Ikeda's method, vortex shedding, free surface*

1. INTRODUCTION

Roll motion of ships is an important issue in safety and habitability of ships becauseit limits ship operability, affects crew performance and dynamic stability and it can lead to ship capsize. Therefore, roll motion is the most critical response of a ship in waves. For a better evaluation of roll motion, the roll damping should be calculated correctly which has a nonlinear character for large amplitudes roll motion in a seaway. The roll damping depends on not only radiated waves but also viscous effects. The roll damping from radiated waves can be computed by using linear potential theory but the viscous damping cannot be computed. The bilge keel provides a vortex generation around the body which increases the viscous effect contribution of total damping. The generated vortices by bilge keels mitigate the roll motion by transferring energy from the ship to the surrounding fluid. Many researchers have studied the viscous roll damping prediction, e.g. Ikeda et al. [1-3], Himeno [4], and they offered some empirical methods for roll damping estimation based on model tests. Since the 1970s, Ikeda's estimation method based on the component analysis model has been used to predict roll damping. In this method, the equivalent linear damping coefficient in the roll equation, B_e, is divided into five damping components as friction, eddy, wave, lift and bilge keel. Most modern potential flow ship motions simulation tools use this method to predict the roll motion. However, Ikeda's method is typically only valid for smaller roll motions which were only performed for roll amplitudes up to 10 degrees, and later extended to 15 degrees, where linearization is applicable. Although these limitations were acknowledged in the development of the models, the method has a few weaknesses and overestimates the results at larger roll amplitudes. The developments in CFD and experimental flow measurements have been beneficial to study these weaknesses and limitations.

Since the roll damping is dominated by vorticity, CFD based Unsteady RANS solvers have the potential to produce superior roll damping predictions compared to existing methods since the effects due to viscosity, creation of vorticity in the boundary layer, vortex shedding, and turbulence are naturally included in the calculations. The advantages, such as low cost and fast computational time compared to experiments, lead researchers to use CFD for the estimation of roll damping.

Yeung &Ananthakrishnan [5] were perhaps the first to attempt to capture the flow attributes through the application of URANS techniques, and their efforts have set the direction for further studies in this area. URANS-equation methods have been used to study the flow around two-dimensional oscillating cylinders (Korpus&Falzarano, [6]; Yeung, et al., [7]; Sarkar&Vassalos, [8]). Bassler [9] investigated 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 was 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. Avalos, et al. [10] developed a 2D, incompressible Navier-Stokes solver to simulate free roll decay of FPSO with and without bilge keels. The simulations were compared with the experiments carried out by Oliviera and Fernandes [11]. It was observed that the vortex size and hence roll damping depends on the amplitude on roll motion and the width of bilge keel. Van Kampen [12] showed a practical method to evaluate the roll damping and motions of an FPSO with aberrant bilge keels and/or riser balconies in waves by using a commercial CFD code and the numerical results were used to modify traditional Ikeda's method. Irkal, et al., [13] carried out numerical simulations using the RANSE solver FLOW-3D to obtain the best configuration of the bilge keel for use in reducing the roll motion. The velocity and vorticity patterns around the bilge keel obtained from numerical simulations and validated with PIV measurements. Yıldız, et al., [14] showed the shallow draft effect on roll damping by using URANS method and validated the results with experiments. They also showed why Ikedas's estimation method overestimates the roll damping values at shallow draft.

Although there have been many studies on roll damping estimation by using experiments or CFD methods, there is still a critical need for development of methods for predicting large amplitude roll damping of ships with appendages. In this study, the effect of large amplitude roll motion on roll damping is investigated by using a commercial CFD code. Also the roll damping coefficients are calculated by using Ikeda's estimation method. The vorticity generation around the hull is visualized by using numerical solver. The effect of vortex shedding and free surface interaction is investigated at different roll amplitudes. It is observed that the roll damping is decreased when the bilge keel interacts with the free surface. Ikeda's method does not consider the freesurface interaction so that the roll damping results are overestimated at large roll amplitudes.

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 of iterations to get rid of those initial peaks. The final motion of the hull will be a pure sine:

$$\emptyset(\mathrm{t}) = \emptyset_0 \sin \omega t \qquad (1)$$

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

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

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

$$\emptyset(\mathrm{t}) = \mathrm{f(t)}\emptyset_0 \sin \omega t \qquad (3)$$

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

$$(I_{\emptyset\emptyset} + a_{\emptyset\emptyset})\emptyset'' + B(\emptyset, \emptyset') + C(\emptyset) = M_E(t) \quad (4)$$

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 $M_E(t) = M_0 sin(\omega t + \varepsilon)$ (5)

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 is acquired via CFD simulations, then M_0 and ε can be calculated with Fourier analysis between timehistory of moments and roll angle. The final step is calculation of roll damping coefficient which can be expressed as follow:

$$B_{44} = \frac{M_0 sin(\varepsilon)}{\emptyset_0 \omega} \qquad (6)$$

Dimension analyses give the following dimensionless representations of the damping coefficient.

$$\hat{B}_{44} = \frac{B_{44}}{\rho \nabla B_{WL}^2} \sqrt{\frac{B_{WL}}{2g}} \qquad (7)$$

3. IKEDA’S ESTIMATION METHOD

Ship roll damping may be computed using Ikeda’s estimation analysis method. In this method, the equivalent linear damping coefficient in the roll equation, B_{44}, can be obtained using a linear combination of physical components, each as a function of roll amplitude, roll frequency, and forward speed.

The prediction method, which is now called Ikeda’s estimation method, divides the roll damping into the frictional (B_F), the wave (B_W), the eddy (B_E) and the bilge keel (B_{BK}) components at zero forward speed, and at forwardspeed, the lift (B_L) is added. The roll damping coefficient, B_{44}, can be expressed as follows.

$$B_{44} = B_F + B_W + B_E + B_L + B_{BK} \quad (8)$$

Ikeda’s method is developed for conventional cargo ships and it has been improved to apply many kinds of ships. However, Ikeda’s method has problems to calculate roll damping when draft is shallow where the bilge keel comes closer to the sea surface during roll motion.

URANS method is a practical way to check the accuracy of the Ikeda’s estimation method for such cases, and it can help us to develop more accurate models to describe and predict roll motion. The main disadvantage of URANS code at this moment is the results of these computations cannot be taken for granted. Therefore, URANS results have to be validated by comparing with experimental results.

4. NUMERICAL SETTINGS

The turbulent flow with a constant density can be described by a set of non-linear coupled partial differential equations which are derived from conservation of mass and momentum. These equations are known as Reynolds-averaged Navier-Stokes equations and conservation of mass that cannot be solved analytically for turbulent flows;

$$\left(\frac{\partial \overline{u_i}}{\partial t} + \overline{u_j}\frac{\partial \overline{u_i}}{\partial x_j}\right) = -\frac{\partial \bar{p}}{\partial x_i} + \mu\frac{\partial^2 \overline{u_i}}{\partial x_j^2} - \frac{\partial \overline{u_i' u_j'}}{\partial x_j} \qquad (9)$$

$$\frac{\partial u_i}{\partial x_i} = 0 \quad for\ i,j = 1,2,3 \qquad (10)$$

p defines the pressure and u shows the velocities at the each direction where i,j=1,2,3 refer to the x,y,z direction. In the present study, these equations are solved numerically by using a finite volume method based RANS solver for the flow around a forced rolling hull. A hull midsection with bilge keel is used for calculations. Table 1 shows the main dimensions of the selected model. The selected model is forced to sinusoidal roll motion at different roll amplitudes.

Table 1: Principle particulars of the model

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

The selected RANS solver discretizes the transport equations before solving the equations. After the discretization step, the location of the free surface is determined by using the Volume of Fluid (VOF). The computational model has to be defined to start this step. Fig. 1 shows the computational model used in this study. There are two cell zones, the moving fluid zone and the remaining stationary zone. The cylindrical fluid zone is rotated with the hull around the roll axis in order not to disturb the region around the body. There is an interface between stationary zone and rigid moving zone which avoids cell-deforming issue. The hull is surrounded by a circular rotating zone (inner region) and rectangular boundary (outer region). Rectangular boundary is located far enough from the body so that the velocity and pressure field generated by the oscillating body is not affected by the outer boundary. The generated mesh around the bilge keel is refined to visualize the vortices better. Fig. 2 shows the midsection of the model and the generated mesh around the hull and bilge keels.

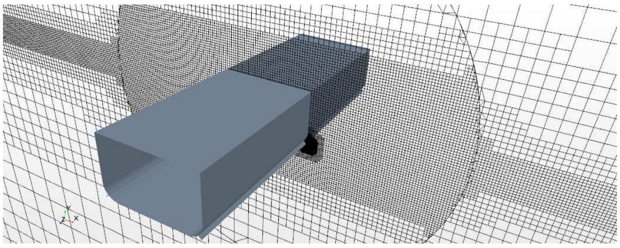

Figure 1: The geometry and computational mesh

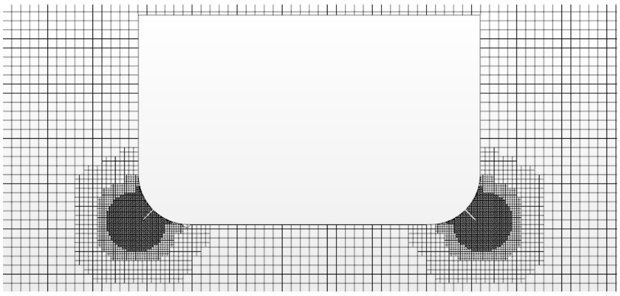

Figure2: The generated mesh around the hull and bilge keels

5. RESULTS AND DISCUSSION

CFD computations have been carried out for the hull at different five roll amplitude values and results have been compared with Ikeda's estimation method. The moments acting on the hull and bilge keels are computed separately when the hull is forced to the roll motion. Fig. 3 and 4 show the total (hull + bilge keel) moments and bilge keel moments at different roll amplitudes. As it is shown on the Fig.3 the total moment increases when the roll amplitude increases. However, the bilge keel moment decreases at the point where the bilge keel interacts with the free surface. This effect cannot be seen on the total moment figure because the bilge keel moment is a small portion of total moment. The effect of free surface interaction can be shown on Fig. 4. The bilge keel moment increases until 20 deg. and it decreases at 27.27 deg. where bilge keels come closer to the free surface.

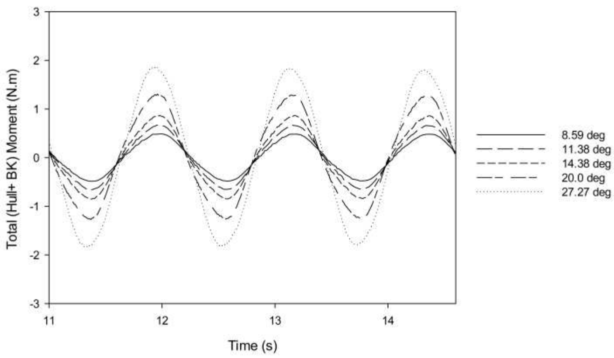

Figure 3: Time history of total (Hull + BK) moment for different roll amplitudes

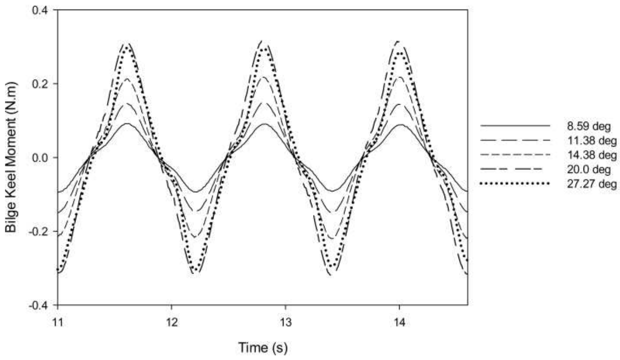

Figure 4: Time history of bilge-keel moment for different roll amplitudes

The roll damping coefficients are calculated numerically by using moments acting on the hull and bilge keels. Fig. 5 shows the numerical results and Ikeda's method results obtained in the present study with bilge keels. The non-dimensional roll damping coefficients of the hull with bilge keels are shown for various roll amplitudes. The agreement between numerical results and Ikeda's method for small to moderate roll amplitudes can be observed. However, Ikeda's assumption overestimates the values when the roll amplitude increases. This is due to free surface effect and vortex shedding from the bilge keels which are not considered in Ikeda's method. The bilge keels interact with the free surface when the roll amplitude increases and this interaction effects the generation of the vorticity around the bilge keels. The generated vortices and vortex shedding affect the force acting on the bilge keels and the bilge keel roll damping.

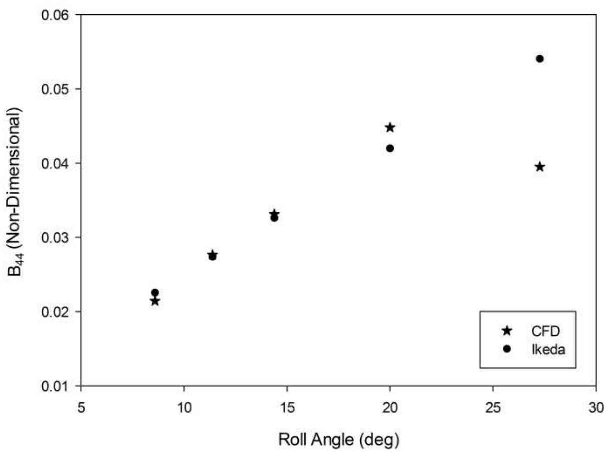

Figure 5: Roll damping coefficients at different roll angles

6. FLOW VISUALIZATION by CFD

The vorticity generation from the bilge keel corresponds to changes in the bilge keel force and the roll damping. The vortex shedding is the main physical phenomena involved in the viscous damping of the roll motion and it affects the flow velocity around the body that may lead to pressure change. To investigate the effect of the roll amplitude on the roll damping, the vorticity evolution near the bilge-keels are simulated and compared for different roll amplitudes. The blue color in the figures denotes negative (clockwise) vorticity, while the red color denotes positive (counter-clockwise) vorticity. And the vorticity (1/s) scale is same for each figure, from -50 to 50. Fig. 6 shows the generated vortices around the hull and bilge keels at 8.59 deg. and 20.0 deg. As it is shown, the size and core of the vortices increase with the increasing roll amplitude. This explains how the roll damping increases when the roll amplitude increases. However, the roll damping decreases when the roll amplitude is 27.27 deg. At this point the bilge keel interacts with free surface as it is mentioned before. The vorticity generations around the hull are compared for different roll amplitudes to investigate the vortex shedding and free surface interaction on roll damping.

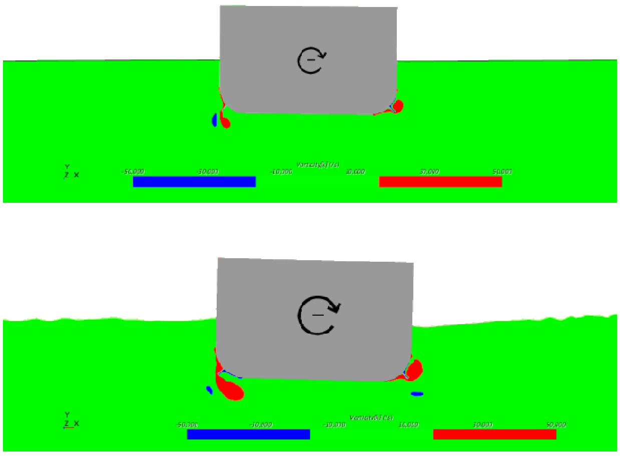

Figure 6: Vorticity contours around the hull at maximum roll speed (top=8.59 deg, bottom=20.0 deg)

Fig. 7 shows the vorticity contours around the bilge keels for 20 deg. roll amplitude, Fig. 8 is for 27.27 deg. The vortices are shown for the half oscillation period for both conditions. As it can be seen in the Fig. 7, the body is at maximum roll speed where the vortices are too strong. The generated positive vortices start to shed while the body is rolling. At the maximum roll amplitude where the roll speed is zero, the positive shed vortices start to dissipate after the hull reaches the maximum roll amplitude.At this point roll direction changes, negativevortex starts to occur from the tip of the bilge keels and rolls up gradually with increasing strength and core size. The previously generated positive vortex interacts with the newly generated positive vortex and dissipates into the surrounding fluid while the body reaches the maximum roll velocity. The more intense negative vortex is dragging the positive vortex that is less intense, as it is also shown in Avalos et al [10]. As the body rolls to maximum amplitude, the newly generated negative vortex starts to shed from the bilge keel. When the hull reverses its direction, a new positive vortex will start to occur from the tip of the bilge keels. As the roll motion progresses in time, a new vortices will be generated every half of an oscillation and a new cycle of vortex shedding will start.

Fig. 8 shows the vorticity contours around the bilge keels for 27.27 deg. where the bilge keel interacts with the free surface. As it is shown on the figure, the vortices start to shed earlier. After the hull reaches at the maximum roll amplitude, the negative vortex starts to occur as same as 20 deg. However, the free surface affects the generation of vortices and the vortex starts to shed just after the maximum roll amplitude. This interaction with the free surface does not allow the vortices to grow up. It can be seen that the size of the vortex for 20.0 deg. condition is bigger than the large roll amplitude condition. This explains the decrease of bilge keel moment at large roll amplitude. The damping from the bilge keel decreases when the vortices become weaker.

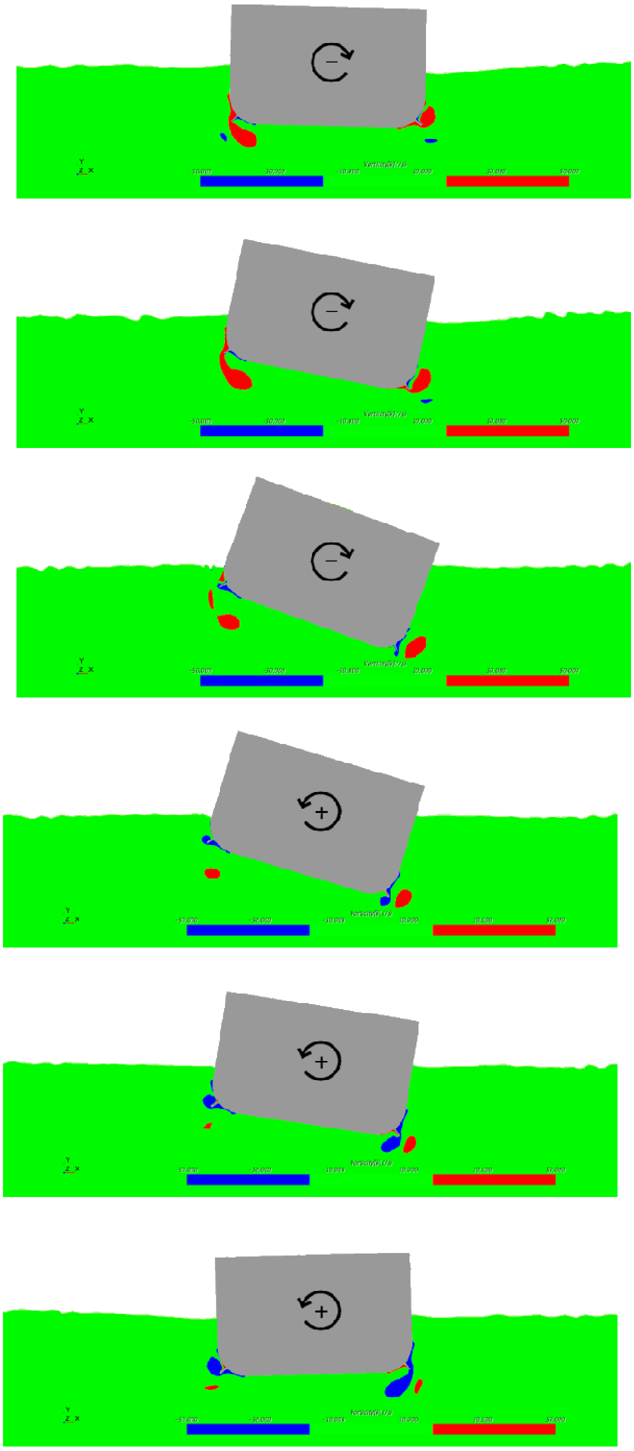

Figure 7: Vorticity contours and vortex shedding around the hull for 20.0 deg. roll amplitude

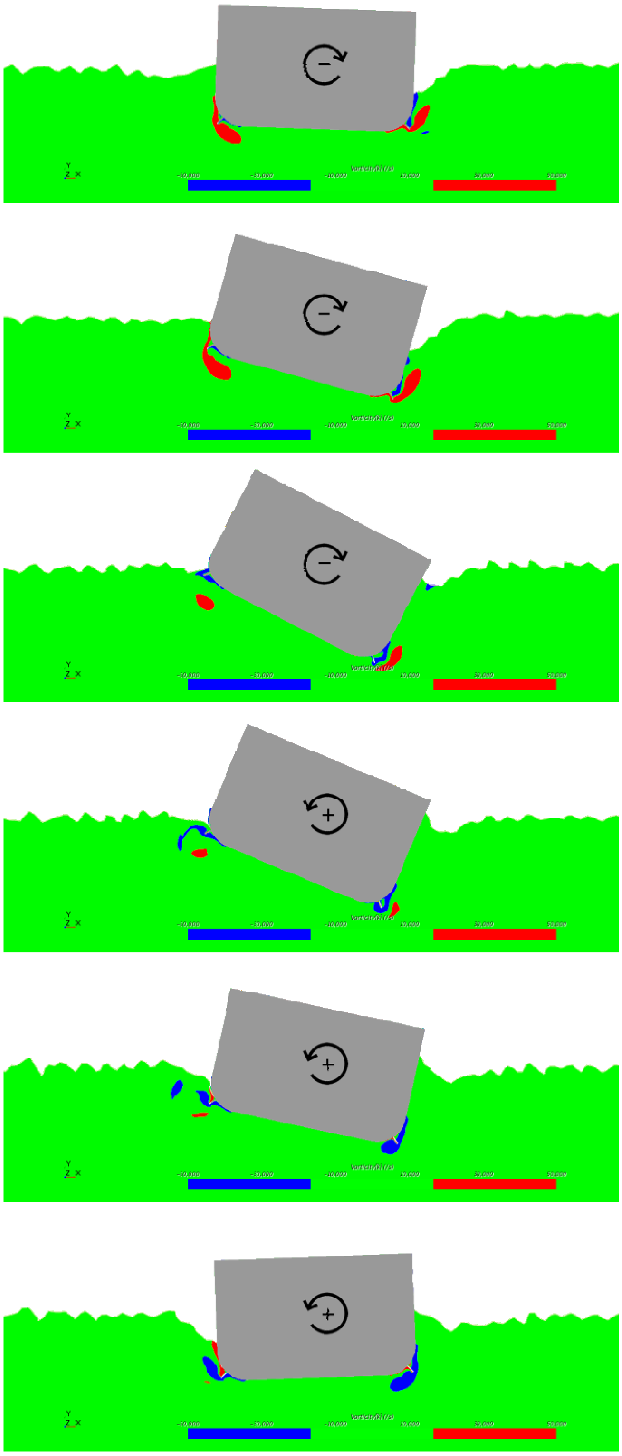

Figure 8: Vorticity contours and vortex shedding around the hull for 27.27 deg. roll amplitude

It is also observed that the free surface disturbance is stronger for 27.27 deg. as Himeno [4] cautions that the bilge keel wave-making component cannot be neglected where bilge keel interacts with free surface. It might be said the wave-making damping increases when the bilge-keel component decreases at large roll amplitudes. Wave-making damping can be calculated by using the radiated wave amplitudes but it will be studied as a future work because the mesh around the free surface needs high quality to measure wave heights.

7. CONCLUSIONS

In this paper URANS numerical solver has been used for the estimation of the effect of large amplitude roll motion on the roll damping. The unsteady flow around a forced rolling hull with bilge keels is computed. Numerical simulations are carried out and the viscous-damping coefficient is computed for variousroll amplitudes. The numerical results are compared with Ikeda's estimation method.

Ikeda's estimation method shows good accuracy for small to moderate angles where linearization is applicable and the numerical results shows good agreement with Ikeda's method until 20.0 deg. However, Ikeda's method overestimates the results for large roll amplitude where the bilge keel interacts with the free surface. Ikeda's method does not consider the free surface effect and vortex shedding so that it overestimates the results.Numerical solver is used to capture the effect of vortex shedding and free surface interaction on roll damping due to large roll amplitudes. The flow around the hull with bilge keels is visualized and the generation of vortices is shown for different roll amplitudes and it is showed that vortices shed from the bilge keel are proportional to amplitude of roll motion. It is observed that the strength and the core of the vortices grow until where the free surface interaction is not effective. This leads to increase of roll damping. The roll damping coefficient starts to decrease when the bilge keel come closer to the free surface because the free surface affects the generation of vortices and vortex shedding.

Results show that the numerical calculation is a practical and fast way to estimate the roll damping and it can be used to modify the existing method especially where the method is not applicable, like large roll amplitudes.

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