Strathprints Institutional Repository

Gu, Yue and Boulougouris, Evangelos and Day, Alexander (2015) A study on the effects of bilge keels on roll damping coefficient. In: Proceedings of the 12th International Conference on the Stability of Ships and Ocean Vehicles (STAB 2015). UNSPECIFIED. ,

A Study on the Effects of Bilge Keels on Roll Damping Coefficient

Yue Gu, Department of Naval Architecture, Ocean and Marine Engineering, University of Strathclyde, Glasgow, UK. yue.gu.2013@uni.strath.ac.uk

Prof. Sandy Day, Department of Naval Architecture, Ocean and Marine Engineering, University of Strathclyde, Glasgow, UK.sandy.day@strath.ac.uk

Dr. Evangelos Boulougouris, Department of Naval Architecture, Ocean and Marine Engineering, University of Strathclyde, Glasgow, UK. evangelos.boulougouris@strath.ac.uk

ABSTRACT

A study of the roll damping of a two-dimensional FPSO model produced by bilge keels using CFD method is presented in this paper. The tool to be utilized is the well-known code Star-CCM+, which uses the Volume of Fluid (VOF) approach to capture the free surface. The results are validated by comparison with experiments. Using the results from a number of simulations, the roll damping coefficient resulting from locating the bilge keels at different positions will be calculated. The analysis of the rolling damping coefficients for the different locations will provide a useful design tool for optimising the roll damping of vessels with bilge keels.

Keywords: roll damping coefficient, bilge keels, FPSO, 2-D, Star CCM+

1. INTRODUCTION

Roll motion although it is a significant parameter in the prediction of a ship's seakeeping performance, is one of the most difficult to calculate for seagoing vessels. This is due to fact that roll damping has a large influence on the roll motion up to the point that it may even cause the vessel's capsize (Haddara, 1989). It plays a dominant role on reducing the roll amplitude and that is why many researchers pay attention to the improvement of its prediction (Pesman at al, 2007). Since 1970s, many investigations have been carried out on the effects of bilge keels, which are used for many years on ships to enhance roll damping (Ikeda, 1977, Ikeda, 1978, Ikeda, 2004). However, due to the complicated nature of roll motion, mainly due to the influence of the viscosity, as well as other factors such as wind, waves and the interaction between the ship and the free surface, it is difficult to make accurate predictions using the potential theory or analytical solutions, which result in many cases in an over-estimation of the roll amplitude (ITTC, 2011). The most well-known and accepted empirical formula is Ikeda's method, but its limitations and inaccuracies have been revealed over time (Yuki, 2003a, Yuki, 2003b, Bassler, 2011). The most accurate way of predicting roll damping remains until today model testing. An efficient and low-cost method to minimise the number of model tests and improve the accuracy of the predictions is the roll damping simulation using CFD (Yang, 2012). Using such method the impact of bilge keels can be simulated and their roll damping coefficient can be predicted quite accurately.

2. BACKGROUND

A study on roll damping on a non-conventional 2-D cross-section was proposed by Yuck (2003a) to investigate the operational efficiency and stability of FPSO. Three kinds of models, namely bilge model, box model and step model, were established in the roll damping coefficient analysis under small roll angle. The results revealed a fact on midships cross-section that affects damping coefficient without bilge keels. Additional work was performed by Van't (2011) to predict the roll damping motion of a FPSO with bilge keels comparing experiment results with CFD simulations using Star CCM+, however, the entire work was limited on two bilge-keels positions.

Comparisons between experimental data and numerical results of roll damping decay for a FPSO with bilge keels was carried out by Avalos (2012, 2013, 2014) to validate accuracy of numerical methods.

Due to the limitation of Ikeda's method for large amplitude roll motions, a DTMB model with bilge keels has been developed by Bassler (2010a, 2010b, 2011) to increase the prediction accuracy of the ship's motions for design assessments.

A numerical model using RANS (Reynolds Averaged Navier Stokes) flow solver compared with experiments has been developed to improved predictions of the bilge keels effect on viscous roll damping coefficients (Querard, 2010). The results revealed that due to friction and eddy making, bilge keels have a dominant impact on the viscous roll damping coefficient.

Considering the effect of bilge keels on the roll damping, Chakrabarti (2001) investigated the features of roll damping with various ship hullform with experiments. Based on Ikeda's method, it was concluded that the impact of bilge keels on the roll damping depends on the locations of the bilge keels.

The effects of putting bilge keels at different positions on the a new non-ballast ship with rounder cross section was investigated by Miyake (2013), and results revealed that the effect of bilge keels on damping motion for a rounder cross-section are much smaller compared with a conventional square cross-section.

In this work, the effect of bilge keels at different locations for roll damping coefficients is investigated in a 2-dimensional FPSO model. Star CCM+ solver is used to simulate roll motion of the rectangular model and FPSO model. Initially, CFD simulations results are compared with previous work for validating the accuracy and feasibility of the scheme. Results obtained by Jung (2006) from roll decay tests on a rectangular structure in calm water and waves are used to be compared. Utilizing the FPSO model provided by Avalos (2012, 2013, 2014), an investigation is performed on the effects of bilge keels at different location on roll damping coefficients.

3. NUMERICAL FORMULAE

3.1 Rolling Motion

A simple equation for ship roll motion including single degree of freedom can be given by

$$A\ddot{\phi} + B(\dot{\phi}) + C\phi = M(\omega t) \qquad (1)$$

However, the damping term $B(\dot{\phi})$ includes linear and nonlinear components

$$B(\dot{\phi}) = B_1\dot{\phi} + B_2\dot{\phi}|\dot{\phi}| + B_3\dot{\phi}^3 + \cdots \qquad (2)$$

It can be assumed that the nonlinear component can be approximated by being linearized so that the damping term can become (Bassler, 2009)

$$B(\dot{\phi}) = B_{44}\dot{\phi} \qquad (3)$$

3.2 Rolling in Calm Water

According to Bhattacharyya (1978), the equation of rolling motion in calm water can be expressed in a differential form given by

$$a\frac{d^2\phi}{dt^2} + b\frac{d\phi}{dt} + c\phi = 0 \qquad (4)$$

where,

a is the virtual mass moment of inertia

$d^2\phi/dt^2$ is the acceleration of rolling

$a(d^2\phi/dt^2)$ is the inertial moment

b is damping moment coefficient

$d\phi/dt$ is angular velocity

$b(d\phi/dt)$ is the damping moment

$c\phi$ is the restoring moment
c is the restoring moment coefficient
ϕ is the angular displacement of rolling.

Parameters of ship roll motion are substituted into a, b and c, and the expression of roll motion in calm water can be given as

$$I'\frac{d^2\phi}{dt^2} + \mathrm{b}\frac{d\phi}{dt} + \Delta GM\phi = 0 \tag{5}$$

where I' is the virtual mass moment of inertia, which is the sum of the actual mass moment of inertia I and the added mass moment of inertia δI

$$I' = I + \delta I \tag{6}$$

Equation (5) is divided by I', then the equation becomes

$$\frac{d^2\phi}{dt^2} + 2\zeta\omega_N\frac{d\phi}{dt} + \omega_N^2\phi = 0 \tag{7}$$

where ζ is the damping factor, ω_N is the natural frequency given by

$$2\zeta\omega_N = \frac{b}{I'} \tag{8}$$

$$\omega_N^2 = \frac{\Delta GM}{I'} \tag{9}$$

4. METHODOLOGY VALIDATION AND ANALYSIS

The present work uses the experimental data provided by Jung (2006) for its validation. Roll decay simulations in calm water and waves use the same setup as the experiment.

4.1 Geometric Characteristics of Model

The model is a rectangular structure, which is 0.3m wide and 0.1m high with 0.05m draft shown as below

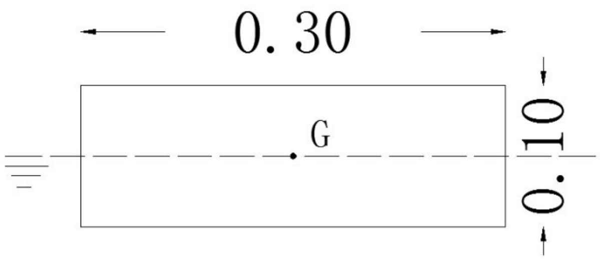


Figure 1 - Definition of geometric feature of model

4.2 Flow Domain in Free Decay Test

The roll decrement simulation is performed in a 2-D domain with the dimension of 5.7m long and 1.8m high with 0.9m water depth, shown as

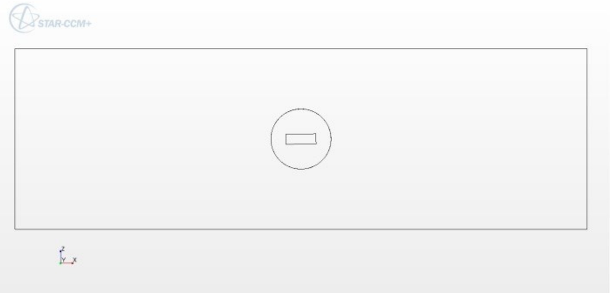


Figure 2 - Flow domain of free decay simulation

4.3 Generation of the Grid

As the body rolls in the domain, not all the mesh would be fixed. A mesh scheme is established by Manzke (2012) including deforming mesh, which changes shapes of grid as the body rolls. However, deforming mesh is decreasing the quality of the calculations. In this work, a finer mesh scheme is utilized so that the mesh around the body can move rigidly with body without deformation. The trimmed mesh and prism layer mesher are used in the entire flow domain except the body itself. Fig.3 shows the distribution of grid through the whole domain, and Fig.4 gives the concentration of refined mesh around the free surface. Fig.5 demonstrates a refined mesh and prism layer mesh distribution around the body.

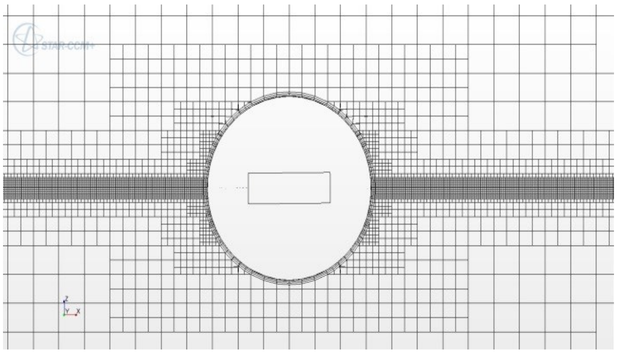


Figure 3 - Mesh scheme through the whole domain

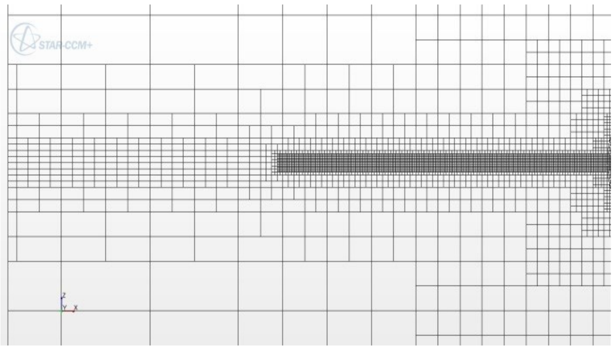


Figure 4 - Mesh distribution around free surface

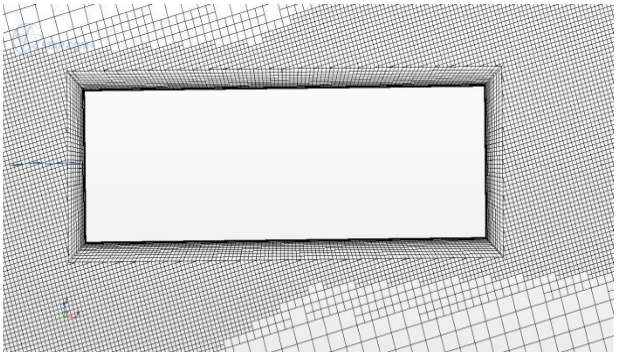


Figure 5 - Refined mesh around the body

4.4 Analysis of Free Decay Simulation

Fig.6 shows the time history of angle of inclination in the simulation of free decay. The body is initialized and released at 15 degree, inclination angle decreases after each time of roll.

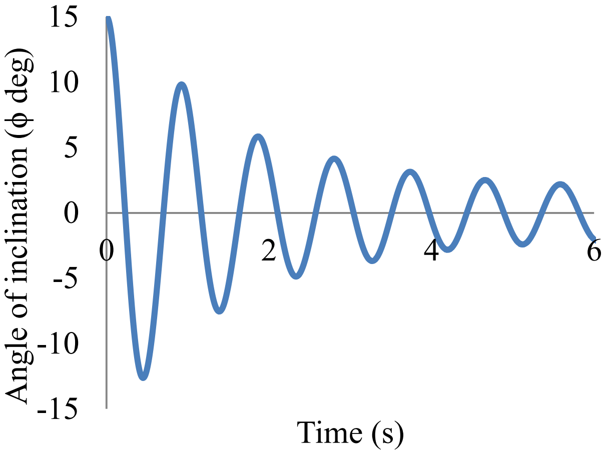


Figure 6 - Time history of angle of inclination

From Fig.6 the natural period of the structure can be obtained T_N= 0.931s, so that the natural frequency is ω_N=6.746rad/s, the virtual mass moment of inertia I'=0.364 kgm^2 and the added mass moment of inertia δI = 0.128 kgm^2, which gives a good agreement with experiment data provided (T_N= 0.93s, ω_N=6.78rad/s and δI =0.124 kgm^2). Fig.7 shows curve of the decrease of angles.

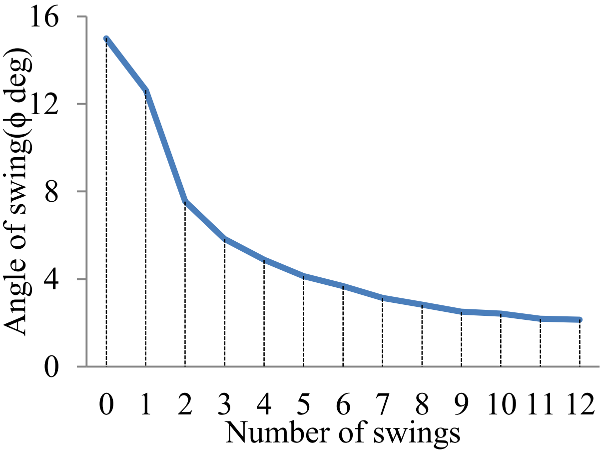


Figure 7- Curve of declining angles

According to the approach suggested by Bhattacharyya (1978), the coefficient K can be found from the trendline of the curve of extinction that can be represented as

$$\delta\phi \text{ per swing} = K\,\phi_m \qquad (10)$$

Analysis of the calculated data gives K=0.3214. With the coefficient K obtained, the damping coefficient b can be obtained by the equation given below

$$b = \frac{KT_N \Delta GM}{\pi^2} \tag{11}$$

So the damping coefficient b is 0.503kg-m-s. Compared with b=0.519kg-m-s from experiment data, the different percentage is 3.16%. And the damping factor ζ=0.103.

Since the simulation results demonstrate a good agreement with experiment data, the methodology can be considered valid for predicting the effect of bilge keels on the damping coefficients of FPSO model.

5. ROLL DECAY SIMULATIONS WITH BILGE KEELS

A FPSO model given by Avalos (2012, 2013, 2014) is used to investigate the damping effects of bilge keels at different locations through a series of roll decay simulations. The results demonstrate the correlation between bilge keels' locations and damping coefficients.

5.1 Characteristics of Models

Table 1 demonstrates the model features of FPSO in the present study, and bilge keels are distributed around the midship frame of FPSO at 10 positions (from position A to position J). Fig. 8 shows the distribution of bilge keels' positions at the cross-section of midships which can be given by

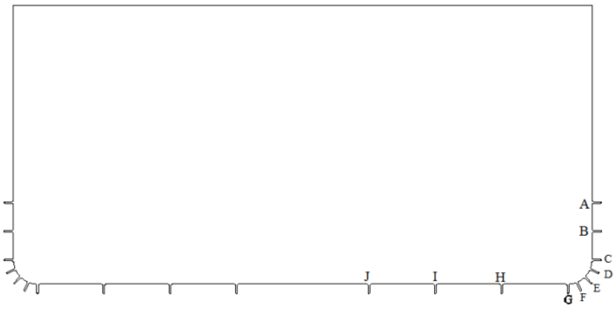


Figure 8 - Bilge keels distributions at midships cross-section

Characteristics of FPSO	Magnitude
Breath	0.725m
Draft	0.196m
Length	0.90m
Centre of gravity (KG)	0.175m
Radius of gyration (Rxx)	0.264m
Mass per unit length	169.76Kg/m
Transverse moment of inertia per unit length	13.269Kg/m
Bilge radius	0.03m
Bilge keel	0.016m

Table 1- Model characteristics of FPSO

5.2 Mesh Generation

Fig. 9 gives a view at the mesh generated based on the present scheme when the bilge keels are located at position E and refined mesh at bilge keels are illustrated by Fig.10.

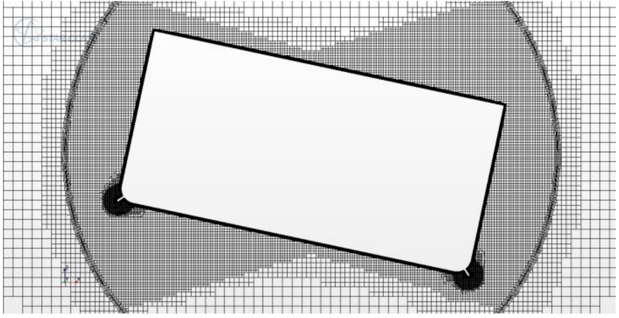


Figure 8 - Generated mesh at position E

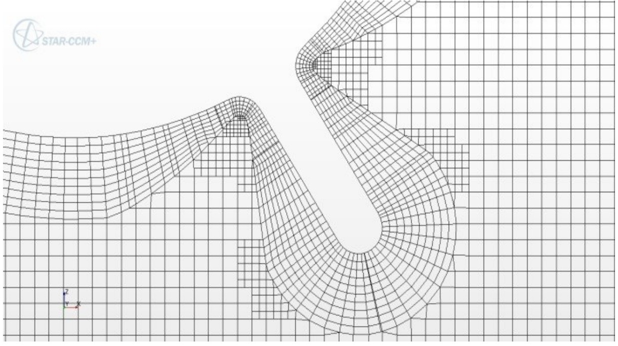


Figure 10 - Refined mesh at bilge keels

5.3 Results

Free decay simulations are carried out with each bilge keel's location (A to J). The results are compared with that of free decay without bilge keels. The initial rolling angle is 12 degree. All results are analysed to obtain the natural period T_N (s), natural frequency ω_N (rad/s), the coefficient Kn (n=1, 2, …, 10 corresponding to position A to J) based on Equ.(10) and the calculated damping coefficient b (kg-m-s) based on Equ.(11). The results can be given as Table 2. Comparison of rolling period between free decay with bilge keels and without bilge keels is shown in Fig.11. It should be noted that with bilge keels, rolling period increases obviously compared with that of the model without bilge keels (from 1.68s to approximately 1.87s).

The same effectiveness can be also seen from Fig.12 (a), which shows the time history of roll decay simulation without bilge keels and with bilge keels, which are located at position E (45° to the bilge). Fig.12 (b) is the result of roll decay test obtained by Avalos at the same position with the same magnitude of bilge keels. The comparison between Fig.12 (a) and Fig.12 (b) shows a good agreement. However, it should be noted that the decay rate is underestimated in both Fig. 12(a) and Fig. 12(b) for the smaller angles of roll oscillation. The phenomenon of under-estimated damping for smaller angle is recommended to be investigated further.

Fig.13 demonstrates the correlation between locations of bilge keels and damping coefficients based on Table 2.

Fig.14 (a) to Fig.14 (d) are the velocity distribution around the FPSO, and it can be clearly seen that the vortices at the bilge corners.

Positions	**T_N**	**ω_N**	**Kn**	**b(kgms)**
A (1)	1.8546	3.3861	0.0464	0.1818
B (2)	1.8661	3.3653	0.0617	0.2433
C (3)	1.8810	3.3386	0.1530	0.6080
D (4)	1.8748	3.3497	0.2225	0.8813
E (5)	1.8787	3.3428	0.2610	1.0360
F (6)	1.8737	3.3516	0.1850	0.7324
G (7)	1.8723	3.3541	0.1697	0.2790
H (8)	1.8375	3.4176	0.0024	0.0093
I (9)	1.8285	3.4345	0	0
J (10)	1.8276	3.4362	0	0
NO BK	1.6816	3.7345	0.0618	0.2196

Table 2 - Results of free decay simulations

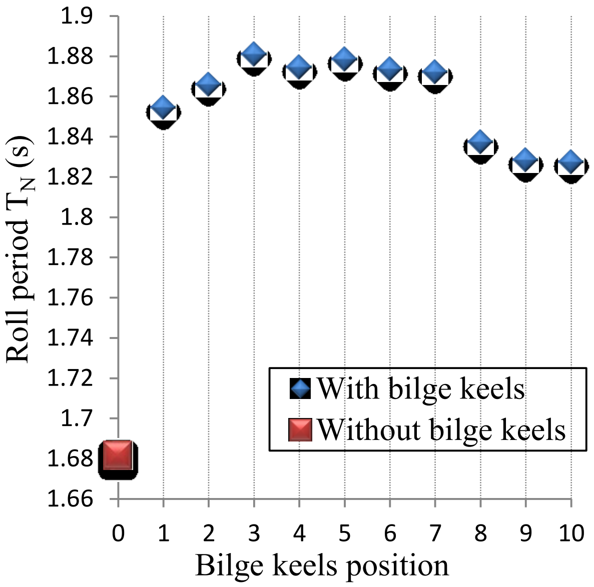


Figure 9 - Rolling period of free decay

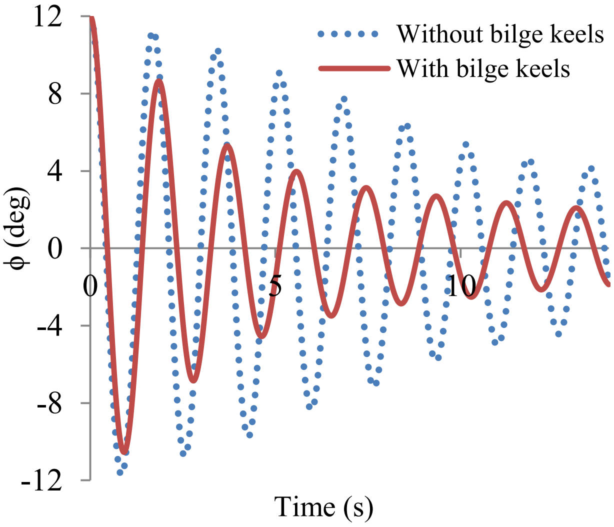


Figure 10 (a) – Results of angle of inclination at present study

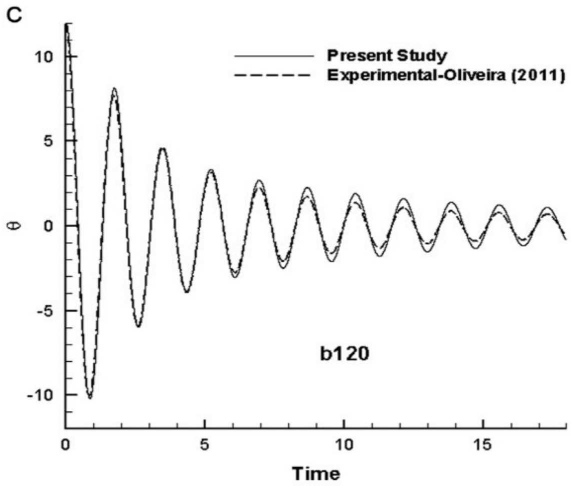


Figure 12 (b) - Result of roll decay test obtained by Avalos

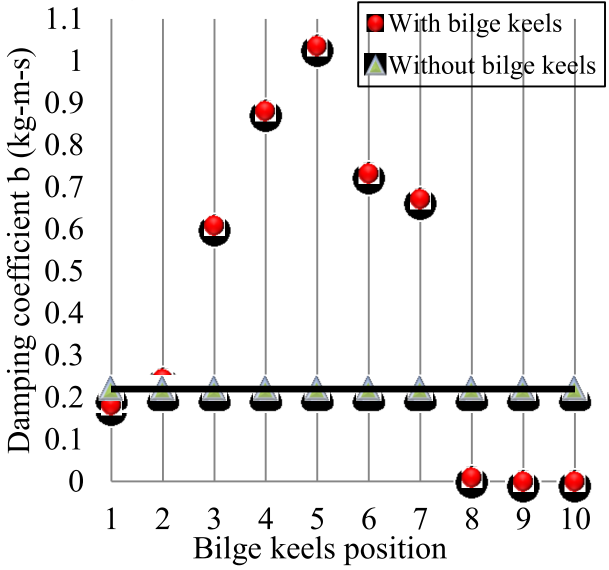
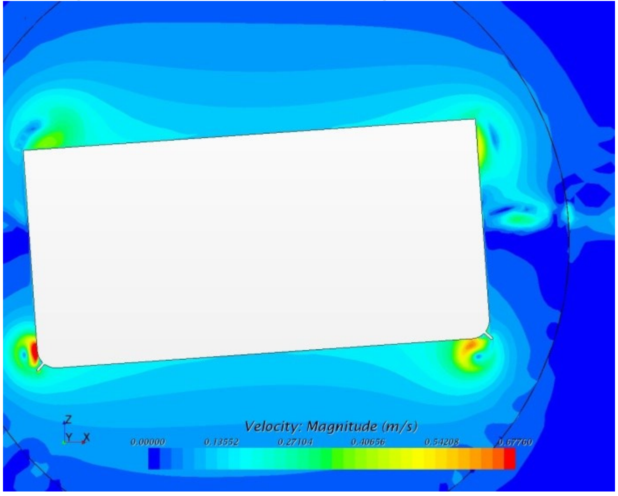
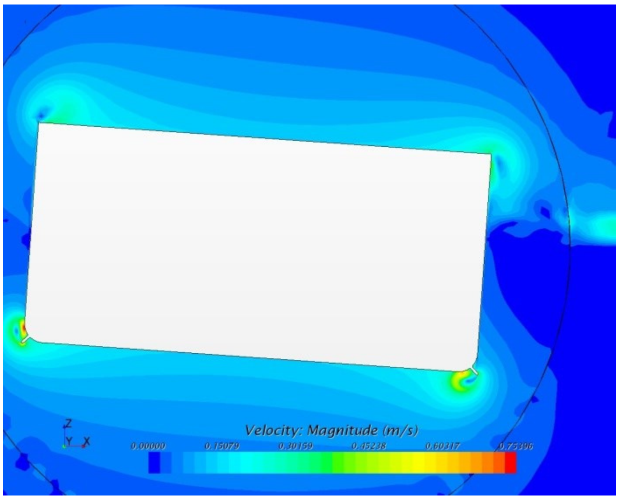


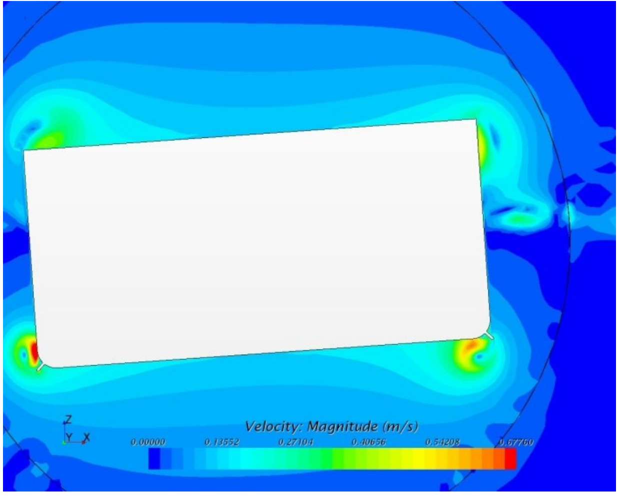
Figure 11 - Damping coefficient of FPSO model with bilge keels at each position (A to J) of bilge keels and without bilge keels



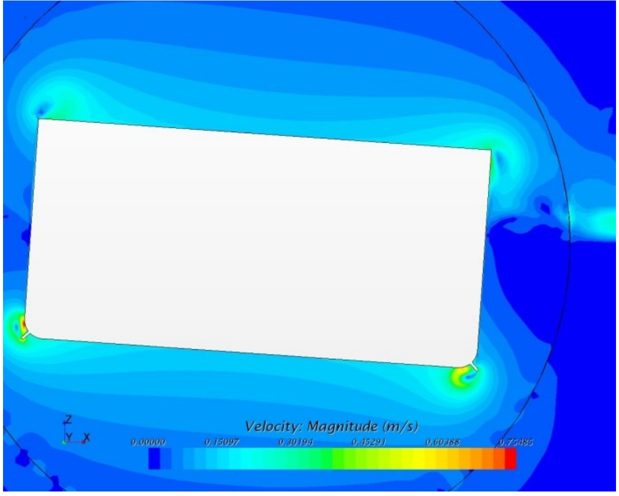
(a)



(b)



(c)



(d)

Figure 14 (a to d) – Velocity and vortex distributions

6. CONCLUSIONS

Table 2 and Fig.11 reveal that bilge keels, which located at ship side and bilge, do have an impact on damping the ship's roll motion. However, the effect can be negligible when bilge keels are positioned at ship bottom.

From Fig.13 it can be seen that bilge keels yield a larger damping coefficient when they are located at the bilge compared with other positions, which means when at the bilge, bilge keels can have a greater impact on the roll motion. Bilge keels at ship side and bottom also affect the damping, and the more they are close to the bilge the larger impact they have on the damping effectiveness.

Comparing results between side locations and bottom locations, bilge keels at the side have greater influence on the roll damping. Additionally, it can be seen from Table 2 that the coefficient K of position H, I and J are close to zero, so that bilge keels that are close to the ship keel are not effective in damping the motion.

Further work will be concentrated on investigating the effect of bilge keels on roll damping when the FPSO is rolling in waves.

7. REFERENCE

Avalos, G. O. G. & Wanderley, J. B., 2012, "A Two-Dimensional Numerical Simulation of Roll Damping Decay of a FPSO Using the Upwind TVD Scheme of Roe-Sweby", The 31st International Conference on Ocean, Offshore and Arctic Engineering, pp. 395-402.

Avalos, G. O. G., Wanderley, J. B. V. & Fernandes, A. C., 2013, "Roll Damping Decay of a FPSO With Bilge Keel", Proceedings of the ASME 2013 32nd International Conference on Ocean, Offshore and Arctic Engineering.

Avalos, G. O., Wanderley, J. B., Fernandes, A. C. & Oliveira, A. C., 2014, "Roll Damping Decay of a FPSO with Bilge Keel", Ocean Engineering, vol. 87(2014), pp. 111-120.

Bassler, C. C. & Reed, A. M., 2009, "An Analysis of the Bilge Keel Roll Damping Component Model", The 10th International Conference on Stability of Ships and Ocean Vehicles, pp. 369-386.

Bassler, C., Reed, A., & Brown, A., 2010, "Characterization of Physical Phenomena for Large Amplitude Ship Roll Motion", Proceedings of 29th American Towing Tank Conference.

Bassler, C. C., Reed, A. M., & Brown, A. J., 2010, "A Method to Model Large Amplitude Ship Roll Damping", Proceedings of the 11th International Ship Stability Workshop.

Bassler, C., Miller, R., Reed, A., Brown, A., 2011, "Considerations for Bilge Keel Force Models in Potential Flow Simulations of Ship Maneuvering in Waves", Proceedings of 12th International Ship Stability Workshop.

Bhattacharyya, R., 1978, "Dynamics of Marine Vehicles", John Wiley & Sons Inc., pp.75-95.

Chakrabarti, S., 2001, "Empirical Calculation of Roll Damping for Ships and Barges", Ocean Engineering, vol. 28(7), pp. 915-932.

Chan, H. S. Y., Xu, Z., & Huang, W. L., 1995, "Estimation of Nonlinear Damping Coefficients from Large-Amplitude Ship Rolling Motions", Applied Ocean Research, vol. 17(4), pp. 217-224.

Haddara, M. R., & Bennett, P., 1989, "A Study of the Angle Dependence of Roll Damping Moment", Ocean Engineering, vol. 16(4), pp. 411-427.

ITTC, 2011, "ITTC-Recommended Procedures: Numerical Estimation of Roll Damping", vol. 7.5-02-07-04.5, pp.1-33.

Ikeda, Y., 2004, "Prediction Methods of Roll Damping of Ships and Their Application to Determine Optimum Stabilization Devices". Marine Technology, vol. 41(2), pp. 89-93.

Ikeda, Y., Himeno, Y., & Tanaka, N., 1978, "A Prediction Method for Ship Roll Damping", Report of the Department of Naval Architecture, University of Osaka Prefecture.

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

Jung, K. H., Chang, K.-A. & JO, H. J., 2006, "Viscous Effect on the Roll Motion of a Rectangular Structure", Journal of Engineering Mechanics, vol. 132**,** pp. 190-200.

Kawahara, Y., & Maekawa, K., 2012, "A Simple Prediction Formula of Roll Damping of Conventional Cargo Ships on the Basis of Ikeda's Method and its Limitation", Journal of Shipping and Ocean Engineering, vol. 2, pp. 201-210.

Miyake, T. & Ikeda, Y., 2013, "A Study on Roll Damping of Bilge Keels for New Non-Ballast Ship with Rounder Cross Section". Proceedings of the 13th International Ship Stability Workshop.

Manzke, M. & Rung, T., 2012, "Prediction of Roll Damping Using Viscous Flow Solvers", The 31st International Conference on Ocean, Offshore and Arctic Engineering, pp. 695-704.

Pesman, E., Bayraktar, D., & Taylan, M., 2007, "Influence of Damping on the Roll Motion of Ships", The 2nd International Conference on Marine Research and Transportation (ICMRT'07), pp. 28-30.

Querard, A. B. G., Temarel, P., & Turnock, S. R., 2010, "Application of RANS to Hydrodynamics of Bilge Keels and Baffles", William Froude Conference on Advances in theoretical and applied hydrodynamics – Past and Future.

Van't Veer, R., Fathi, F., & Kherian, J., 2011, "On Roll Hydrodynamics of FPSO's Fitted with Bilge Keels and Riser Balcony", ASME 30th International Conference on Ocean, Offshore and Arctic Engineering.

Yang, B., Wang, Z.-c., & Wu, M., 2012, "Numerical Simulation of Naval Ship's Roll Damping Based on CFD", Procedia Engineering, vol. 37, pp. 287-293.

Yuck, R. H., Lee, D. H., & Choi, H. S., 2003, "Estimation of Roll Damping Coefficients for Non-conventional Mid-ship Sections", The Thirteenth (2003) International Offshore and Polar Engineering Conference, pp. 540-543.

Yuck, R. H., Lee, D. H., Choi, H. S., Jin, Y. M., & Bang, C. S., 2003, "A Study on Roll Damping of 2-D Cylinders", International Journal of Offshore and Polar Engineering, vol. 13(03), pp. 205-208.