Analyse on several crucial factors for CFD simulation of roll damping

Min Gu, *China Ship Scientific Research Center, Wuxi, China* gumin702@163.com
Shuxia Bu, *China Ship Scientific Research Center, Wuxi, China* bushuxia8@163.com
Ke Zeng, *China Ship Scientific Research Center, Wuxi, China* 398638829@qq.com

ABSTRACT

Ship roll damping is one of key factors for the large amplitude roll motions, and the accurate prediction of a ship roll damping is very difficult. CFD method is one of important methods for the accurate prediction of roll damping. In this paper, several crucial factors for CFD simulations, such as boundary condition, wall function, mesh quantity and quality are analysed based on one ship model. Secondly, the influences of bilge keels on roll damping are also studied. Finally, several questions related to the CFD simulation of roll damping are discussed and the suggestions for the simulation are also proposed.

Keywords: *roll damping, crucial factors, CFD simulation.*

1. INTRODUCTION

The roll damping is a critical hydrodynamic factor to accurately predict large amplitude roll motion, such as synchronous roll or parametric rolling phenomena. At present, the simulation of roll damping is dominated by empirical formulations, experiment or CFD method.

In general, the most common empirical method is Ikeda’s simplified method. The method decomposed ship roll damping into seven parts and combined them linearly to calculate roll damping for wall-sided hull forms at small angles, with and without forward speed (Himeno, 1981). Currently, vulnerability criteria for parametric roll and dead ship conditions are suggested to use the Ikeda`s simplified method. The simplified method can be used quite well for most traditional ships. However, if the ships are outside the application range of Ikeda’ method, or the large amplitude roll motion in moderate or extreme wave, the accuracy of the damping coefficient is low. The experience or semi-experience formulas can`t cover all characteristics for unconventional ships, which limits the application of empirical formulations.

As the development of the second generation of intact stability criteria, the correspondence group on Intact Stability also proposed that the roll damping could be calculated by roll decay/forced roll model test or CFD simulation (United States & Japan, 2014). Although the model tests can give the reliable results, and the PIV measurement promote the analysis of detailed flow characteristics for roll damping recent years, but high cost and complexity in local flow measurement still hold back its application. Particularly, it is difficult for the large-scale model test (Haddara & Bass, 1988).

In the last decade, the numerical methods of Computational Fluid Dynamic (CFD) keep a rapid development. Direct CFD simulations are becoming feasible for calculating the roll damping of ships due to the viscous effects are important. In terms of high-performance computing systems become faster and more efficient, the simulation based on CFD methods is adopted by more and more researchers. Forced roll method and free decay method are two main methods for calculation of the roll damping by CFD, but the experience and principle of the modelling of this phenomenon are still in developing.

Over recent years, numerous researchers conducted CFD simulations to estimate damping coefficients with experiment data to improve accuracy of CFD technology. For instance, Chen et al. (2001), simulated with RANS method using overset mesh in conjunction with 6 Degree-of-Freedom (DoF) motion for time domain simulation of barge roll decay. Yang et al. (2013) performed numerical simulations of free decay for DTMB 5512 bare hull model at Fr=0.138 and 0.280 and using Fluent with a dynamic mesh technique. The paper found that the natural period is overestimated by 1.3% for the low speed case and under-estimated at higher speed by 2.50%. Begovic et al. (2015) and Simon et al. (2018) presented the roll decay simulations for DTMB 5415 by Star CCM + at zero speed. The authors investigated the accuracy and efficiency of the numerical approach with different meshes, time steps and turbulence models. Handschel et al. (2012a, 2012b) used sliding interface mesh to calculate roll damping coefficients of a Post-Panamax container ship Duisburg Test Case in model scale at two forward speeds by free roll decay and forced roll motion. The decay simulations are free in 3 DOF, heave, sway and roll. The authors concluded that the simulation of the forced roll case is more stable and results in less computational time, especially for large roll amplitudes. And then, considering roll amplitude, ship speed, and vertical position of the roll axis on roll damping, the authors applied RANS numerical setup to calculate roll damping coefficients of a Ro-Pax ferry at full scale.

In our previous studies (Gu Min, et al, 2015), the forced roll motions of one 2D ship section based on the methods of orthogonal design and variance analysis were carried out, in which different calculation parameters for the roll damping was analyzed. Then the feasibility of CFD for the prediction of the roll damping was validated by taking one pure car carrier and one standard model 2792 as examples, in which two methods were used during numerical simulations: one is sliding interface method and another is dynamic overset grid method (Gu Min, et al, 2016). We (Gu Min, et al, 2018) also conducted the free roll decay motions under different scale factors of the three-dimensional ship and two-dimensional ship section.

In this paper, according to the previous studies, firstly we discuss several crucial factors for better CFD simulations, such as boundary condition, wall function, mesh quantity and quality et al. Secondly, the effects of bilge keels on roll damping are also studied. Finally, several other questions related to the CFD simulation of roll damping are discussed and the suggestions for the simulation are also proposed. The aim of the paper is to give some proposers to improve the accuracy for CFD simulation and discuss some factors that effects the simulation of roll damping.

2. COMPUTATION METHOD AND NUMERICAL SET UP

Mathematic model

The numerical simulations for the roll damping conducted based on RANS model. The free surface is modelled with the two phase VOF approach with a High-Resolution Interface Capturing (HRIC) scheme based on the Compressive Interface Capturing Scheme for Arbitrary Meshes. The pressure-correction algorithm of SIMPLE type is used for the pressure-velocity coupling. An Algebraic Multi-Grid (AMG) solver to accelerate the convergence of the solution. A segregated flow solver approach is used for all simulations.

The wall function approach was used for the near wall treatment, the approach is formulated to assure reasonable answers for meshes of intermediate resolution considered to capture the boundary layer flow with acceptable accuracy. The mesh quality (y+) has the most important effect on the roll damping, according to our study, the values of wall y + ≈ 1 is appropriate.

The non-dimensional roll damping coefficients can be got by formula (1).

$$B_{44}=\frac{M_R}{\omega\phi_0}\Rightarrow\hat{B}_{44}=\frac{B_{44}}{\rho\nabla B^2}\sqrt{\frac{B}{2g}} \qquad (1)$$

Where ϕ_0 is the initial roll amplitude, ω is the frequency of rolling, B is the width of model, ∇ is the volume for the model, M_R is the instant roll moment at the maximum rolling angular velocity.

Boundary Condition, Mesh Model and Time Step

Boundary conditions have effects on the simulation results, but the effects are not obvious. For the forced roll motions of 2D ship section, all wall boundary conditions are appropriate. For the free roll decay of 3D ships, the boundary of the computational domain is composed of inlet boundary, outlet boundary, wall boundary (hull surface). All of the outer domain boundary is velocity-inlet, except the outlet boundary is the pressure-outlet.

The mesh is the critical factor for CFD simulation. Based on our previous studies, a dynamic overset grid method and sliding method could perform the roll damping simulation with a pure car carrier and CEHIPAR 2792. The roll periods calculated by the overset gird method agree with the experimental data better than the sliding mesh method, but the roll amplitudes calculated by the sliding mesh method have higher precision. We choose a RoPax to conduct further validation, the main particulars of the RoPax are given in Table 1, the hull geometry is shown in figure 1.

We can see from figure 2 that the roll amplitude caculated by the overset mesh agree well with the experimental data. We can also find in table 2 that the roll periods calculated by the overset gird method are within 1% error comparing with experiment results. In the table 3, we can obtain the same conclusion with our previous study, but the error is a little bigger than the experiment at small initial heel.

According to the ITTC Procedures and Guidelines (2011) recommendation for periodic phenomena (e.g. roll decay, vortex, shedding, incoming waves etc.) use at least 100 time steps per period. From the previous work, the convergence is obtained with 500 to 1000 time steps per period.

Especially for the dynamic overset mesh, the numerical stability of donor and acceptor cells scheme needs very short time step. The setting of time steps should guarantee the convective courant number less than 5.

Table 1: Principal particulars of the RoPax.

Items	Model
Mean draught: T	0.145m
GM:	0.064 m
KG:	0.195m

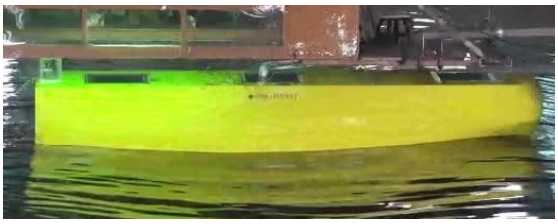

Figure 1: Hull geometry of the RoPax.

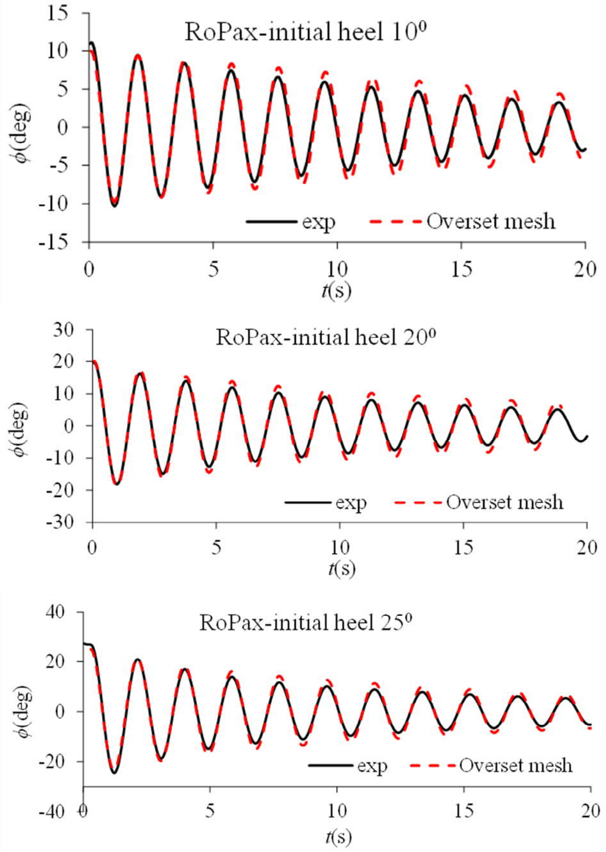

Figure 2: Free decay curves for a RoPax with initial heel 10º、20º and 25º.

Table 2: Roll periods with overset mesh.

Initial heel	Exp	Overset mesh	
	Value	Value	Error
10	14.85	14.74	0.74%
20	14.78	14.80	0.17%
25	14.77	14.74	0.19%

Table 3: Results of 2α calculated by different methods.

Initial heel	Exp	Overset mesh		sliding mesh		Ikeda	
	Value	Value	Error	Value	Error	Value	Error
10	0.0082	0.0050	39.02%	0.0060	26.83%	0.0046	43.90%
20	0.0103	0.0082	20.39%	0.0089	13.59%	0.0072	30.10%
25	0.0119	0.0092	22.69%	0.0100	15.97%	0.0085	28.57%

3. EFFECT OF BILGE KEEL

Even at small roll amplitudes, the bilge keel damping components have a large portion to the total damping and these contributions increase with both roll amplitude and roll frequency. In Ikeda's method, the bilge keel-hull interaction component is assumed not to depend on forward speed (Bassler et al, 2009).

The bilge keel provides a vortex generation around the ship which increases the viscous effect. The generated vortices by bilge keels suppress the roll motion by transferring energy from the ship to the surrounding fluid. Particularly, the exit of bilge keel leads to the flow separation, which increases the difficulty for CFD simulation.

To study the effect of the bilge keel on CFD simulation, we calculated the section of Series 60 non-dimensional roll damping coefficients with and without bilge keel by forced roll motion, as experimental tests on its forced roll have been conducted by Ikeda (Ikeda et al. 1977). During the calculation, the roll centre is located in the intersection between waterline and mid-perpendicular. The non-dimensional frequency ($\hat{\omega}$) is equal to 0.861, and the initial roll amplitudes are 0.1rad, 0.13rad, 0.15rad, 0.2rad respectively. The results are shown in figure 2.

We can see that non-dimensional roll damping from CFD simulation are in good accordance with the experimental results, while the damping with bilge keel is significantly larger than bare section. As the increasing of roll amplitude, the roll damping almost increases linearly. It indicated that the bilge keel damping is important for the roll damping accuracy in CFD simulation.

To further study the effect of the bilge keel on roll damping directly, we show the vorticity contours around the hull section at 1/4, 1/2, 3/4 and 1 period in forced roll motion.

The vorticity around the ship model section with bilge keel is obviously stronger than the bare ship model. The vorticity generation from the bilge keel changes 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.

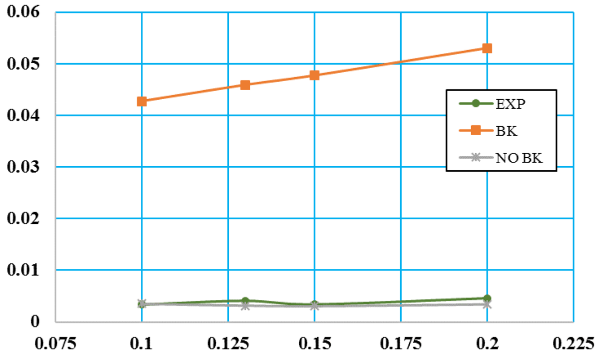

Figure 3: The non-dimensional damping coefficients for different roll amplitudes. (the Series 60 section S.S.5)

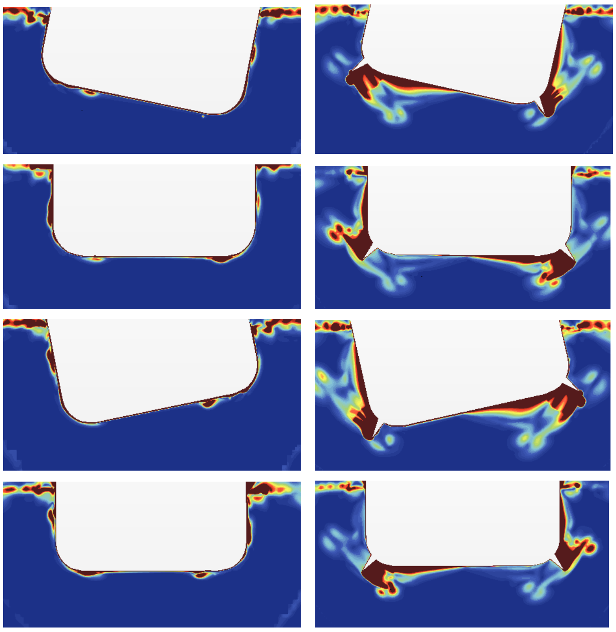

Figure 4: Vorticity contours around the hull section at 1/4, 1/2, 3/4 and 1 period (roll amplitude 0.2rad)

At this point roll direction changes, vortex starts to occur from the tip of the bilge keels and rolls up gradually with increasing strength. The vortex always follows the bilge keel, we can find vorticity generation around the bilge keel root at roll direction.

4. OTHER FACTORS

Scale effect

The large roll damping is strongly nonlinear, which has relationships with fluid viscosity and flow characteristics, such as the flow separation and vortex shedding. The scale effect could be important to simulate the roll damping. Nowadays, the model to full-scale is based on the Froude law of similarity. The Reynolds number are different between model-scale and full-scale, which affect the boundary layer of hull and flow separation.

Since the difference between different scales is mainly in the difference of Re, which lead to the different thickness of the first gird layer. To obtain the sufficient accuracy, the value of y+ should guarantee to be located near 1.

According to the research, for the 2D ship section with bilge keels, the scale effects on roll damping coefficients are obvious, especially for the large initial roll amplitude. However, for the ship without bilge keels, the scale effects can be ignored. The reason may be that the bilge keels roll damping possesses an important part of the total roll damping, and the formation and shedding of the vortices around bilge keels are obvious. The example results are shown in figure 5 and 6.

Influence of degree of freedom

The effect of degrees of freedom is investigated with the pure car carrier, the simulations are performed with 3-DoF – roll, sway, and heave, 2-DoF – roll and heave.

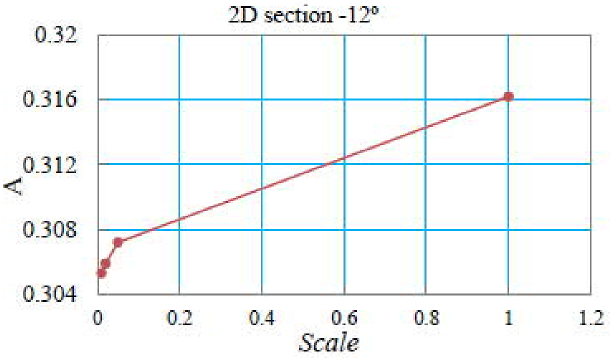

Figure 5: Comparisons of linear roll damping coefficients with different scale factors for a 2D ship section.

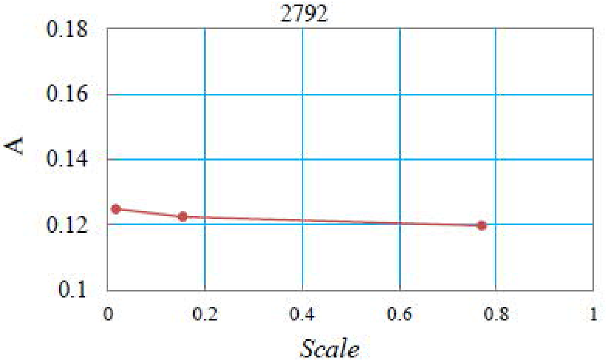

Figure 6: Comparisons of linear roll damping coefficients with different scale factors for CEHIPAR 2792.

It can be noted from figure 7 that the differences in roll amplitude with sway and without sway are negligible. It can be seen from figure 8 that coupling with sway can decrease the heave amplitude. In the simulation, as shown in figure 9, we find that the model drifts along one side, this phenomenon may cause from the pressure difference at the initial time. However, the model was constrained with spring at the horizontal position, the drift motion was not observed in the model test. The difference between the CFD simulation and model test for the drift motion needs further research.

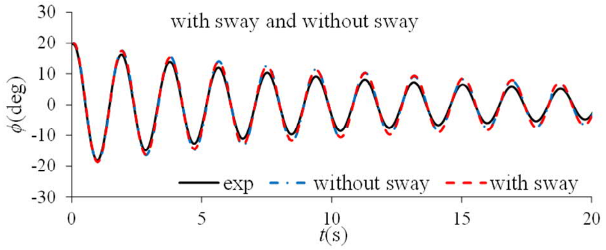

Figure 7: Comparisons of roll decay curve with sway and without sway for pure car carrier.

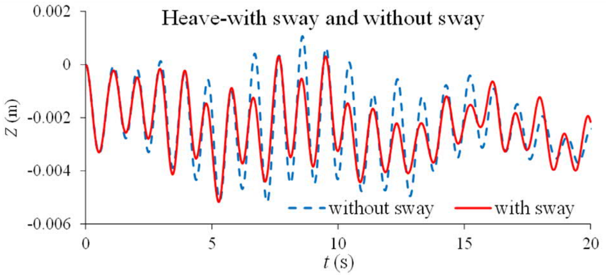

Figure 8: Heave amplitude with sway and without sway for pure car carrier.

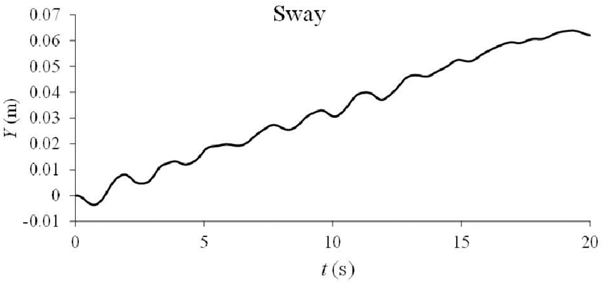

Figure 9: sway motion in CFD simulation.

5. DISCUSSIONS

In this paper, we summarize some crucial factors for CFD simulation of roll damping. In general, roll damping can be estimated using semi empirical methods, computational fluid dynamics (CFD) calculations, model tests or full-scale tests. None of these methods may be sufficient to capture all roll damping behaviour of a given ship in any given condition separately.

The method based on RANS numerical solver has been used for the estimation of the roll damping successfully. The unsteady flow around a forced rolling and free roll decay is computed. The numerical results have a good agreement with experimental data in some conditions. Considering different dynamic mesh method, the time step may be a key factor, it usually should be less than 1/500 period for the roll damping simulation.

The flow around the hull with bilge keels is visualized and the generation of vortices is shown, it is observed that the strength of the vortex, to simulate the roll damping of ship model with bilge keel, the mesh around the bilge keel should be refine to capture the vortex variations.

Scale effects on roll damping coefficients are very obvious, especially for the large initial roll amplitude with bilge keel. The influence of viscosity around bilge keels may be the main reason for the scale effects of roll damping. The full-scale model test needs to be conducted to validate the scale effects with CFD simulation.

The simulation of roll damping is still a topic in developing. More works need to be made in future to improve accuracy of roll damping. Considering the speed effects on the roll damping simulation, comparing with the forced roll model test may be a promising. The uncertainly of the experimental and numerical simulations are both important works needed to be done.

6. ACKNOWLEDMENTS

This research is supported by Ministry of Industry and Information Technology of China (No. [2017] 614). The authors sincerely thank the above organization.

REFERENCES

Begovic, E., Day, A.H., Incecik, A., Mancini, S., Pizzirusso, D., 2015. Roll damping assessment of intact and damaged ship by CFD and EFD methods. In: Proceedings of 12th International Conference on Stability of Ships and Ocean Vehicles. Glasgow, 2015, ISBN-13: 978-1-909522-13-8.

Bassler C C, Reed A M. 2009.An analysis of the bilge keel roll damping component model[C]//Proc. 10th Intl. Conf. Stability of Ships and Ocean Vehicles.

Chen, H.C., Liu, T., Huang, E.T., 2001. Time domain simulation of large ship roll motions by a chimera RANS method. In: Proceedings of 11th ISOPE Conference, ISBN 1-880653-51-6.

Gu, M., Jiang Lu, Shuxia Bu, Chengsheng Wu, GengyaoQiu, 2015, Numerical Simulation of the Ship Roll Damping, 12th STAB, Glasgow UK, pp:341-348.

Gu, M., Bu, S., Qiu, G., Zeng, K., Wu, C., Lu, J., 2016. Validation of CFD simulation for ship roll damping using one pure car Carrier and one standard model. In: Proceedings of the 15th International Ship Stability Workshop, 13-15 June 2016, Pp. 165–172, Stockholm, Sweden.

Gu, M., Bu, S., Lu Jiang, 2018, Numerical Simulation of the Ship Roll Damping, 13th STAB, Japan, pp:323-330.

Himeno, Y., 1981, Prediction of Ship Roll Damping-State of the Art, Dept. of Naval Architecture and Marine Engineering, Univ. of Michigan, Report 239.

Handschel, S., Köllisch, N., Soproni, J.P., Abdel-Maksoud, M., 2012a. A numerical method for estimation of ship roll damping for large amplitudes. In: 29th Symposium on Naval Hydrodynamics Gothenburg, Sweden, pp. 26–31 August 2012.

Handschel, S., Kollisch, N., Abdel-Maksoud, M., 2012b. Roll damping of twin-screw vessels: comparison of RANSE with established methods. In: Proceedings of the 11th International Conference on the Stability of Ships and Ocean Vehicles, Athens, Greece, pp. 887–897.

ITTC Procedures and Guidelines, 2011. Practical Guidelines for Ship CFD Applications.7.5-03-02-03.

Ikeda, Y., Himeno, Y., & Tanaka, N., 1977a, “On Eddy Making Component of Roll Damping Force on Naked Hull”, Journal of the society of Naval Architects of Japan. Vol. 162, pp. 59-69.

Simon, Begovic, E., Day, A. H., & Incecik, A. 2018. Verification and validation of numerical modelling of DTMB 5415 roll decay. Ocean Engineering, 162, 209-223.

United States and Japan, 2014, “Draft Guidelines of Direct Stability Assessment Procedures as a Part of the Second Generation Intact Stability Criteria, IMO SDC1/INF.8, Annex 27.

Haddara, M.R. BASS, D.W., 1988, “Non-linear Models of Ship Roll Damping”, International Shipbuilding Progress, 35/401, pp. 5-24.

Yang, C.L., Zhu, R.C., Miao, G.P., Fan, J., 2013. Numerical simulation of rolling for 3-D ship with forward speed and nonlinear damping analysis. J. Hydrodyn. 25 (1), 148–155.