Numerical Simulation of Naval Ship’s Roll Damping Based on CFD

YANG Bo*, WANG Zuo-chao, WU Ming
Dalian Naval Academy, No.667 Jiefang Road Zhongshan Square, Dalian 116018, China

Abstract

Roll damping test is used to calculate roll damping coefficient, which is an important coefficient in predicting ship seakeeping capability. And because of the complexity of naval ship’s shape (with bulbous bow and transom stern), it’s rare to find the numerical simulation of its roll damping motion. In this paper, DTMB5512 model’s roll damping motions at different initial roll angles are simulated based on CFD, vessel’s roll damping coefficients are calculated through the simulation results, and the results show good agreements with the tank test data.

Key words: CFD; vessel; roll; damping coefficient

Roll damping coefficient plays an important role in the vessel seakeeping, which is the base for the precise prediction of vessel motion in wave [1]. Vessel’s roll damping coefficient is related to the flow feature of the surrounding flow field, and is difficult to get theoretically. It can be obtained through the ship model tank test which is long-time-taken, high-cost and difficult to change the ship model.

Numerical simulation based on CFD, which has the advantages of low cost, flow field measurement without contactor and more specific information, has become an important method in the research of vessel hydrodynamic, and especially a hot issue in seakeeping research recently. Currently, the prediction of longitudinal motion in regular waves and the hydrodynamic prediction of still water roll of some overseas researchers achieve satisfied precision [2][3][4]. The domestic research of seakeeping with the usage of CFD relatively lags behind. Wu [5] did a numerical simulation of Wigley model in regular head waves. Zhu [6] did a numerical simulation of container model’s 2D profile turbulent flow. Huang [7] simulated of a crane model’s roll damping motion in still water. The research of seakeeping complicated

* Corresponding author. Tel.: 86-134-7894-2590; fax: 86-0411-8585-7783.
E-mail address: bisecond@163.com.
model such as the naval ship with the bulbous bow and transom stern is rare compared to the above relatively easy simulation.

Based on the CFD theory, with the re-development on the Fluent platform, the author conducted a numerical simulation of roll damping motion with the DTMB5512 destroyer model on the condition of different original roll angles. The rolling damping coefficient is also obtained through the simulation and the results show good agreement with that of tank test.

1. Numerical calculation method

1.1. Controlling equations

Taken as incompressible viscous fluid, water is controlled by equations of continuity, momentum and turbulence, which are presented as follows:

\[
\frac{\partial u_i}{\partial t} + \frac{\partial}{\partial x_j}(u_i u_j) = - \frac{\partial P}{\partial x_j} + \frac{\partial}{\partial x_j}\left(\mu \frac{\partial u_i}{\partial x_j} - \frac{\partial u_j}{\partial x_i}\right) \quad (1)
\]

\[
\frac{\partial k}{\partial t} + \frac{\partial k}{\partial x_j}(u_i u_j) = \frac{\partial}{\partial x_j}\left(\alpha_k \mu_{\text{eff}} \frac{\partial k}{\partial x_j}\right) + G_k + \epsilon \frac{\partial \epsilon}{\partial t} + \frac{\partial}{\partial x_j}\left(\alpha_\epsilon \mu_{\text{eff}} \frac{\partial \epsilon}{\partial x_j}\right) + \frac{C_{\mu} \epsilon}{k} \frac{C_k}{k} \frac{k}{\epsilon} + \frac{C_{\epsilon} C_{\alpha}}{k} \left(\frac{C_k}{k} \frac{k}{\epsilon} + \frac{C_{\epsilon} C_{\alpha}}{k} \right) \quad (2)
\]

Here, \( x_i, x_j \) are the Cartesian coordinates, \( i \) and \( j \) can be taken 1,2,3; \( u_i \) is the mean-time velocity in \( x_i \) coordinate; \( u'_i \) is the fluctuation of velocity in \( x_i \) coordinate; \( P \) is pressure; \( t \) is time; \( \mu \) is coefficient of kinematic viscosity; \( k \) is the turbulent kinetic energy; \( \epsilon \) is the turbulent dissipation rate.

\[
\mu_{\text{eff}} = \mu + \mu_t \; ; \; \mu_t = \rho C_{\mu} k^2 / \epsilon \; ; \; C_{\mu} = 0.0845 \; ; \; \alpha_k = 1.39 \; ; \; C_{\epsilon} = C_{\alpha} - \eta (1 - \eta/\eta_0) / (1 + \beta \eta^2) \; ; \; C_{\epsilon} = 1.42 \; ; \; C_{\alpha} = 1.68 \; ; \; \eta = \left(\frac{2 E_{\eta} \cdot E_{\beta}}{k} \right)^{1/2} / \epsilon \; ; \; E_{\eta} = \frac{1}{2} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \quad (3)
\]

The method of VOF is used in this paper to simulate the free surface (the interface between water and air), the control equation of volume fraction is:

\[
\frac{1}{\rho_q} \left[ \frac{\partial}{\partial t} (C_q \rho_q) + \nabla \cdot (C_q \rho_q \vec{v}_q) \right] = \sum_{p=1}^{n_q} (m_{pq} - m_{wp}) \quad (4)
\]

Here, \( m_{pq} \) is the mass transported from phase \( q \) to phase \( p \); \( \rho_q \) is the density of phase \( q \); \( t \) is time.

1.2. The coupled calculation of vessel’s motion and flow field

Compared to the research of resistance and maneuverability of vessel, the differences of features of seakeeping are fluid-solid coupling motion, namely the vessel is driven by the hydrodynamic force and moment, the vessel motion affects its surrounding flow field otherwise. Thus, the coupling calculation between the ship motion and fluid flow is the key numerical simulation of the paper.

The simulation is done as:
(1) Fix the vessel model from its initial floating state, and initialize the flow field.
(2) Step with the time step \( \Delta t \) and calculate the velocity-pressure field.
(3) Calculate the rolling moment $M$ and calculate the rolling angular acceleration $\ddot{\phi}$ through the control equation $I_{xx} \ddot{\phi} = M$, where $M$ is the roll moment and $I_{xx}$ is the roll moment of inertia.

(4) The rolling angular velocity $\dot{\phi} = \dot{\phi} \Delta t$ is obtained through the integration of angular acceleration.

(5) The variation of angular $\varphi = \dot{\phi} \Delta t$ is obtained through the integration of angular velocity.

(6) Update the float state of ship.

(7) Return to step 2 and repeat the following steps until the calculation finished.

2. Rolling damping coefficient calculation method

Fig. 1 presents the typical rolling damping curve. The difference $\Delta \varphi = \varphi_k - \varphi_{k+1}$ and the average $\varphi_m = \frac{(\varphi_k + \varphi_{k+1})}{2}$ can be gotten through the amplitude of two adjoining phases $\varphi_k$ and $\varphi_{k+1}$. Fig. 2 shows the curve of $\Delta \varphi = f(\varphi_m)$ which is also called perishing curve and it can be documented that vessel’s rolling damping coefficient $\mu$ can be calculated as:

$$2 \mu_{pp} = \frac{2}{\pi} \frac{\Delta \varphi}{\varphi_m}$$ (5)

Fig. 1 the rolling damping curve  
Fig. 2 the extinction curve

3. Analysis of computational example and comparison

3.1. The computational example

The ship model DTMB5512, modeled the US navy DDG51 destroyer which is also recommended by the ITTC for CFD simulation, was used in this paper. This model’s tank test data is abundant and reliable. Refer to reference [8], all the simulation’s Froude number is 0.280, and the model’s initial roll angle is $5^\circ$, $10^\circ$, $15^\circ$ separately.

Table 1 parameters of Model DTMB5512

| Item      | Length(m) | Breadth(m) | Draft(m) | Volume of displacement(m$^3$) | $C_b$ |
|-----------|-----------|------------|----------|------------------------------|-------|
| data      | 3.048     | 0.410      | 0.132    | 0.0826                       | 0.506 |

3.2. Computational domain and grid

Fig. 3 shows the scale of computational domain, in which $L$ is the length of ship. The whole-domain structural grid (hexahedron and prism) was realized with the usage of multi-block
grid. And 10 boundary layers are set near the hull. The zero dimension distance $y+ \text{ varies } 1 \sim 5$ and the mesh numbers are around 1,500,000.

Fig. 3 the computational domain

3.3. The boundary conditions

The boundary conditions are set as follows:
- Inlet—velocity inlet, providing velocity magnitude and water’s volume fraction;
- Outlet—pressure outlet, providing pressure in still water;
- The hull—no slip wall;
- Outer boundary (including the bottom, top and wall surface of tank)—velocity inlet, same as inlet.

3.4. Analysis of experimental data

Fig. 4-Fig. 6 show the experimental results and make a comparison with the results of reference [8].

Fig. 4 Simulation results of 5°

Fig. 5 Simulation results of 10°
Table 2 shows the rolling damping coefficient calculated from the extinction curve.

| Initial angle | 5°  | 10°  | 15°  |
|---------------|-----|------|------|
| Experimental data | 0.1258 | 0.1256 | 0.1304 |
| Simulation data | 0.1261 | 0.1229 | 0.1302 |
| Error(%)      | 0.24 | 2.15 | 0.17 |

Through Table 2, it can be seen that the method that presented in this paper can be used to calculate the roll damping coefficient precisely.

4. Conclusion

Based on CFD, warship model’s roll damping motions are simulated, and a method is proposed to calculate vessel’s roll damping coefficient.

(1) The rolling damping coefficient is unrelated to the initial roll angle.
(2) If roll angle is less than 20°, the rolling damping resistance varies linearly rather than non-linearly.

Reference

[1] Li Jide. The seakeeping of vessel[M], in haerbin:Harbin engineering university press.2007.10
[2] Robert V. Wilson, Pablo M. Carrica, Fred Stern. Unsteady RANS method for ship motions with application to roll for a surface combatant [J]. Computers and Fluids. 2006, (35), 201-524
[3] L. Gui, J. Longo, B. Metcalf, J. Shao, and F. Stern. Forces, Moment and Wave Pattern for Naval Combatant in Regular Head Waves [J]. Experiments in Fluids. 2002, 32(1): 27-36
[4] Martin Irvine, Jr., Joseph Longo, and Frederick Stern. Pitch and Heave Tests and Uncertainty Assessment for a Surface Combatant in Regular Head Waves [J]. Journal of Ship Research, 2008, 52(2): 146–163
[5] WU Cheng-sheng, ZHU De-xiang, GU Min. N-S CFD simulation of wave-induced ship motions in regular head waves[J]. Journal of Ship Mechanics, 2008, 12(5), 692-696
[6] ZHU Ren-chuan, GUO Hai-qiang, MIAO Guo-ping, YU Jian-wei. A Computational Method for Evaluation of Added Mass and Damping of Ship Based on CFD Theory [J]. Journal of Shanghai Jiaotong University, 2009, 43(2), 198-203
[7] Huang Changqing, Wang Xuelin, Hu Yujin. Numerical Simulation of Hydrodynamic Coefficients of Crane Ship Based on CFD [J]. China Mechanical Engineering, 2011, 22(17): 2076-2079
[8] Martin Irvine Jr. Towing Tank Tests for Surface Combatant for Coupled Pitch and Heave and Free Roll Decay Motions [D]. Iowa: the Graduate College of The University of Iowa, 2004