Numerical simulations and analysis of the zig-zag maneuvers of an oil tanker based on a body-force propeller

HAO Hao1,*, CHEN Weimin2 and WU Zixin3

1Shanghai Ship and Shipping Research Institute, Shanghai, China
2Key Laboratory of Marine Technology Ministry of Communications, PRC
3State Key Laboratory of Navigation and Safety Technology

*Email: jihemao88@outlook.com

Abstract. The course change quality is a crucial measure of ships’ maneuverability and is closely related to the ship navigation safety. Research on zig-zag motion of ships is essential to voyage safety. STARCCM+ based on the ship 6-DOF motion and overset grid technology are used to numerically simulate the zig-zag maneuver of an oil tanker. To simulate the zig-zag motion, a body-force propeller model is adopted instead of the real propeller. The rotation speed of virtual propeller is controlled to achieve the steady self-propulsion state of the ship model and then the rudder turns from 10° to -10° according to the orientation of the ship model. By solving viscous flow field, the motion state and detailed flow field information of the ship model are presented. To verify the accuracy of numerical prediction results, ship model test is launched. Through comparison of results, the numerical simulation can provide reference for preliminary assessment for the course change quality of ships.

1. Introduction

The maneuverability test of a self-propelled ship model is an unconstrained free self-propelled test, which can directly measure various motion parameters, and can more intuitively analyze and compare the maneuverability of the ship. Therefore, it has been widely used for a long time. The zig-zag steering test is a very important steering test method proposed by G. Kempf in 1943 to determine the steering response of a ship. So far, it has been regarded as an indispensable test for both real ships and self-propelled models. However, the zig-zag test of real ship requires high-qualified testing personnel and enormous cost. Although ship model tests are easier than real ship tests, they also cost much and inevitably have scale effects. In recent years, due to the development of basic computer application technology, CFD (Computational Fluid Dynamics) methods have made great progress in the field of ship hydrodynamics.

The numerical simulation of the hydrodynamics based on the computational fluid dynamics method has a series of advantages such as low cost, time saving and easy access to detailed flow field information that are not available in real ship and ship model tests. G. Ryan successfully applied the Body-force method and overset grids technology to simulate the zig-zag movement of a underwater vehicle, but the influence of heel and trim was ignored during the calculation[1]. WU Zhaohua uses the Body-force model to replace the propeller, and solve the force and moment of a container ship during its turning motion. The calculated results are in good agreement with the theoretical values, indicating that the body-force method is efficient and feasible in solving the ship maneuvering...
motion.[2]. By solving the unsteady RANS equation, Carrica uses the overset grid method to perform numerical simulations on the turning and zig-zag motion of DTMB5512 ship model and the calculated results match well with experimental ones[3]. WANG Jianhua uses dynamic overset grid technology to simulate the turning motion of standard ship model ONRT. The trajectory and various characteristic parameters of turning motion got by calculation are basically consistent with ones got by experiment [4]. SUN Chenguang uses Naoe-FOAM-SJTU solver to numerically simulate the emergency stopping maneuver of KVLCC2 model with propeller. The calculated results indicate that the discrepancy between numerical prediction results and test data is within 5%[5]. XIAN Guo combines body-force method, overset mesh technology, 6-DOF(Degree of Freedom) motion model and VOF(Volume of Fluid) model to simulate the zig-zag motion of a ship, and compares the numerical simulation results of the heeling, trim, overshoot angle, initial turning time with the test results[6].

This paper uses overset grid technology, 6-DOF motion model and Body-force propeller model to simulate numerically the zig-zag motion of an oil tanker. And the RANS (Reynolds-averaged Naiver-Stokes) equation and the k-Epsilon turbulence model are adopted. The model test is performed to verify the accuracy of the numerical calculation.

2. Numerical simulation methodology

2.1. Governing equation

In a fixed coordinate system, the Reynolds average continuity equation and momentum equation of the incompressible fluid are as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} + \frac{\partial (\rho w)}{\partial z} = 0$$  \hspace{1cm} (1)

This is the formula of continuity equation, where $\rho, t, u, v$ and $w$ represent density, time, and velocity component respectively.

$$\frac{\partial (u)}{\partial t} + \nabla \cdot (\rho u\vec{v}) = - \frac{1}{\rho} \frac{\partial p}{\partial x} + \rho \nabla^2 u + f_x$$  \hspace{1cm} (2)

$$\frac{\partial (v)}{\partial t} + \nabla \cdot (\rho v\vec{v}) = - \frac{1}{\rho} \frac{\partial p}{\partial y} + \rho \nabla^2 v + f_y$$  \hspace{1cm} (3)

$$\frac{\partial (w)}{\partial t} + \nabla \cdot (\rho w\vec{v}) = - \frac{1}{\rho} \frac{\partial p}{\partial z} + \rho \nabla^2 w + f_z$$  \hspace{1cm} (4)

This is the formula of momentum equation, where $p$ and $f_i$ represent the pressure acting on the fluid cluster and the sum of the body force acting on the infinite body.

2.2. Body-force model of propeller

The body-force model is used to equate the thrust and torque produced by the propeller. The method ignores the influence of the geometric shape of the propeller blades, and distribute the thrust according to the radius change in the cylindrical area defined by the diameter of the propeller disk and the longitudinal thickness of the propeller. The distribution of the force is optimized by Goldstein. And its formulas are as follows:

$$f_{hs} = A_x \frac{r^2 \sqrt{1 - r^*}}{r^* (1 - r_h) + r_h}$$  \hspace{1cm} (5)

where $f_{hs}$ is axial force and $f_{hs}$ is tangential force; $f_{hs} = A_x r^* \sqrt{1 - r^*}$

$$r^* = \frac{r - r_h}{1 - r_h}; r_h = \frac{R_H}{R_p}; r^* = \frac{r}{R_p}$$  \hspace{1cm} (6)

$$A_x = \frac{105}{8} \frac{T}{\pi \Delta (3R_H + 4R_p)(R_p - R_H)}$$  \hspace{1cm} (7)
\[ A_\theta = \frac{105}{8} \frac{Q}{\pi \Delta R_P (3R_{H} + 4R_f)(R_P - R_H)} \]  

where \( R_P, R_H, r, T \) and \( Q \) represent the radius of the propeller, the radius of hub, radiation radius, thrust and torque of open water propeller.

The propeller in this paper is right-handed, and the open water performance curve of this propeller is shown in figure 1.

![Figure 1. Open water performance curve.](image1)

2.3. Geometric model and the setting of calculation

The ship is an oil tanker and its basic parameters are shown in table 1, and the model of it is shown in figure 2.

| Parameters                                | Values          |
|-------------------------------------------|-----------------|
| Lpp                                       | 3.43 m          |
| B                                         | 0.57 m          |
| Draft                                     | 0.22 m          |
| Longitudinal position of center of buoyancy | 1.77 m         |
| Height of center of gravity               | 0.19 m          |
| Rolling moment of inertia                 | 12.64 kg \cdot m^2 |
| Pitch moment of inertia                   | 245.96 kg \cdot m^2 |
| Initial moment of inertia                 | 266.02 kg \cdot m^2 |

![Figure 2. Model of ship.](image2)

In the numerical calculation, the overlapping grid method is used to divide the grids. The total length of the calculation domain is 5 times the length of the ship. The front end is about 2 times the length of the ship in the positive direction of the X axis. The boundary type is set as the velocity inlet. The rear end is about 3 times the length of the ship in the negative direction of the X axis. The boundary type is set to pressure outlet. The upper boundary is at a distance of 1 time the ship’s length from the origin above the Z axis, the lower boundary is at a distance of 1.5 times the ship’s length from the origin below the Z axis, and the side boundary is about 2 times the length of the ship of the Y axis. The completed grid is shown in the figure 3 and figure 4.
2.4. Numerical simulation results and analysis
This paper calculates the zig-zag movement of the ship model under the speed of 1m/s when the rudder rotates between 10 degrees and -10 degrees, and the characteristic parameters of the movement are obtained. Figures 5, figure 6, and figure 7 respectively show wave pattern, pressure distribution on the ship and time histories of ship motion.

Figure 5. Wave pattern for self-propulsion in calm water.

Figure 6. Pressure distribution on the ship hull and rudder.

Figure 7. Time histories of ship motion.

Figure 8 shows the wave patterns of the ship model at the first and second overshoot angle. It can be seen that the wave pattern on both sides of the ship model show obvious asymmetry, which is consistent with the actual situation.
Figure 8. Wave pattern during one zig-zag turn.

Figure 9 shows the wake field distribution at the cross section of the propeller and rudder axis at the first and second overshoot angles. It can be clearly seen from the figure that the flow field of starboard rudder is more complicated at the first overrun angle. And the flow field of starboard rudder is more complicated at the second overshoot angle. It can be known that steering will change the side force of the rudder and turn the ship model.

Figure 9. Wake field around rudder during one zig-zag turn.

3. Ship model experiment and comparison with numerical results
This experiment is carried out in the ship model maneuvering tank of Shanghai Ship and Shipping Research Institute. Figures 10 and figure 11 are the ship model and the experimental process respectively.

Figure 10. Model of ship.

Figure 11. Status of ship during zig-zag motion.

Figure 12 shows the comparison between numerical calculation results and experimental data, it can be seen that the rudder angle and the heading angle of the numerical calculation are in good agreement with the test results. Table 2 is the comparison of the characteristic parameters during zig-
zig motion between the calculation and the test results. It shows that the numerical simulation results are reliable.

![Figure 12](image)

**Figure 12.** Time histories of rudder and yaw angle of 10/10 zig-zag maneuver.

| Parameters               | Test values | Calculated values | Error   |
|--------------------------|-------------|-------------------|---------|
| First overshoot angle    | 11.2°       | 10.1°             | -9.82%  |
| Second overshoot angle   | 28.2°       | 23.98°            | -14.96% |
| First overshoot time     | 5.1 s       | 4.68 s            | -8.24%  |
| Second overshoot time    | 10 s        | 8.28 s            | -17.2%  |
| Initial turning ability  | 4.74 m      | 4.91 m            | 3.59%   |

**4. Conclusion**

In this paper, overset grid technology and body-force method are used to numerically simulate the zig-zag motion of an oil tanker. During the process of calculation, characteristic parameters of zig-zag motion are monitored. And they are tested in ship model test. By comparing the calculation and test results, the following conclusions are got:

1) Through comparison of test and numerical results, accuracy of calculation method meets the requirements of actual engineering needs. And it proves that it is reasonable to replace a real propeller with body-force propeller model.

2) The detailed flow field near the hull and rudder that cannot be provided by the model test is shown through numerical calculation, which provides a theoretical basis for analyzing ship motion.

3) The rudder angle and the heading angle of the numerical calculation are in good agreement with the test results, it proves that ship motion in numerical calculation is basically consistent with the experiment.

**References**

[1] RYAN G , Improved underwater vehicle control and maneuvering analysis with computational fluid dynamics simulation[D]. Virginia: Virginia Poly-technic Institute and State University, 2013.

[2] WU Zhaohua, CHEN Zuogang, and DENG Deheng. Numerical study of hydrodynamic force on ships in turing motion based on a body-force propeller model[D]. Journal of Shanghai Jiao Tong University, 2013.

[3] Carrica P M. DES simulations of KVLCC1 in turn and zig-zag maneuvers with moving propeller and rudder[C].//Proceedings of the SIMMAN 2008 Workshop on Verification and Validation of Ship Maneuvering Simulation Methods. Lyngby, Denmark: [s.n.], 2008.

[4] WANG Jianhua, WAN Decheng CFD simulation of ship turning motion in waves. Chinese Journal of Ship Research, 2019, 14(1): p.1-8.

[5] SUN Chenguang, WAN Decheng, CFD numerical simulations of stopping maneuver of ship model using overset grid technology[J]. Chinese Journal of Ship Research, 2019, 14(2): p.8-14.

[6] XIANG Guo, OU Yongpeng. Numerical simulation and analysis of the zig-zag maneuvers of a ship model [J]. Journal of Wuhan University of Technology, 2016.