CFD numerical simulations of inertia stopping of a very large gas carrier using overset grid technology and body-force propeller

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Abstract. With the development of International shipping, waterways all over the world are becoming increasingly crowded. Research on inertia stopping ability of large ships is essential to voyage safety. At present, the inertial stopping of ship is mainly measured by ship model test, and there is little work to study the performance using CFD technology. STARCCM+ based on the ship 6-DOF motion and overset grid technology and body-force method are used to numerically simulate the inertia stopping maneuver of a very large gas carrier. By controlling the rotation speed of the propeller, the ship is in a stable state of motion. Then set the speed to zero. The motion state and detailed flow field information of the ship model during motion can be got by solving viscous flow field. To verify the accuracy of numerical prediction results, ship model test is launched. Both the trajectory of the ship and the value of the characteristic parameter match very well.

1. Introduction
The rapid development of world industry is inseparable from energy. As a major form of energy, natural gas is in increasing demand. Due to the large load capacity and relatively low transportation cost, VLGC has gradually become the main ship type for natural gas transportation. However, it faces a greater risk of collision during navigation because of the large draft and large inertia, especially when the water depth is restricted such as entering and leaving the port. In most cases, ship collision accidents are caused by the pilot's careless mastery of maneuverability, among which the stopping performance of the ship plays a key role. The stopping test, also known as the "inertial test", is a test which belongs to the ship performance test. The main engine of the ship moves at full speed to the stop to measure the trajectory of the ship and glide time. But the cost of model test is very high.

In recent years, the application of CFD (Computational Fluid Dynamics) calculation method in ship maneuvering motion has made great progress. Abba studies the oblique towing problem of KVLCC2 under different working conditions including different drift angles and different turbulence models. The effect of the free surface is ignored in the numerical simulation of the static oblique towing test. Finally, he summarizes the computational advantages of different turbulence models under different working conditions[1]. Liu Yi uses the commercial software starccm+ to carry out the numerical simulation of the oblique towing test of the standard ship model KCS at different drift angles and calculates the working conditions of different rudder angles, considering the heave and pitch motion of
the ship in the calculation model[2]. Wan Decheng performs numerical calculations on the oblique towing test of the large cruise ship KVLCC2 at different drift angles and different draughts and simulates the bottom suction effect of the hull under shallow water conditions, and gives a lot of flow field information around the hull[3]. Mofidi uses self-developed hydrodynamic software to numerically simulate the maneuvering motions of ship at different speeds, and dynamic overlapping grid technology are adopted to process large-scale maneuvering motions of the model. The error between values of test and the values of the numerical prediction is within 10%. It is pointed out that the simplified propeller volume force model is the main reason for the prediction error[4]. Because existing ship maneuverability optimization algorithms has the problem of low convergence, Liu Bingjie tries to solve it by applying the decomposition-based multi-objective evolutionary algorithm to ship design and proposing a constrained multi-objective evolutionary algorithm for ship maneuverability design. The algorithm can provide more design schemes, and they have better convergence[5]. In order to improve the accuracy of the mathematical model of ship maneuvering in the port, Zhang Qiang gives a mathematical model of ship considering the propeller reversing characteristics. The model fully considers the mutual interference of the ship, rudder and propeller, and improves the accuracy of forecasting ship maneuverability in the port[6].

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 \( \omega \) represent density, time, and velocity component respectively.

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

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

$$\frac{\partial w}{\partial t} + \nabla \cdot (\rho u w) = -\frac{1}{\rho} \frac{\partial p}{\partial z} + u \nabla^2 w + f_z$$ \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:

$$f_{b\theta} = A_b \cdot \frac{r^* \sqrt{1 - r^*}}{r^*(1 - r_h) + r_h}$$  \hspace{1cm} (5)

where \( f_{b\theta} \) is axial force and \( f_{b\theta} \) is tangential force; \( f_{b\theta} = A_r r^* \sqrt{1 - r^*} \)

\[ r^* = \frac{r - r_h}{1 - r_h} \]

\[ r_h = \frac{R_d}{R_p} \]

\[ r = \frac{r}{R_p} \]  \hspace{1cm} (6)
\[ A_X = \frac{105 \cdot T}{8 \pi \Delta (3R_H + 4R_P)(R_P - R_H)} \] (7)
\[ A_\theta = \frac{105 \cdot Q}{8 \pi \Delta R_P (3R_H + 4R_P)(R_P - R_H)} \] (8)

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.

### 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 and longitudinal grids of it are shown in figure 2 and figure 3.

**Table 1.** Basic parameters of the ship.

| Parameters                              | Values   |
|-----------------------------------------|----------|
| Lpp                                     | 3.87 m   |
| B                                       | 0.63 m   |
| Draft                                   | 0.20 m   |
| Longitudinal position of center of buoyancy | 1.94 m   |
| Height of center of gravity             | 0.22 m   |
| Rolling moment of inertia               | 16 kg \cdot m^2 |
| Pitch moment of inertia                 | 331 kg \cdot m^2 |
| Initial moment of inertia               | 358 kg \cdot m^2 |

**Figure 2.** Model of ship.

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 calculation domain is divided with the ship center as the origin, and its size is -1.5L<X<3L,-2L<Y<2L and -L<Z<0.5L, where L is the captain and the bow is facing the X direction.
2.4. Numerical simulation results and analysis
During the stopping test, the propeller rotates to accelerate the ship model. When the test speed is reached, the propeller stops rotating. This paper calculates the inertia stopping movement of the ship model under the speed of 1.3 m/s, and the characteristic parameters and trajectory of the movement are obtained. Figure 4 shows wave pattern before the propeller stops turning.

Figure 4. Wave pattern for self-propulsion in calm water.

Figure 5 shows the wave patterns at $V_s=0.6$ m/s. 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 5. Wave pattern at $V_s=0.6$ m/s.

Figure 6 shows longitudinal velocity distribution in cross section. There are wakes of a certain size on both sides of the stern. The longitudinal velocity of the fluid near the right side is greater than that of the left side. This phenomenon explains why the hull deflects to the right.

Figure 6. Longitudinal velocity distribution in cross section.

In order to study the mechanical mechanism of the ship stopping during the inertia stopping, the force situation during the hull maneuvering process was analyzed. Figure 7 shows the longitudinal force of the hull, and figure 8 shows the curve of speed versus time.
Figure 7. Longitudinal velocity versus time. Figure 8. Longitudinal force versus time.

Although longitudinal force of the hull fluctuates during movement, it tends to decrease gradually as the speed of the ship decreases. When the speed drops to zero, the hull resistance nearly drops to zero.

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. Figure 9 and figure 10 are the ship model and the experimental process respectively.

Figure 9. Model of ship.

Figure 10. Status of ship during experiment.

The numerical calculation results are compared with the test results in Figure 11, it can be seen that the trajectory of the numerical calculation are basically consistent with the test results. Characteristic parameters of inertia stopping motion are compared in Table 2. It shows that the numerical simulation results are reliable.

Figure 11. Comparison of trajectory.

| Parameters         | Test values | Calculated values | Error  |
|--------------------|-------------|-------------------|--------|
| Stop stroke        | 41.76 m     | 42.95 m           | 2.85%  |
| Glide time         | 108 s       | 104.82 s          | -2.94% |
4. Conclusion
In this paper, CFD method combined with overset grid technology and body-force method are used to simulate the inertia stopping the ship model. And characteristic parameters of the movement are tested in ship model test. Through this research, the following conclusions are obtained.

1) Through comparison of test and numerical results, accuracy of calculation method meets the requirements of actual engineering needs. It is feasible to use the CFD method to replace the model test to predict the inertial stopping performance of ship model.

2) The trajectory of ship model are in good agreement between the test results with the numerical ones, it proves that ship motion in numerical calculation is basically consistent with the experiment.

3) The paper uses the time-averaged method to numerically simulate the inertia stopping motion, but the accuracy of capturing large-separated flow around the hull is poor. More accurate separation vortex simulation method will be adopted to solve this problem to get a more precise flow field simulation and numerical prediction results with higher precision.

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