Direct Numerical Simulation of the Motion response AT rotary in regular waves

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ABSTRACT: Numerical simulation of the 6DOF(six-degree-of-freedom) response motion of ship in wave is one of the most challenging maneuvering tasks.Based on the DTMB5415 model, this paper uses an in-house code to simulation the rotational motion in calm water and regular wave.The simulation process uses a viscous CFD code that combines 6DOF solid motion equations and overset grids.The RANS equation is solved by finite difference method and the projection algorithm, simulation of propeller motion using a body-force model,and the level set method is used to simulate the free surface.Taking into account the validation of the reliability of the in-house code, this paper simulates the rotation of the modified DTMB5415 model in calm water, the motion of the ship is well matched with experiment. This article mainly studied the characteristics of the trajectories of turning circle, roll, speed lose, etc, and are helpful to judge the influence of the wave about the rotational motion. The results indicate that the rotation trajectory in the regular wave is obviously deviate from the rotation trajectory in the calm water. The speed loss in the regular wave is more than in the calm water, and the velocity of turning maneuver in the regular wave will always fluctuate.

Key Words: 6-DOF; rotational motion; numerical simulation; regular wave

INTRODUCTION

The ship maneuverability is the performance of ship to maintain or change its speed and course according to the driver's intention. It relates to security of ship closely. Rotary test is an important way to test the ship maneuverability [1]. In particular, the rotary test is to enable the ship to set the speed of direct sailing stability, rudder to a certain angle and remain unchanged, the ship into the rotation.Ship maneuverability simulations are typically carried out in calm water. Compared with the rotary motion in the calm water, the rotational motion in the wave is obviously more complicated. Usually, the longer the wave length, the higher the wave height, the more intense the ship's motion. This paper studies rotary motion of DTMB5415 in calm water and regular wave. This helps us to understand the effect of waves on the ship's rotational motion.

In the past, the motion equation of ship was established, and the trajectory and relative parameters of the ship were obtained by using the Runge-Kutta differential equation[2], and the precondition of this method was to establish the proper mathematic model, the key of which was hydrodynamic derivative. In recent years, the numerical method of ship maneuverability prediction based on CFD is more and more popular.Muscari[3] simulated the rotational motion of KLCCC2 using the RANS equation with 3-DOF, but did not consider the free surface. Carrica[4] simulated the rotational motion of KLCCC1 using the RANS equation with 6-DOF, which considered the free surface and solved it with the DES method.

MATHEMATICAL MODEL

Governing Equations

The computations are performed with the RANS in open water, which solves the continuity equations and unsteady incompressible RANS equations

$$\frac{\partial u_i}{\partial x_i}=0 \tag{1}$$

$$\frac{\partial \overline{u_i u_j}}{\partial x_j}=-\frac{1}{\rho}\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}[\gamma(\frac{\partial \overline{u_i}}{\partial x_j}+\frac{\partial \overline{u_j}}{\partial x_i})]-\frac{\partial(-\overline{u'_i u'_j})}{\partial x_j}+f_i \tag{2}$$

$\overline{u'_i u'_j}$ is the Reynolds stress with turbulent pulsation; u_i is the fluid mean-velocity component.

The Froude number and Reynolds number are defined as:

$$\mathrm{Fr}=\frac{u_0}{\sqrt{gL}},\mathrm{Re}=\frac{u_0 L}{\nu} \tag{3}$$

ν is the fluid viscosity coefficient.The turbulent equation uses a wide range of SST(Shear-Stress Transport) equation turbulence model to close the governing equation.The equations for turbulent flow energy k and turbulent dissipation rate ω are:

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_j}(\rho k u_i)=\frac{\partial}{\partial x_j}(\Gamma_k\frac{\partial k}{\partial x_j})+G_k-Y_k+S_k \tag{4}$$

$$\frac{\partial}{\partial t}(\rho\omega)+\frac{\partial}{\partial x_j}(\rho\omega u_i)=\frac{\partial}{\partial x_j}(\Gamma_\omega\frac{\partial k}{\partial x_j})+G_\omega-Y_\omega+D_k+S_\omega \tag{5}$$

Γ_k and Γ_ω are the diffusion ratios of k and ω; Y_k and Y_ω are the turbulent diffusion term; G_k is the turbulent kinetic energy generated by average velocity gradient; G_w is the production term of ω equation; S_k and S_ω are the custom source term.

6-DOF model of ship motion

6-DOF model of ship motion as shown in the Fig.1:

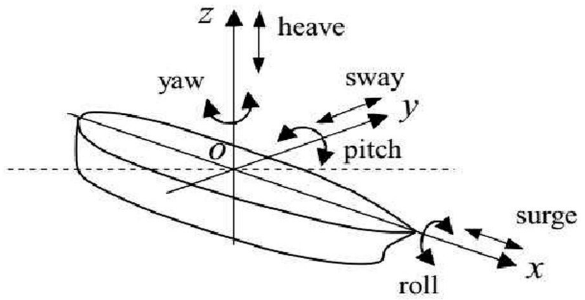

Fig.1 6-DOF model of ship motion

The general equations of ship space motion are:

$$\mathrm{m}(\dot{u}-vr+wq)=F_x \tag{6}$$

$$\mathrm{m}(\dot{v}-wp+ur)=F_y \tag{7}$$

$$\mathrm{m}(\dot{w}-up+up)=F_z \tag{8}$$

$$I_x p+(I_z-\dot{I}_y)qr=M_k \tag{9}$$

$$I_y p+(I_x-\dot{I}_z)pr=M_m \tag{10}$$

$$I_z p+(I_y-\dot{I}_x)qp=M_N \tag{11}$$

F_x, F_y, F_z are external force acting on the ship; M_K, M_M, M_N are moment; u, v, w are line velocity;p, q, r are the angular velocity.

Numerical simulation of waves

The wave theory is used to simulate regular waves by the height and length of incident wave.Regular wave can be realized by defining the initial boundary condition, and its can be formed by linear superposition of a series of harmonic waves of different amplitude, length of wave and wave direction. It also integrates a variety of wave spectra, simulates the marine environment by the given wave spectra, has reached the simulated ship in the high ocean conditions about the airworthiness motion response[5].

In order to describe the change of free surface over time, using the level-set[6] method to deal with, ignoring the air density and viscous effect, the water surface as a free interface,

Φ is the distance from any point of the field to the free surface. at any time, φ=0 for all points on the free surface.

$$\frac{\partial\varphi}{\partial t}+v\nabla\varphi=0 \tag{12}$$

"v" represents the vector of the velocity within the basin, the fluid is solved in the local area of the φ<=0, and the free liquid surface position (φ=0) is obtained by means of interpolation.

$$\nabla v\cdot n_j=0\ ,\ n_j=\frac{\partial\varphi/\partial x_i}{|\partial\varphi/\partial x_i|} \tag{13}$$

The grid quality of level-set method is stable and easy to control, and the simulation of free surface is more accurate.The free liquid surface position at the inlet of the flow field is set to the cosine function.

$$\eta(\mathrm{t})=\mathrm{Acos}(\mathrm{kx}-\omega t+\varphi) \tag{14}$$

The velocity of the fluid particle at the inlet is set to:

$$u=A\omega\frac{\cosh k(z+d)}{\sinh kd}\sin(kx-\omega t+\varphi) \tag{15}$$

$$w=A\omega\frac{\sinh k(z+d)}{\sinh kd}\sin(kx-\omega t+\varphi) \tag{16}$$

This kind of wave-making method is easy to be realized in practical operation, and it can achieve ideal effect with effective wave-eliminating methods. In the process of regular wave simulation, two methods of wave extinction are used, the first attempt is to reduce the wave's reflection on the boundary by simply using the sparse mesh near the end of the mesh, on the other hand, the damping wave and the outlet sparse mesh are combined to achieve the extinction. Both methods have obtained good wave-extinction effect.

1).Sparse mesh

Grid dissipation is a gradually sparse grid near the end of the grid, which can cause its amplitude attenuation by calculating the sparse grids in wave propagation. Specifically, this is the use of numerical dissipation to simulate wave decay, compared with the homogeneous grid, this method can also reduce the computational load[7]. However, it is too passive to rely on the grid dissipation, not only the sparse degree of the mesh is difficult to handle, but also the influence of the numerical viscosity of the grid dissipation region on the continuous wave propagation.

2). Damping method

The expression of the momentum equation after modification is:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=g_x-\frac{1}{\rho}\frac{\partial p}{\partial x}+v[\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}]-\mu(x)u \tag{17}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=g_y-\frac{1}{\rho}\frac{\partial p}{\partial y}+v[\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}]-\mu(x)v \tag{18}$$

The μ is the damping coefficient, and the linear damping form is adopted in the direction of wave propagation in the region with damping method:

$$\mu(x)=\begin{Bmatrix} a_s(x-x_0)/L_s & x>x_0 \\ 0 & x\le x_0 \end{Bmatrix} \tag{19}$$

The X_0 represents the beginning of the elimination of the wave position; a_s is the wave-extinction strength coefficient. however, the large value may cause more serious reflection wave, so it is necessary to get a better wave-eliminating effect to choose a reasonable a_s.

VALIDATION

In order to validation the reliability of the the in-house code. the simulation and experimental of the modified DTMB5415 model's turning circle in calm water are compared.

Geometry and data

This paper regard the modified DTMB5415 model based on some requirements as research object, the main parameters of modificati DTMB5415 model as indicated in the Table.1

Fig.2 Full appended modified DTMB 5415 model

Table 1. The main parameter of Modified DTMB5415 model

Ship parameter		Full Scale	Model
Scale	λ	----	34.16
Length overall	L_{oA} / m	175	5.15
Length of waterline	L_{wl} / m	162	4.74
Length between perpendiculars	L_{pp} / m	161.6	4.73
Maximum beam of waterline	B_{wl} / m	21.6	0.632
Design draft	d/m	4.73	0.138
Displacement	∇ /ton	8384.5	0.205
Rudder Area	A_R / m^2	15.4	0.0167
Aspect ratio	λ_A	1.26	1.26
Propeller diameter	D/m	6.15	0.18
Area ratio	A_e / A_0	0.58	0.58
Number of blades	Z	5	5

The simulation and experiment were performed at Fr = 0.232 and Re= 7.5×10^6, corresponding to a velocity of 1.58 m/s for a length L = 4.74 m.The ship is installed with a five-bladed propeller.The simulation of turning motion at 25° rudder angle was compared with experiments.

Table 2. Parameter for turning circle

δ =25° Fr=0.232			
Variable	EFD	CFD	Error%
Tactical diameter(m)	22.763	20.86	8.4
Relative turning diameter	4.42	4.05	8.4
Transfer(m)	10.82	10.5	3
Max roll in(°)	1.24	1.14	8
Max roll out(°)	0.97	0.94	3
Speed lose	0.865	0.846	2.2

Through comparing the simulation and experiment results on modified DTMB5415 model ' s turning circle. The numerical solver is well matched with experiment.Almost all simulated values have an error of less than 10% compared to the values of experiment.It indicates the reliability of the in-house code.

GEOMETRY CONDITION AND GRID

Geometry and data

In this paper, DTMB5415 is used as the object of study, and the geometrical model of DTMB5415 is shown in the Fig.2. Considering the speed and difficulty of calculation, this paper chooses the model ship as the research object, and the geometric parameters of the full scale ship and model ship are shown in the Table.3

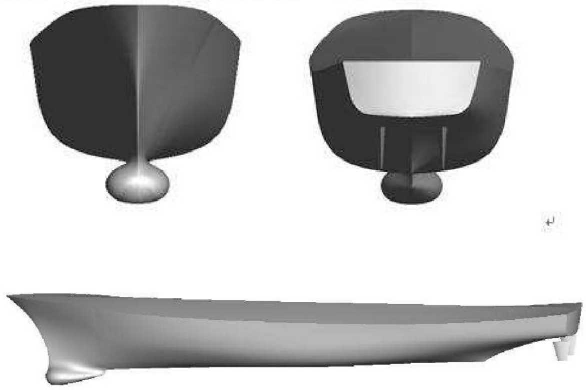

Fig.3 DTMB5415 model

Table.3 The main parameter of DTMB 5415 model

Ship parameter		Full Scale	Model
Scale	λ	----	35.48
Length between perpendiculars	L_{pp} / m	142	4.002
Maximum beam of waterline	B_{wl} / m	19.06	0.537
Design draft	d/m	6.15	0.173
Displacement	∇ /ton	8424.4	0.189
moment of inertia to x axis	I_{XX} /B	0.37	0.37
moment of inertia to z axis	I_{ZZ}/L_{PP}	0.25	0.25
Rudder Area	A_R/m^2	15.4	0.0122
Aspect ratio	λ_A	1.26	1.26
Propeller diameter	D/m	6.15	0.173
Area ratio	A_e/A_θ	0.58	0.58
Number of blades	Z	5	5

Condition

The simulation and experiment were performed at Fr = 0.248 and Re=6.22×10^6,corresponding to a velocity of 1.55 m/s for a length L = 4.007 m.In this paper, the rotary motion of the model ship under regular wave and calm water is studied, the direction of the wave is β=0°, wave height is A=0.017L, wave length is λ=1.5L.The ship is installed with a five-bladed propeller.Simulation of steady turn at 35° rudder deflection using constant RPM propulsion.

Grid

In order to take into the consideration of the grid size, three sets of girds are adapted to perform the simulations of the DTMB5415 with predicted turning motion in calm water, the results were verified by doing the grid convergence study. Grid generation is the key to the CFD method, grid quality directly affects the precision of the simulation results, the quantity directly affect the period of simulation.The medium and coarse grids for verfication study are coarsened from fine grids using non-integer refinement ratio $\sqrt{2}$ .The fine grid includes a 55-block grid system with 4.22M grid points. The smallest and largest blocks contain 2.88M and 6.27M grid points. Table.4 presents the overview of the three sets of computational grids and the simulation results.

Table 4. the description of the three sets of girds

δ=35° Fr=0.248			
Variable	fine	medium	coarse
Total grid number	2.88M	4.22M	6.27M
Relative turning diameter	2.21	2.33	2.35
Max roll in(°)	1.66	1.57	1.59
Max roll out(°)	1.61	1.52	1.55
Speed lose	0.705	0.701	0.698

By comparison with relative turning diameter, roll angle and speed lose, the results show that there is no significant difference in the simulation results of the medium and coarse grid groups .Therefore, a medium mesh having about 4.22 million cells is selected as the final mesh. After consider the simplicity of calculation, only the grid of hull and rudder is established. which simplifies the model greatly, improves the calculation speed and facilitates the study of the calculation results.
Because the grid size of rudder is smaller than the grid size of hull, the hull grid should be refined to match with the rudder grid. Appendages are handled by using overset grids. The grid of model and background grid are shown in the Fig.4-5:

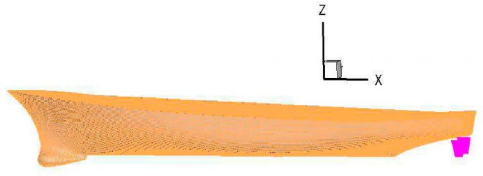

Fig.4 Grid of model

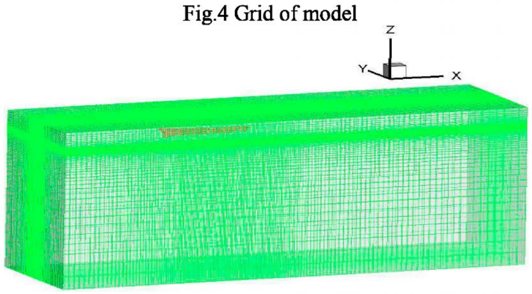

Fig.5 Background grid

The background grid is 5.5Lx1.7Lx2.4L (L is the length of model). The z-direction grid length 2.4L is designed to to simulate the navigation of deep water waves. In addition, the background grid is refined at the hull grid in x, y, z-coordinates. The hull grids and rudder grids are exactly the same in different computing conditions, and the totally grid number of each computing condition also is the same, but the refinement of the background grid in the wave height range is slightly different.And in order to more accurate simulate the regular wave,20 nodes are refined in the wave height range grid. The number of grid nodes are shown in the Table.5:

Table.5 Grid nodes

Grid	Grid nodes(M)
Background	1.19
Left rudder	0.31
Right rudder	0.31
Hull	2.41
Total	4.22

Simulation Design

The procedure of simulation for the turning motion is divided into three parts.The first step is the fixed propeller speed after the ship reaches the target speed,which is the self-propulsion stage.Then the regular wave is added (There is no such step in the calm water). Finally, start turning at a constant propeller speed.
The self-propulsion stage are performed with only 3-DOF, with the model restrained from yaw, roll and sway motions.The propeller speed remains constant after the ship completes the self-propulsion stage.Then the turning motion runs at a constant propeller speed, and the rudder angles are fixed to the specific value. This stage carried out with 6-DOF.
ITTC recommends measuring ship turning motion by obtaining turning trajectories, roll and speed lose.
Because simulation of propeller motion using a body-force model, the open water curve of the propeller needs to be fitted to the software.The body-force propeller model requires the thrust and torque coefficients K_t and K_q ,which obtained from the open water curves of the propeller. The open water curve of propeller and fitting formula are shown in Table 6 and Fig 6.

Table 6. The fitting formula for the open water curve of propeller

$$K_t or K_q = a + bJ + cJ^2; J = V / nD$$

Coefficient	Kt	10Kq
a	-0.103	-0.183
b	-0.325	-0.629
c	0.670	1.34

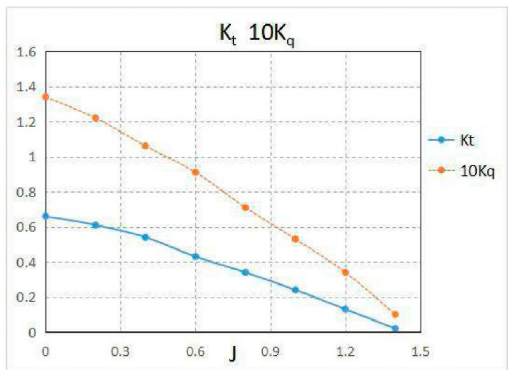

Fig 6 Open-water propeller characteristic from experiment

Numerical results and discussio

Numerical simulations of the turning motion of the DTMB5415 in calm water and regular waves were carried out. Trajectories for turning circle maneuver in the Fig.7:

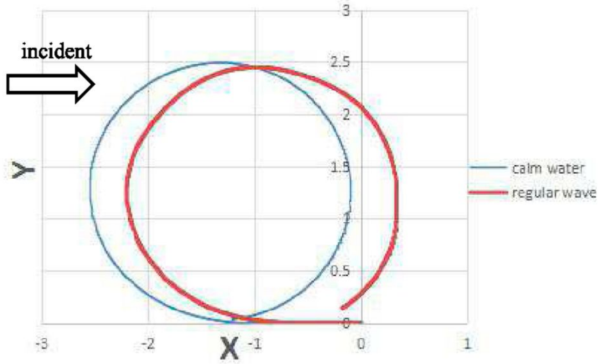

Fig.7 Trajectories for turning motion under calm water and regular wave (A=0.017L , λ=1.5L)

X-coordinate is x trajectory of ship relative length of ship, y-coordinate is y trajectory of ship relative length of ship. It can be shown from the figure that the rotation trajectory in the wave is obviously offset by the rotation trajectory in the calm water, the offset distance is 0.43L, and the direction of the offset is the same as the direction of the wave, because of the action of the wave on the ship, the thrust in the direction of the wave is generated, which eventually offsets the overall rotation trajectory.Roll angle predicted in the Fig.8-9:

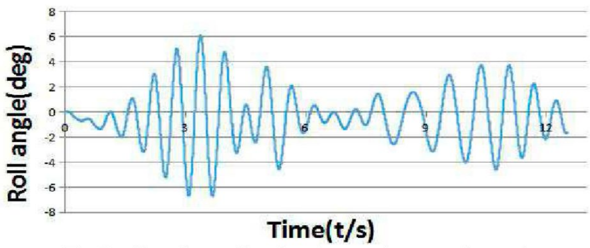

Fig.8 roll angle predicted under regular wave in turning maneuver(A=0.017L , λ=1.5L)

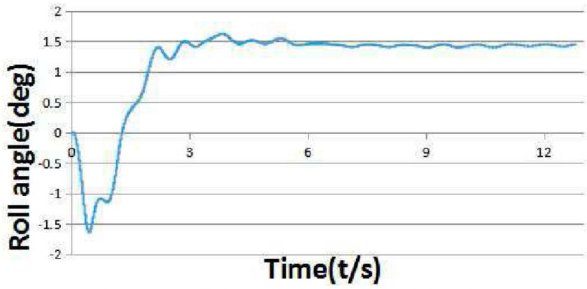

Fig.9 roll angle predicted under calm water in turning maneuver

It can be shown that the amplitude of roll angle in the wave is significantly larger than that in the calm water,the maximum roll angle in the wave is 6.54°, the maximum roll angle in the calm wave is 1.57°,the former is 417% of the latter. This is because the movement of the ship in the wave and the movement of the waves are coupled, resulting in the movement of the ship in the wave to become more intense than in the calm water. Finally, the amplitude of the roll angle of the wave is larger, In addition, the roll angle of the rotary motion in the calm water will eventually be relatively stable, while the roll angle of the wave is always vibrating up and down, which is also due to the action of the wave. Waves are cyclical, the role of the force on the ship is also cyclical, the movement of the ship has not been stable, the roll angle in the wave cannot stabilize finally.

The predicted of velocity are shown in Fig.10

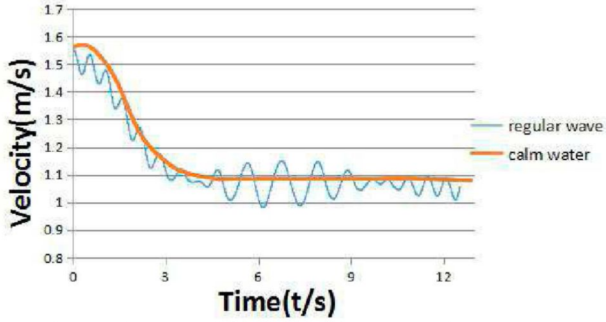

Fig.10 velocity predicted under calm water and regular wave (A=0.017L , λ=1.5L)in turning maneuver

As expected, at the beginning of the maneuver, the velocity achieve max , with the turning motion of the hull going on, the value of the velocity decreases, because of the impact of waves, speed has been fluctuating back and forth. Finally, the velocity in the calm water will gradually stabilize, but will fluctuate continue in the wave.The speed lose is 0.701 in calm water. Generally speaking, the speed of rotation in the wave is less than the speed of rotation in the calm water.

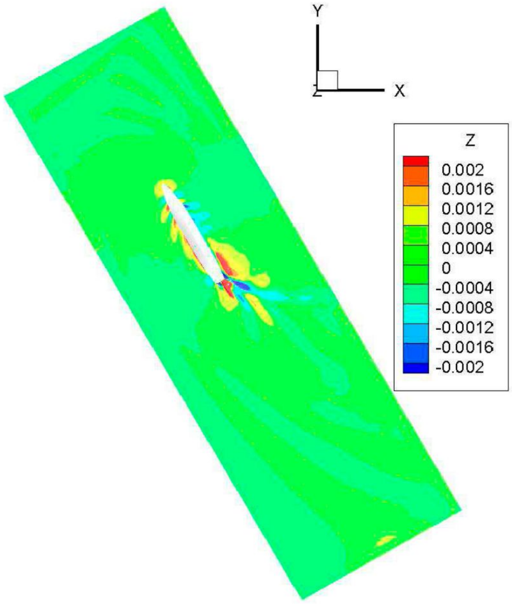

Fig.11 free surface of the ship in turning maneuver under calm water

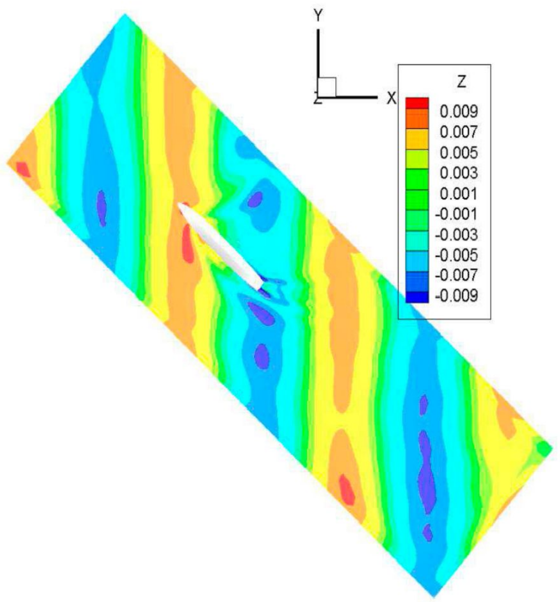

Fig.12 free surface of the ship in turning maneuver under regular wave

The free surfaces when the ship is just beginning to rotate are shown in Fig.11-12.Z is the height of the free surface after the non secondary, which indicates the ratio about the height of the simulated free surface and length of the ship. It can be shown that the trajectory of the ship on the free surface from figure , and the trajectory is obviously curved fluctuations in Fig.11,it represents the waves. Notice the waves around ship, the free surface has an apparent asymmetry around the hull. On the other hand, at the front of the ship and far from the ship's rear,the free liquid surface is basically symmetry, which is obviously caused by the turning maneuver.

CONCLUSIONS

The numerical study of DTMB5415 on turning maneuver in calm water and regular waves is carried out by the in-house code, the results indicate that:

1. The rotation trajectory in the wave is obviously offset with the rotation trajectory in the calm water, the offset distance is 0.43L, and the direction of the offset is the same as the direction of the wave.
2. The maximum roll angle in the regular wave is 6.54°, the maximum roll angle in the calm water is 1.57°.
3. The speed of turning maneuver in the wave is less than the speed of turning maneuver in the calm water, and the speed of turning maneuver in the wave will always fluctuate, on the contrary, in the calm water will eventually stabilize.

The turning tests of DTMB5415 model are simulated. The simulation process uses a viscous CFD code that combines 6DOF solid motion equations and overset grids.The RANS equation is solved by finite difference method and the projection algorithm, and the level set method is used to simulate the free surface,simulation of propeller motion using a body-force model.It is accurate enough to simulate the true flow around the ship.

In the future, we can study the influence of different wave directions,wave length and wave height on the rotational motion.Then, we can also try to simulate the turning motion in irregular waves.

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