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REVIEW OF SHIP MANEUVEARABILITY IN WAVES

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ABSTRACT

Ships are often disturbed by waves during actual navigation.Waves will not only make the ship sway but also make the maneuvering trajectory of ship change significantly, which puts forward higher requirements on the ship's maneuvering performance.In this paper, the essence of ship maneuvering motion in waves is analyzed,and maneuverability of ships is investigated under different waves,and model maneuvering test and numerical methods in waves are reviewed. Due to the significant developments in computational fluid dynamics(CFD), the use of CFD for the study of ship maneuvering motion in waves holds great promise for engineering applications.Finally the challenges and suggestions in numerical simulation on ship maneuverability in waves are summarized.

Keywords: Ship Maneuverability In Waves;Model Test;Numerical Simulation;Overset grid;Computational Fluid Dynamics.

NOMENCLATURE

λ	Wave length [m]
L	Ship length [m]
ϕ	Roll angle [°]
r	Yaw rate [°/s]
Ψ	Heading angle [°]
θ	Pitch angle [°]
δ	Rudder angle [°]
β	Drift angle [°]
ρ	Fluid density [kg m^{-3}]
CFD	Computational Fluid Dynamics
ITTC	International Towing Tank Conference

1. INTRODUCTION

With the development of international trade, ships are developing along the trend of enlargement, which puts forward higher requirements for the maneuverability of ships. In actual navigation, ships are inevitably affected by environmental disturbances such as wind, waves, and currents (Zhou,2000). In particular, the effect of waves will not only induce the ship's six-degree-of-freedom motion, but also reduce the ship's propulsion efficiency, which makes the ship's maneuverability worse. For example, when a ship is sailing at high speed in an oblique wave or quartering sea, if it is not properly maneuvered, it may simultaneously traverse, drift and roll.The maneuverability in the wave can be regarded as a combination of maneuverability in calm water and the problem of seakeeping performance. The fluid viscosity force dominates and changes slowly when the ship is in maneuvering motion in calm water. For the wave-induced ship movement, the force is dominated by the non-viscous force, and the main part (the first-order wave force) shows a trend of high-frequency change (Zhang,2016).In order to improve the accuracy of numerical prediction of maneuverability in waves, most methods seek to simultaneously deal with the the two forces of different properties on ship motion.At present, there are four popular research methods for maneuverability in waves(ITTC,2011): experimental methods; numerical simulation methods based on unified theory; numerical simulation methods based on two-time scale model;numerical simulation methods based on CFD.

The model test method is divided into captive mode test and free-running model test (Cao,2020), which is still the most reliable method for studying maneuverability in waves, but this method requires accurate propeller and rudder control systems, and equipment for measuring the movement of six-degree-of-freedom of the ship. In addition, in order to truly restore the actual flow field during the maneuvering motion of the ship, a test tank similar to the actual environment is required. So the cost of the ship model test is very high, and the current test method cannot give the fine flow field structure around the hull, propeller and rudder during the maneuvering motion.

Numerical simulation methods based on two-time scale model and unified theory are the most widely used, both methods are potential flow theory, but differ in the treatment of specific details (Li,2022). The unified theory is usually based on the six-degree-of-freedom equation of the ship's motion in calm water, and the forces caused by the waves are included in the equation to form a unified rigid body motion equation to describe the ship's motion in the wave.Based on the two-time scale method, the total ship motion is divided into low-frequency ship maneuvering motion and high-frequency wave-induced motion, and they are described by two different sets of motion equations. The high-frequency motion is determined by the first-order wave force, while the second-order drift force is included in the ship's maneuvering motion equation to reflect the influence of the wave on the manoeuvring motion.

At present, CFD is the most popular method. The CFD method can not only realistically reflect the situation of the ship moving in waves, but also can analyze the details of the flow field around the hull and the appendage.So this method can discover the interaction between the hull and the appendages, and help researchers better understand maneuverability of ships in waves.

2. Experimental method

Since Davison conducted its first experiment of ship maneuvering motion in waves in 1948, significant progress has been made in the research on this issue(Zhao,1984). The maneuverability test of the ship in the waves, mainly consists of the captive mode test and the free-running model test. The propulsion device is usually installed in the stern of the ship in the free-running model tests, and the rudder is rotated to make the ship rotate.The trajectory, roll angle and other motion parameters during the ship’s motion can be obtained in the test. The captive mode test is to install the ship model in a specific test device to force the ship to make specific movements.The hydrodynamic force, torque and six-degree-of-freedom motion response of the ship model can be measured. Free-running model test mainly includes turning test and zig-zag test,while the most common captive mode test is PMM test (Zhang,2018).The current wave maneuverability tests are mainly free-running model tests.

XU(2007,2008)conducted PMM tests in waves. They measured the hydrodynamic and horizontal displacement of the ship model, researched the calculation method of the drift force including drift damping and drift additional mass, and compared the calculated drift force with the test results. They concluded that significant wave drift damping will be appeared even in low-frequency and low-speed oscillations. Fig. 1 is the special mechanism they designed to conduct PMM test.

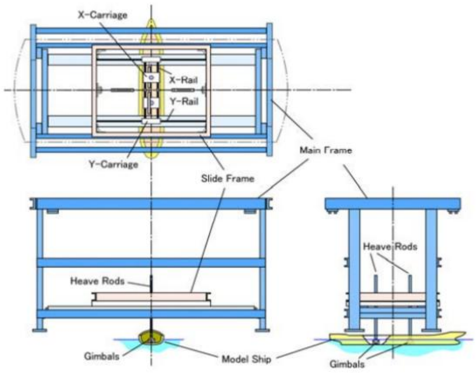

Figure 1. Structure of the PMM device

Dong Jin Jim (2019)carried out the free-running model test in waves of KVLCC2 tanker. He carried out a total of 30 sets of tests in regular waves with different wave heights, wavelengths and wave directions, and concluded that the speed of the rudder has little effect on the low-frequency maneuvering motion. When the wavelength is less than the ship length, the drift distance of the motion trajectory is large. The relative drift angle is maximum when the wavelength is equal to the ship length. When the wave height and wavelength are the same, the results of the drift angle and drift distance in the steady motion phase are basically the same.Fig. 2 is the model of KVLCC2.Fig.3 is the set up for free-running model test.Fig.4 is the Coordinate system settings for the test.

Figure 2. Ship model of KVLCC2

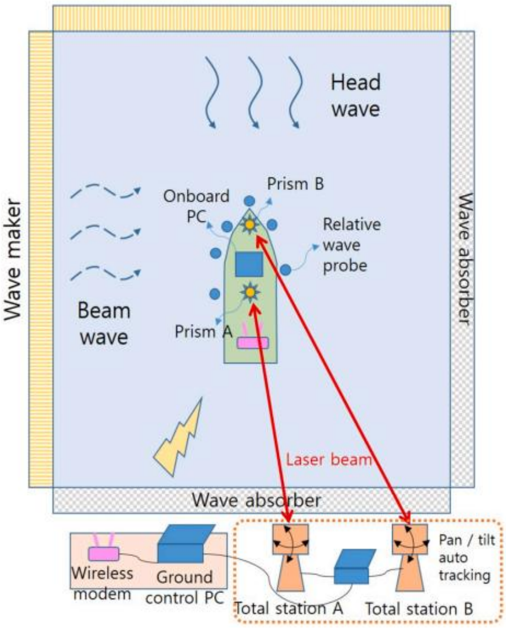

Figure 3. Set up in basin for test

Fan (2000) conducted free-running ship model tests in regular waves of the S175 container ship in a wind, wave and current tank with a scale of 24mx9mx0.8m.Experimental contents include turning motion and zig-zag motion. Due to the small size of the ship model, it is not possible to install conventional heading gyroscopes. The author has specially developed a ship model induction gyro magnetic compass, which is characterized by light weight and high accuracy.The wave height is set to 0.02m, 0.015m, 0.01m respectively, the wave period is set to 0.57s, 0.8s, 1.13s respectively, and the wavelength to length ratio is set to 0.01, 0.015, and 0.0066 respectively. The experiment found that constant diameters in the head sea decrease compared to that in calm water, but the constant diameters increase when the ship turns in the following sea. From the perspective of the advance , there is no change in the head sea , but it increases in the following

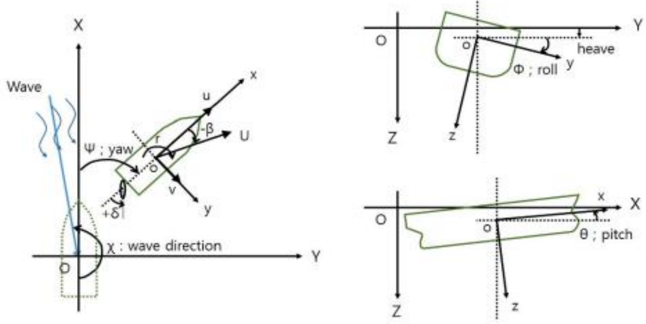

Figure 4. Coordinates system

sea. The wave period has little effect on the constant diameter and the advance, it mainly affects the drift distance.In the zig-zag tests, both the first and second overshoot angles increase compared to those in calm water.Hasnan(2019) carried out the turning test in irregular waves using KVLCC2 and KCS ship models.The speed of ships ranges from 5kn to 15kn and the two ships are tested in five different irregular waves.These five irregular waves are all head waves,and their wave height and the period of the waves are also the same. Their difference lies in the phase of the waves.The test results show that when the speed decreases, the advance of ships decreases, but tactical diameters does not change significantly, and the drift distance and drift angle increase. The trajectories of ships in different irregular waves has changed slightly,the author thought it is due to the slowly changing second-order wave force during the turning motion.Sun(2001) performed a study on the maneuverability of an engineering ship in irregular waves at the China Ship Science Research Center, the main size of the tank is 69mx46mx4m, and the wave maker is air-type. Irregular waves similar to the actual sea state were selected, and the spectrum were selected according to biparametric spectrum recommended by ITTC (Wu, 1998). The test results show that the drifts of the trajectory in the direction of the wave is related to the rudder angle, speed and sea state. The larger the speed, the smaller the steering angle.The larger the wave height, and the greater the drift. The swing amplitude of the turning motion in the wave is related to the direction of the wave, and the swing amplitude is the largest in beam sea.

3. Unified theory

In the eighties of the last century, Hirano (1981) first directly added the second-order wave force obtained by the experiment to the three-degree-of-freedom MMG model for calculating maneuverability in waves, without considering the roll motion. Mccreight (1986) established a six-degree-of-freedom mathematical model for ship maneuverability in waves , which is added hydrodynamic coefficients related to wave frequency. Hamamoto and Kim(1993)proposed a horizontal ship-following coordinate system, which divides the ship's six-degree-of-freedom oscillation motion in waves into manoeuvring motion in the horizontal plane, lateral roll motion, longitudinal pitching and heaving motion.The equation combines maneuverability, dynamic stability and seakeeping for research.Fan(2001) added the propeller speed equation on the basis of Hamamoto and Kim to account for the change of propeller speed in the maneuvering movement of the ship. In this paper, the S175 container ship is used as the research object, and the advance distance and constant diameter under different wavelengths and wave directions are calculated.Baily (1997)formally proposed the unified theory.He added the incident force, radiation force and diffraction force in the wave to the equation of maneuvering motion, and the method also considered the influence of the wave memory effect on the maneuverability of the ship. Nishimura (2003) added incident force to the equation of ship motion, and studied the maneuverability of small fishing boats in waves.The equation takes into account that the inertial force in each direction of the ship will change with the frequency of the incident wave.Sutulo (2006) proposed an auxiliary variable method to solve the time-domain radiation force expressed by fluid memory effect, and carried out standard maneuverability simulations such as direct flight, turning motion and zig-zag motion.

Subramanian (2015)established a nonlinear unified model, and used the time domain strip theory to calculate the turning motion of S175 ship in regular waves, considering the effect of nonlinear recovery force caused by instantaneous wet surface. At the same time, in order to improve the calculation speed, the free surface conditions still adopt the linear treatment, and the action of the second-order wave force is considered by the square of the velocity potential gradient. In order to solve the movement of the hull in waves,three coordinate systems are set up.The Earth fixed coordinate system is to track the movement of the position of the ship's center of gravity, the hydrodynamic framework is to solve the boundary value problem, and the rigid body coordinate system is to solve the ship's force.Fig.5 shows the three coordinate systems.The mixed boundary value problem is solved by using a source distribution technique.Fig.6 shows the details of the distribution technique.Although the calculation results of tactical diameter, advance distance and constant diameter are larger than experimental ones, the approximate trajectories of the ship are basically consistent with the test. Although this calculation method has both accuracy and efficiency, when the steepness of the wave increases, the accuracy of the calculation drops significantly.Fig.7 shows the results of comparison.

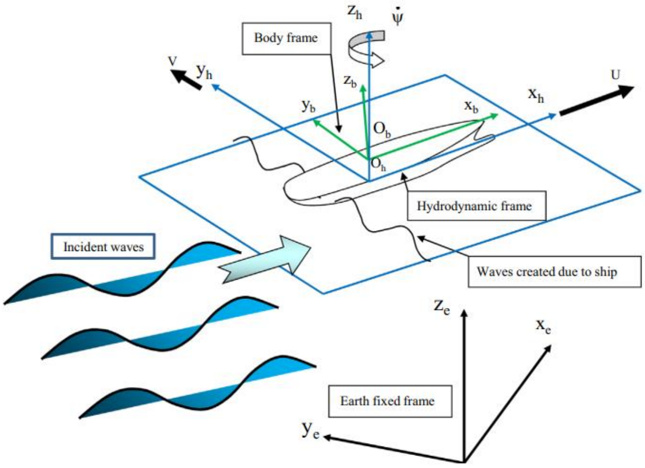

Figure 5. Three coordinates systems used

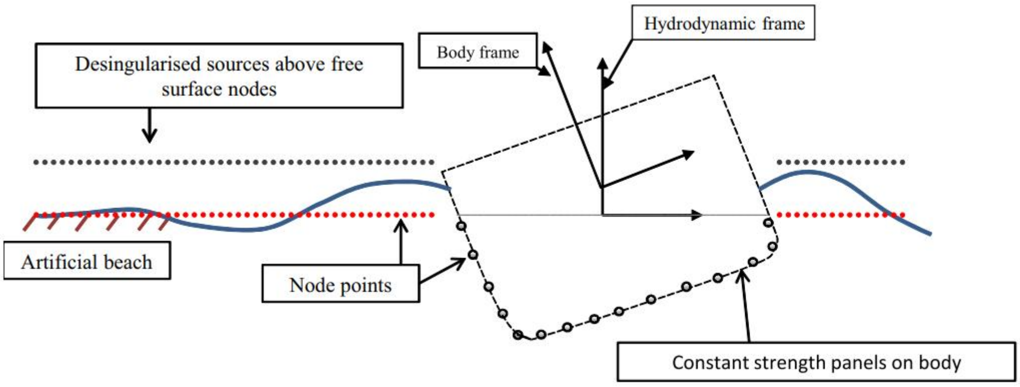

Figure 6. Details at a given station

Although there is still no unified conclusion on the mechanism of ship maneuvering motion in waves, it is basically believed that the second-order wave force has a significant effect on ship maneuverability, which should not be ignored in numerical simulation. Because the unified theory combines the manipulation motion and the wave-induced motion together, the calculation accuracy of the second-order wave force is often difficult to guarantee.

4. **Two-time scale model**

In the 90s of the last century, Nonaka(1980) believed that the movement of the ship in the wave in an ideal fluid is a superposition of the first-order high-frequency motion, the first-order low-frequency motion and the second-order low-frequency motion. Through model experiments, Inoue(1966)found that the trajectories of ships in waves drifts significantly compared with ones in calm water, the author believed that drifts are mainly caused by the second-order wave drift force.On the basis of these theories, the two-time scale method was gradually developed and summarized by Skejic and Faltinsen(2008).Yasukawu (2009)calculated turning performance in regular waves considering the six-degree-of-freedom motion of ships.He used the three-dimensional panel method to calculate the high-frequency wave force,and used Maruo's far-field integral formula to calculate the second-order wave drift force.Wicaksono(2019)used the two time scale method to simulate the turning motion of SR108 container ship in regular waves, in which the seakeeping performance was solved by the enhanced unified theory based on the slender body theory.The comparison between the simulation results and the experimental ones shows that the calculation accuracy of the method in long waves is relatively high.Based on the two time scale theory, Yu(2016)established the equations of three-degree-of-freedom manipulation motion and five-degree-of-freedom seakeeping motion, and studied rolling, surf riding and broaching-to based on the equations. Based on the theory of two time scale model, Zhang (2021)established a numerical model of manipulation motion in regular waves by using the time-domain Rankine panel method, and verified the accuracy of the method by comparing the calculation results with experimental ones. Seo(2011) developed a ship motion time domain program based on the three-dimensional Rankine panel method to solve the problem of ship maneuvering in waves, and calculated the second-order mean drift force by direct pressure integration method. The author calculated the turning performance of S175 container ship at different wave directions and different ratios of wavelength to ship length.Fig.8 shows the solution grid.Fig.9 shows the wave contours during turning motion in waves.Fig.10 shows the comparisons of turning trajectory in regular waves.

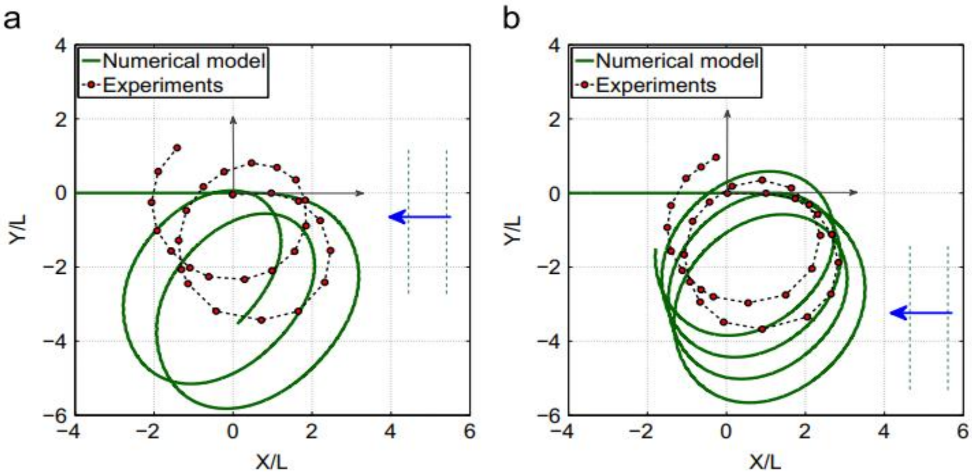

Figure 7. Turning circle maneuver of S-175.(a)λ/L=1,head seas,H/λ=1/50.(b)λ/L=1.2,head seas,H/λ=1/60

The two time scale model describes the movement of ships in waves with two sets of equations. Although the two sets of equations are independent in their solution, the coupling of them can be achieved by the interactive transfer of data. It can actually be regarded as a new form of unified theory.The two time scale method has certain advantages in the calculation of second-order wave forces. However, many related studies combine the seakeeping calculation program with the manipulative calculation program, while ignoring the influence of the manipulation motion on the wave force.

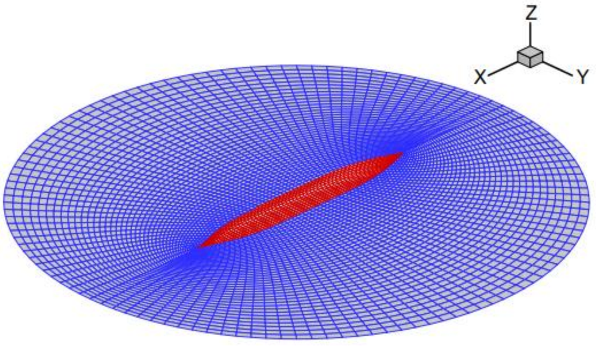

Figure 8. Panel model for S-175

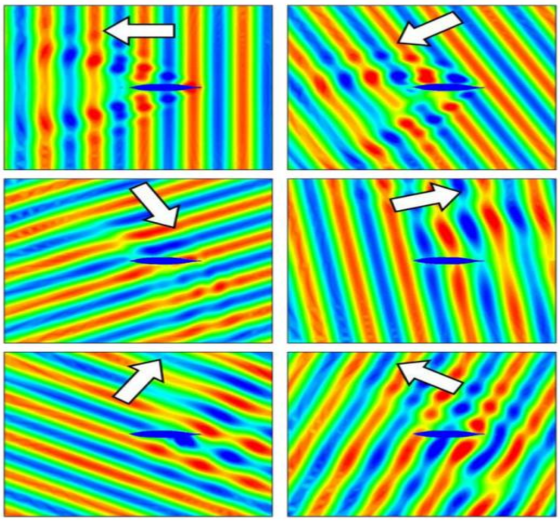

Figure 9. Wave contours for S-175 during turning motion

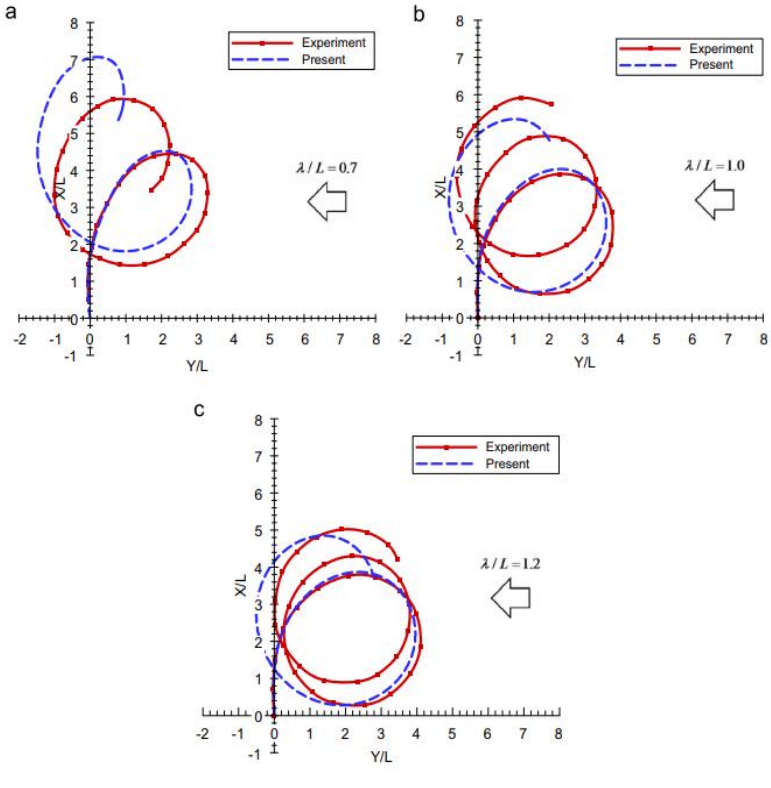

Figure 10. Comparison of turning trajectories in regular waves

5. CFD approach

The first successful application of CFD to numerically simulate the turning motion of a ship in regular waves was Stern(2008).Carriba(2010)and Shen(2015) developed the lagged model and Suggar code on openfoam to handle large movements of ships in maneuvering motion and improve the efficiency of calculations. Data processing is shown in the Fig.11. Shen updated these two technologies into the naoe-FOAM-SJTU solver to calculate the zig-zag motion of the KCS, and the calculation results matched the experimental ones well.Shen(2014,2016) also developed a spectroscopic method to ensure that the irregular waves generated correctly during the calculation process. Moreover, this method is applied to predict the motion response of three different ship models in irregular waves, and the results show that the irregular waves generated by this program can obtain the same good motion response as regular waves.

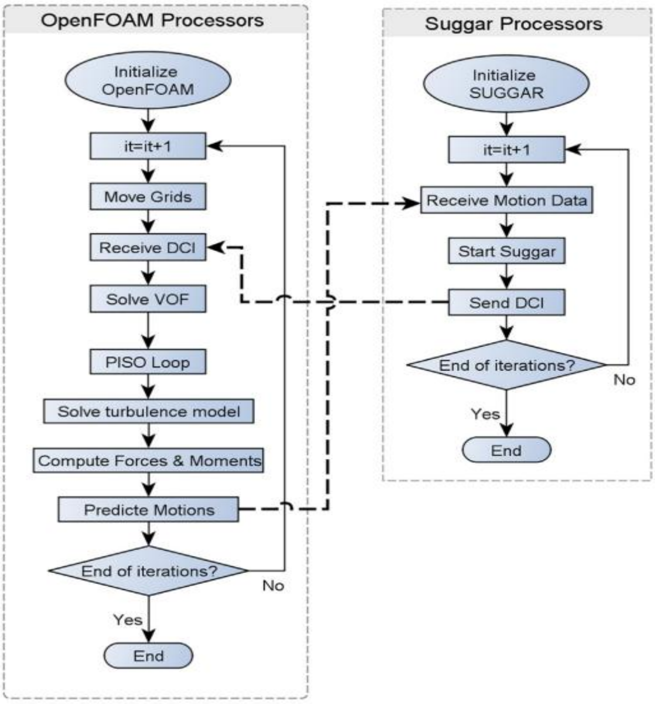

Figure 11. Exchanges between openfoam and Suggar in lagged mode

When the overset grid is used to handle the movement of the propeller and rudder,special attention is required to mesh when the gap is small. Mofidi (2014)used overset grids to simulate zig-zag motion of KCS fitted with semi-balanced horn rudders.The difficulty of the problem was that the gap in the rudder root was too small, and the author solved this problem by developing a technique with a hierarchy of bodies.Fig.12 shows grids around rudder.

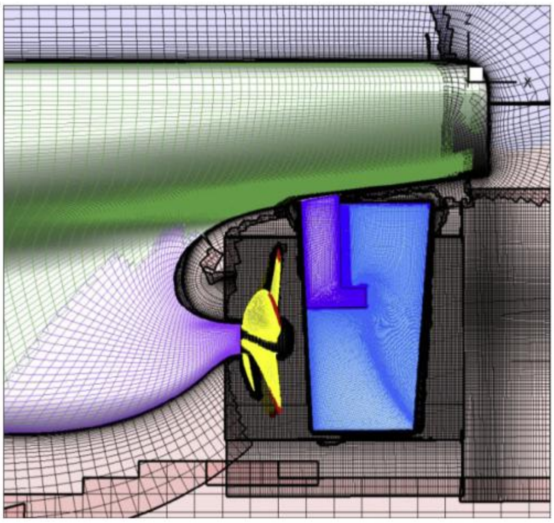

Figure 12. Overset grid around rudder

To study the effect of regular waves on propeller propulsion performance, Sigmund(2017) studied the performance of propellers when a cruise ship and an ultra large containership sailed in calm water and waves. In numerical calculations, he used the slip grid to process the rotation of the propeller and took into account the influence of the free surface. By comparing with the experimental results proves that the RANS solver can study the performance of propellers in waves well.Carrica (2008)used CFD-Ship-Iowa version 4 to simulate the broaching event of the DTMB5613 ship in irregular waves.The software is based on unsteady Reynolds-averaged Navier – Stokes and applys single phase to process interfaces ignoring the effects of air.The large movement of the ship is processed with overset grids and waves are generated by the Bretschneider spectrum.Fig.13 shows the outline of the overset grid.Fig.14 shows the structure of ship during broaching.Fig.15 shows the trajectories of ship.

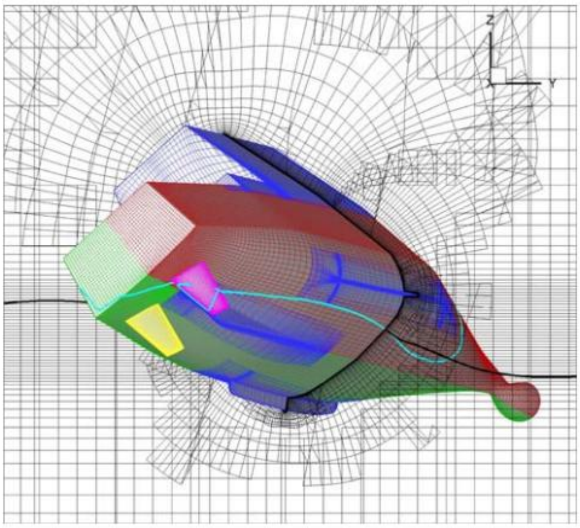

Figure 13. Outline of the overset grid

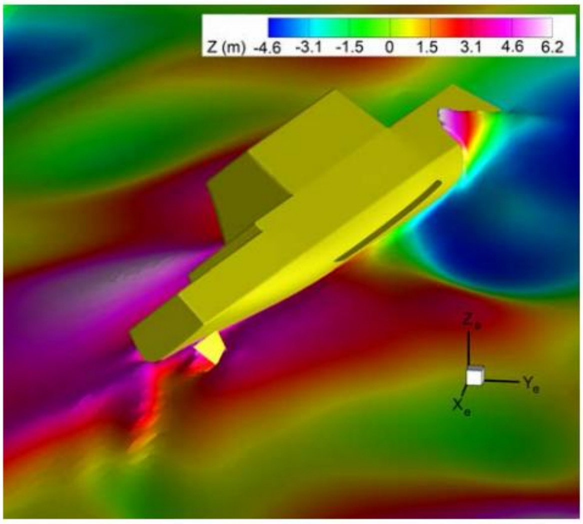

Figure 14. Structure of ship during broaching

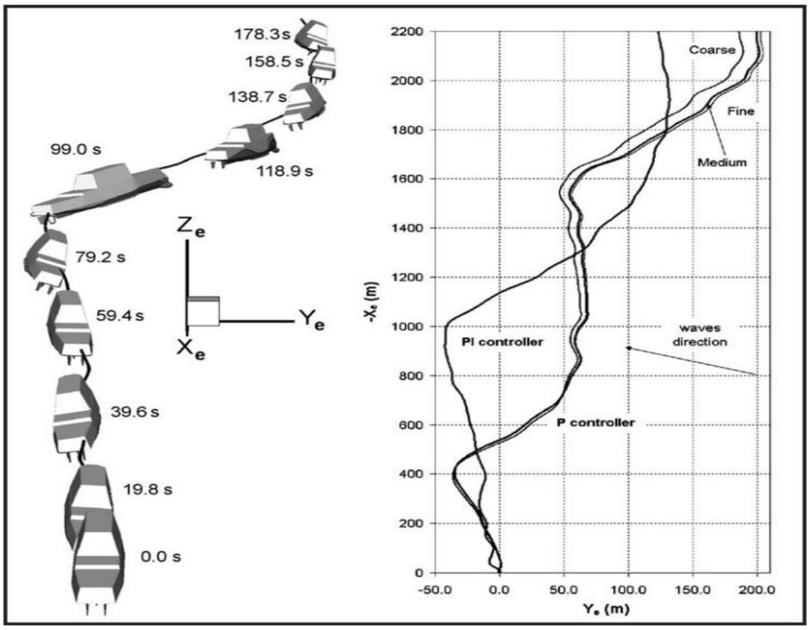

Figure 15. Trajectories of ship

Wang (2018)used naoe-FOAM-SJTU solver to perform a simulation of turning motion in waves using the fully appended ONR Tumblehome ship . He used overset grids to deal with the complex motion of the ship, propeller and rudder system, and used the regional wave making method to generate waves. The RANS equation is used to solve the control equation, and he selected SST k-ω as the turbulence model. The equations are discretized by the discrete format that comes with openfoam.The 2nd-order backward Euler scheme is used for temporal discretization and the convection terms is discretized by the 2nd-order TVD scheme.The time step is set to 0.0005s, corresponding to the time for the propeller turning 1.5 degrees. Through comparison with the experimental results, it is found that the error of characteristics between calculation and test is within 10%. Wang(2018) used the same setup to calculate the ship's zig-zag motion, and also achieved good calculation results.Fig.16 shows the arrangement of the overset grid.Fig.17 shows the grid distribution around stern.Fig.18 shows the diagram of wave generation zone.Fig.19 shows the comparison of trajectories of turning circle.Fig.20 shows the free surface during turning circle.

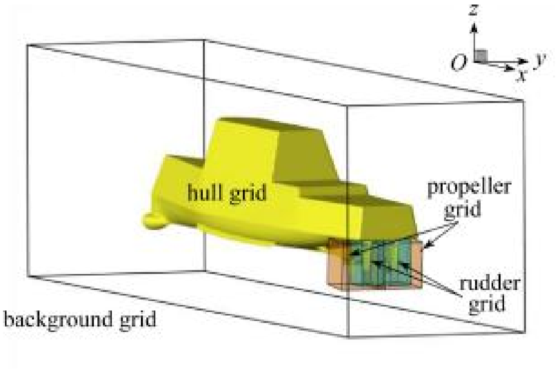

Figure 16. The arrangement of the overset grid

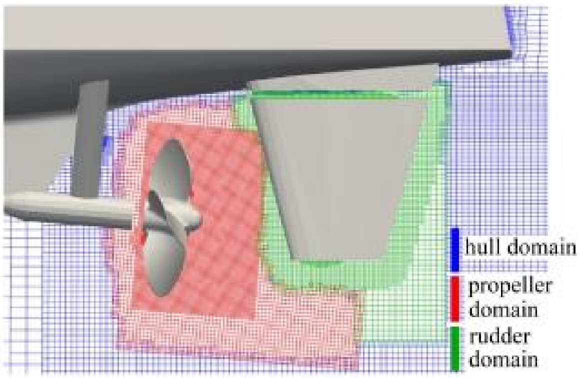

Figure 17. The grid distribution around stern

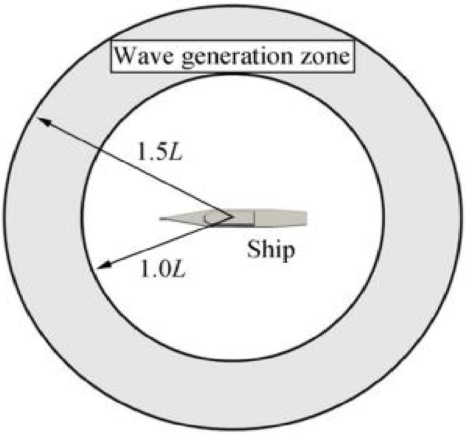

Figure 18. The diagram of wave generation zone

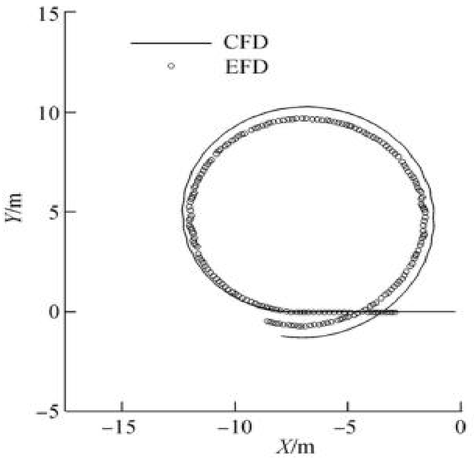

Figure 19. The comparison of trajectories of turning circle

Mofidi(2015)used CODE REX to calculate the turning motion of KCS in regular and irregular waves, and he came up with a series of methods to improve the computational efficiency of ship’s turning motion.REX used a single phase flow to deal with the RANS equation, Suggar is obtained to ensure the connectivity of overset mesh,and six-degree-of-freedom is incorporated with a hierarchy of bodies. These methods to improve computational efficiency include local time stepping for propeller, the decomposition of overset process, and use of coarse grid. Fig.21 shows the details of overset grid.Fig.22 shows the trajectory of turning circle in regular and irregular waves.Fig.23 and Fig.24 show the top view of free surface in regular and irregular waves respectively.

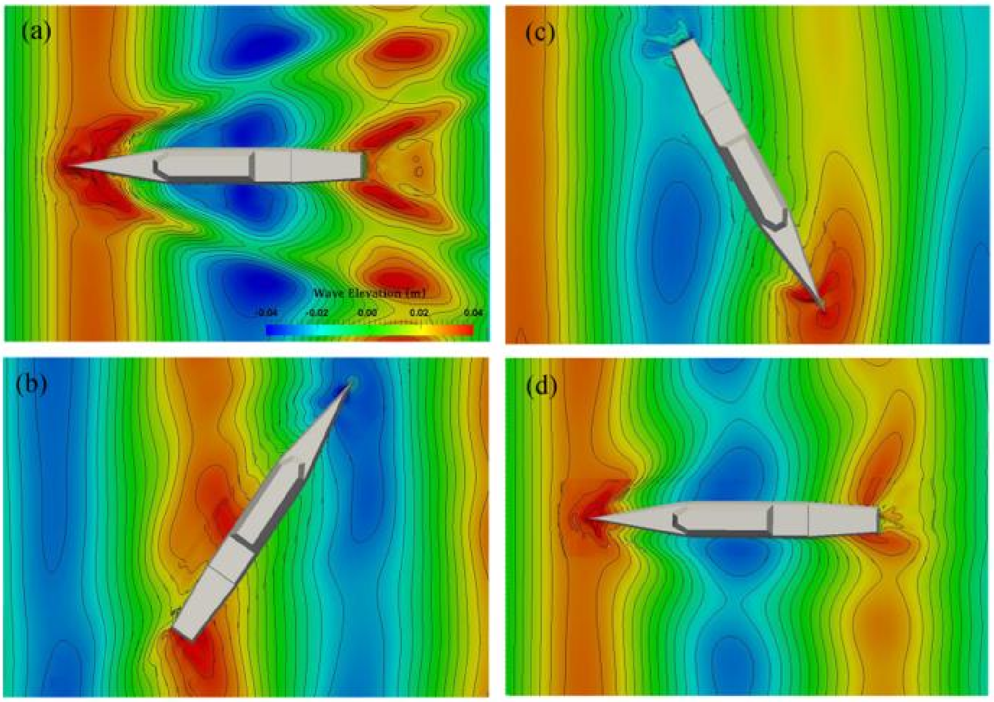

Figure 20. The free surface during turning circle(a-d correspond to heading change of 0, 120, 240 and 360, respectively)

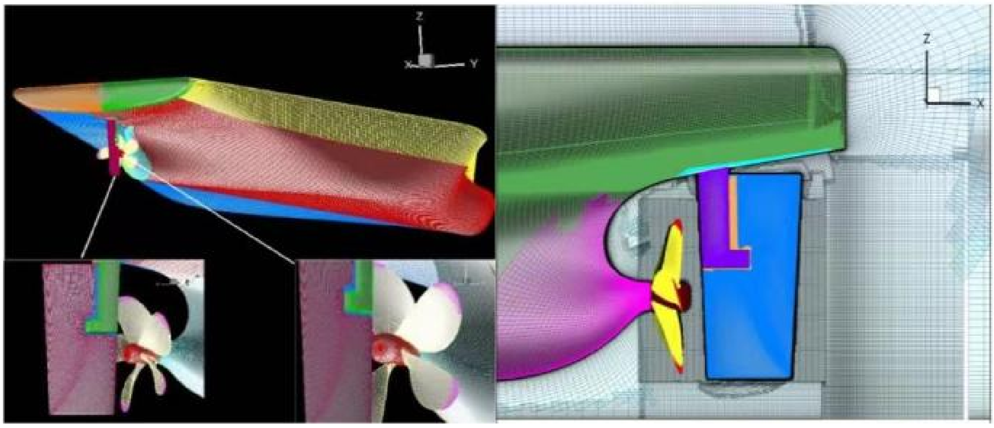

Figure 21. Overset grid details

CFD technology is the directest way to calculate the maneuvering motion of a ship in waves, and this method can analyze the details of the flow field around the hull and the appendage, so as to discover the interaction between the hull and the appendage. Accurate simulation of ship movement in waves needs to consider the large free surface deformation, significant interaction between the propeller and the rudder, and large motion of hull.And as things stand, the study of ship maneuvering motion in waves with CFD is still very time-consuming.

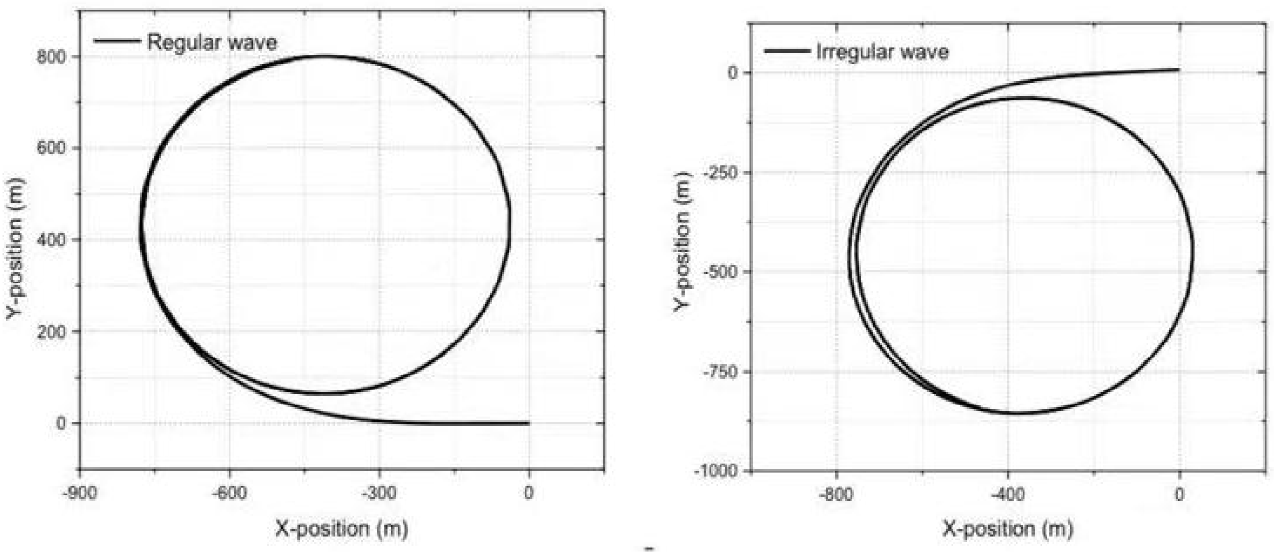

Figure 22. Trajectory for turning circle in regular and irregular waves

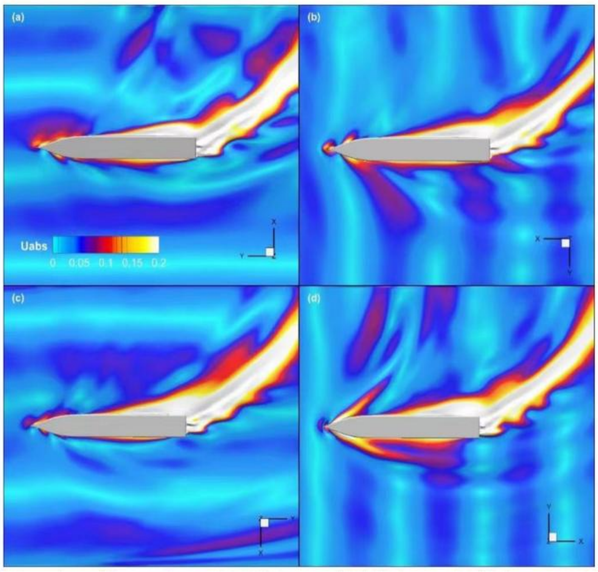

Figure 23. Free surface in regular waves

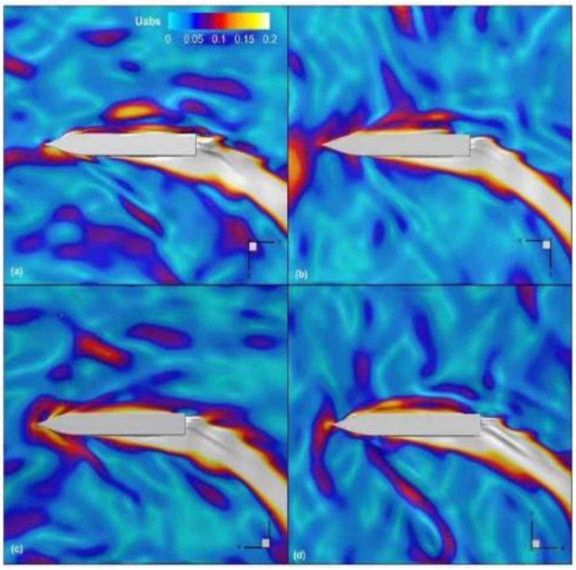

Figure 24. Free surface in irregular waves

6. CONCLUSIONS

This paper describes the research progress of ship maneuverability in waves. Research methods can be divided into the experimental method, potential flow methods, and the CFD method that considers viscosity. The experimental method is the most reliable but too expensive. The two potential flow methods are the most commonly used, but neither of them can fully consider the force of ship in the waves, so it is difficult to improve their calculation accuracy. CFD technology can most realistically reflect the movement of a ship, and with the advancement of solver and mesh technology, the motion that can be simulated is becoming more and more complex. Since the current CFD technology is mainly based on the RANS method, the accuracy of capturing the separation flow around the propeller and rudder is poor. But we can try to solve it using a more accurate method called separation vortex method.The CFD calculation is currently time-consuming, but I believe that the upcoming development of computility can solve it.

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