VIII International Conference on Computational Methods in Marine Engineering
MARINE 2019
R. Bensow and J. Ringsberg (Eds)

naoe-FOAM-SJTU SOLVER FOR SHIP FLOWS AND OCEAN ENGINEERING FLOWS

JIANHUA WANG AND DECHENG WAN*

State Key Laboratory of Ocean Engineering, School of Naval Architecture, Ocean and Civil Engineering, Collaborative Innovation Center for Advanced Ship and Deep-Sea Exploration, Shanghai Jiao Tong University, 200240 Shanghai, China
*Corresponding author: dcwan@sjtu.edu.cn

Key words: Ship hydrodynamics, ocean engineering, 6DoF motion, overset grid, naoe-FOAM-SJTU solver,

Abstract. Ship and ocean engineering flows is a very complex and highly non-linear problem. Traditional experimental methods and potential flow theory have limitations in predicting the complex flows. A CFD solver naoe-FOAM-SJTU is developed based on the open source platform OpenFOAM with the purpose of simulating various ship and ocean engineering flow problems. In the present paper, the self-developed modules, i.e., wave generation and absorption, 6 degrees of freedom (6DoF) motion, mooring system and overset grid are introduced to illustrate the development of the CFD solver. Furthermore, extensive applications to ship flows and ocean engineering flows using naoe-FOAM-SJTU solver are conducted and validated by available experimental data. It has been proved that the CFD solver naoe-FOAM-SJTU is suitable and reliable in predicting the complex viscous flows around ship and offshore structures. Future development of naoe-FOAM-SJTU solver will focus on further enhancement of accuracy and efficiency for CFD simulations of complex flows in ship and ocean engineering.

1 INTRODUCTION

Viscous flow around floating structures with free surface is one of the typical features in ship and ocean engineering. Understanding the hydrodynamic performance of ship and ocean structures can help people design safer and more productive ocean structures. With the development of scientific knowledge, many fundamental problems about the ship and ocean engineering flows have been solved. Among them, the resistance and stability of ships and platforms in calm water can be precisely predicted. However, dynamic features of real ship and ocean structures are complicated including violent sea environment, the large motion of floating structures, high Re turbulent flow, ship hull-propeller-rudder interaction, multi-scale flows, etc. In order to get better understanding of flow mechanism, researchers have focused on resolving complex viscous flow in ship and ocean engineering.

There are some typical features in ship flows and ocean engineering flows, such as multi-system interaction, nonlinear free surface, high Re turbulent flow, and so on. The potential flow and experimental test used to be the major approaches in the past researches. However, the computational fluid dynamic (CFD) approach has become a powerful tool to investigate these complex flow problems with the development of high-performance computing (HPC). One of the advantages of CFD method is that it can obtain more detailed flow field information, which make it easier to analyze the in-depth mechanism. CFD simulation can overcome the difficulties of nonlinear phenomenon and multi-system interactions that can hardly be estimated by potential flow method. Furthermore, the cost of CFD computations is relatively lower compared with the expensive facilities of experiment. Therefore, more and more researchers apply CFD method to study the complex flow problems in the field of ship and ocean engineering.

Despite the powerful capability of CFD, it is still challenging to handle various complex viscous flows in ship and ocean engineering, such as violent free surface waves, complex motions with ship hull-propeller-rudder interaction, large amplitude platform motions with mooring lines, vortex-induced vibration (VIV) of marine risers, and so on. Therefore, it is very essential to develop a specific CFD solver to investigate the performance of ship flows and ocean engineering flows. In the present paper, emphasis is put on the development of the naoe-FOAM-SJTU solver for complex flows in ship and ocean engineering. The naoe-FOAM-SJTU solver, which is developed by the Computational Marine Hydrodynamics Lab (CMHL) in Shanghai Jiao Tong University (SJTU), can be used as a powerful tool to estimate the hydrodynamic performance of ship and offshore structures. It can also be utilized to obtain a better understanding of the complex ship flows and ocean engineering flows.

In this paper, main modules in naoe-FOAM-SJTU solver is firstly introduced, where the wave generation and absorption, 6DoF motion, mooring system, overset grid are described in detail. Then, typical applications for ship and ocean engineering flows using the developed modules are presented. Finally, a brief conclusion is drawn.

2 NAOE-FOAM-SJTU SOLVER

The present naoe-FOAM-SJTU[1,2] solver is developed based on the open source platform OpenFOAM[3]. Based on the supported features in OpenFOAM, the development for naoe-FOAM-SJTU solver is mainly through the implementation of specific modules. Figure 1 demonstrates the main framework of the present CFD solver naoe-FOAM-SJTU.

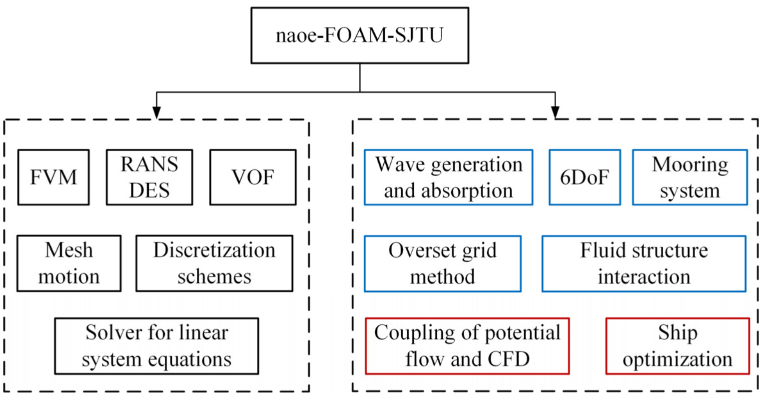


Figure 1: Main framework of naoe-FOAM-SJTU solver

The CFD solver is developed based on OpenFOAM and the built-in modules, such as finite volume method (FVM), discretization schemes, solver for linear system equations. Further implementation of ship and ocean engineering modules in the solver is shown in the right column of Figure 1, where the blue marked modules are already developed and modules in red are the ongoing work at present. The basic modules in OpenFOAM has been explained in the OpenFOAM user guide, thus, only the specific modules are illustrated herein.

2.1 Wave generation and absorption

For ship and ocean engineering flows, wave environment is the most typical situation. Therefore, ocean wave generation should be done firstly for the development of a marine hydrodynamic CFD solver. So far, there have already been several modules developed based on OpenFOAM, such as waves2foam[4], olaFlow[5,6]. In the present solver, two wave generation approaches[7–9] have been implemented, one is the modelling of a piston or flap type wavemaker, another one is the velocity-inlet boundary conditions (BC). A piston or flap type wavemaker is achieved by giving the prescribed wave profile to the movement of the wave boundary incorporated with the moving mesh technique in OpenFOAM. This procedure is usually used to generate regular waves, solitary waves, freak waves just like the wavemaker in an actual wave basin.

The inlet BC type wavemaker imposes both the velocity of water particles and the position of free surface at the incident wave boundary. Figure 2 illustrates the code structure of wave generation module based on inlet BC in naoe-FOAM-SJTU solver.

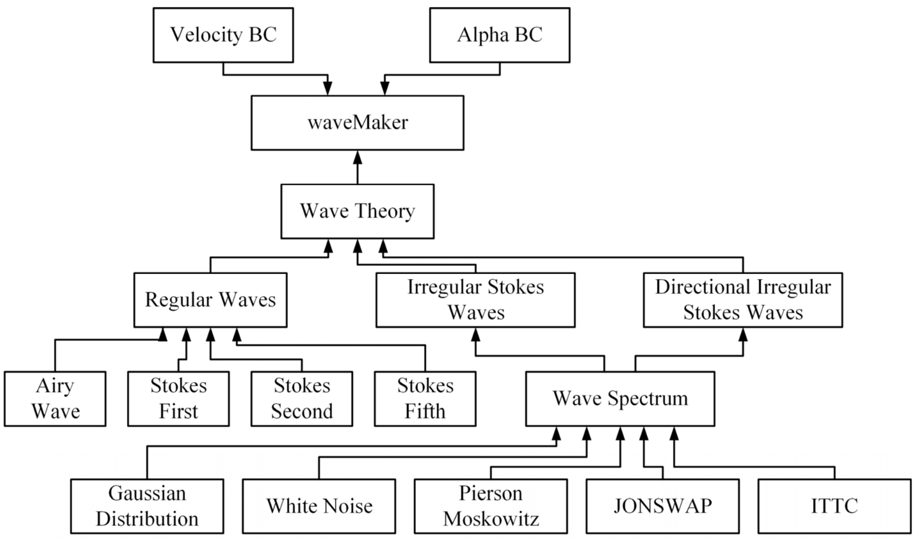


Figure 2: Code structure of wave generation module in naoe-FOAM-SJTU solver

The present wave generation module can generate both regular and irregular waves according to corresponding wave theories. Regular waves vary from the airy wave to the fifth-order Stokes waves. For the irregular waves, a wave spectrum based correction approach[9] is used in the present wave generation module. The most frequently used spectrum, such as PM, JONSWAP, one/two parameter ITTC, are implemented to the present solver to extend the ability of generating various ocean waves. The present wave generation module has been applied to many benchmark cases and the results are validated by available experimental results[10].

Wave absorption, also called wave damping is implemented in the solver using a sponge layer ahead the outlet boundary with a certain length. In the damping zone, the wave can be absorbed by adding a source term in momentum equation. The detailed implementation can be found in the reference[7].

2.2 6DoF motion and overset grid module

To estimate the flow characters of floating structures in ship and ocean engineering, the motion behavior should be computed firstly. In naoe-FOAM-SJTU, a 6DoF motion solver based on Euler angle description is implemented. Two coordinate systems, i.e. earth-fixed coordinate system and ship-fixed coordinate system, are employed to calculate the rigid body motions. During the process of 6DoF computation, the forces and moments are first computed in the earth-fixed coordinate system. Then the predicted values are transformed into ship-fixed coordinate system for the calculation of accelerations. After that, the accelerations are integrated to obtain the ship velocities, which are then transformed back to earth-fixed coordinate system to get the ship displacement by integrating the velocities. Detailed implementation of 6DoF motion solver can be found in reference[2].

The motion of ship hull and offshore platforms can be computed through the above process. However, when considering complex motions of ship hull-propeller-rudder system or floating offshore wind turbines, the 6DoF motion solver should be extended to have the ability of handling complex motion with a hierarchy of bodies. In naoe-FOAM-SJTU solver, a multi-level motion solver is implemented through the combination of dynamic overset grid technology. Figure 3 demonstrates the motion level of ship-propeller system.

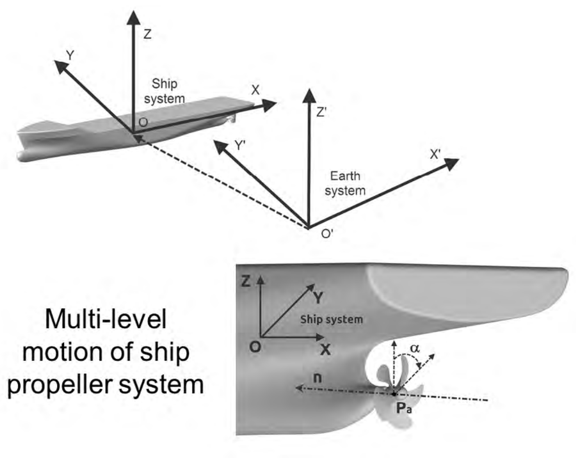


Figure 3: Multi-level motion solver for ship-propeller system

The strategies to compute the movements of propeller, rudder, turbine and other appendages depend on what problem to solve. For example, self-propulsion simulation employs a PI controller to update the rotation of propeller. The 6DoF motion module with a hierarchy of bodies can be used to simulate various complex conditions in ship and ocean engineering incorporating with the dynamic overset grid method.

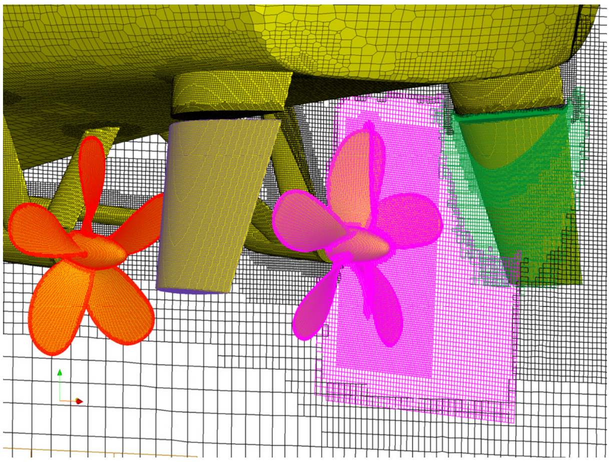


Figure 4: Overset grid arrangement around ship hull propeller and rudder

The dynamic overset grid module in naoe-FOAM-SJTU solver is implemented with the purpose of handling with large amplitude motion or multi-level motion. Figure 4 shows a typical overset grid arrangement around ship hull, propeller and rudder. The computational grids for each part have overlapping areas, in which the flow information is interpolated. In the present solver, the suggar++ program[11] is utilized to compute the domain connectivity information.

2.3 Mooring system module

Mooring lines are widely used in ocean engineering to keep the stability of floating platforms in ocean waves. In order to resolve the ocean engineering flows, a mooring system module is required to predict the performance of offshore platforms. In naoe-FOAM-SJTU solver, a mooring system module is developed based on OpenFOAM and several types of mooring lines are implemented. The main framework of the mooring system module is shown in Figure 5.

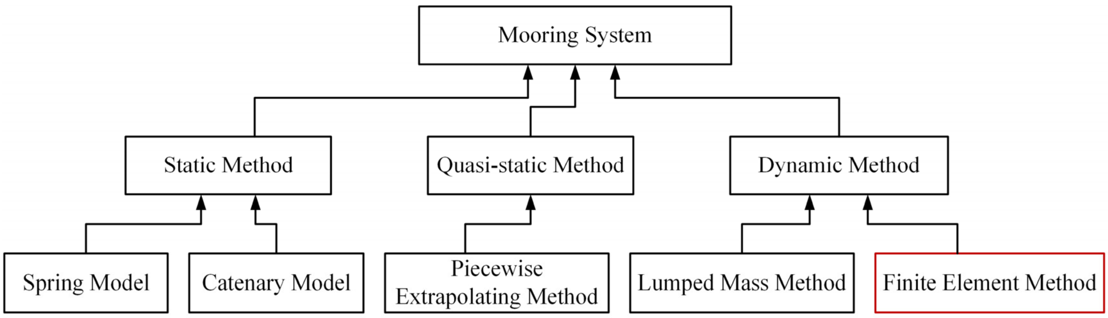


Figure 5: Main framework of mooring system module

The module is divided into three categories according the equations, i.e. static method, quasi-static method and dynamic method. In static method, the spring model and catenary model are implemented. As for the quasi-static approach, a pricewise extrapolating method (PEM) is adopted to discretize the mooring line into several segments, where the equations of static equilibrium for each segment is solved. In addition, the PEM approach can consider the different structural properties for mooring lines consist of different components. Both the static and quasi-static method ignore the effect of mooring line movement. Thus, a dynamic module including 3D lumped mass method (LMM) and finite element method (FEM) is also implemented. The restoring force of mooring lines computed by LMM and FEM approach is obtained by solving the dynamic equations of motion, where the inertial force related with mooring line motion can be considered. The present mooring system module has been applied to predict mooring forces of various floating structures in wave environments[12–14].

Other developed modules as shown in Figure 1 have been described in the reference[15], and they are not discussed here.

3 APPLICATIONS TO SHIP FLOWS AND OCEAN ENGINEERING FLOWS

3.1 Ship flows

Based on the developed modules for ship flows, the naoe-FOAM-SJTU solver has been applied to various conditions in ship engineering. Ship advancing in calm water is the most fundamental study in ship hydrodynamics and several benchmark computations have been carried out to validate the present CFD solver.

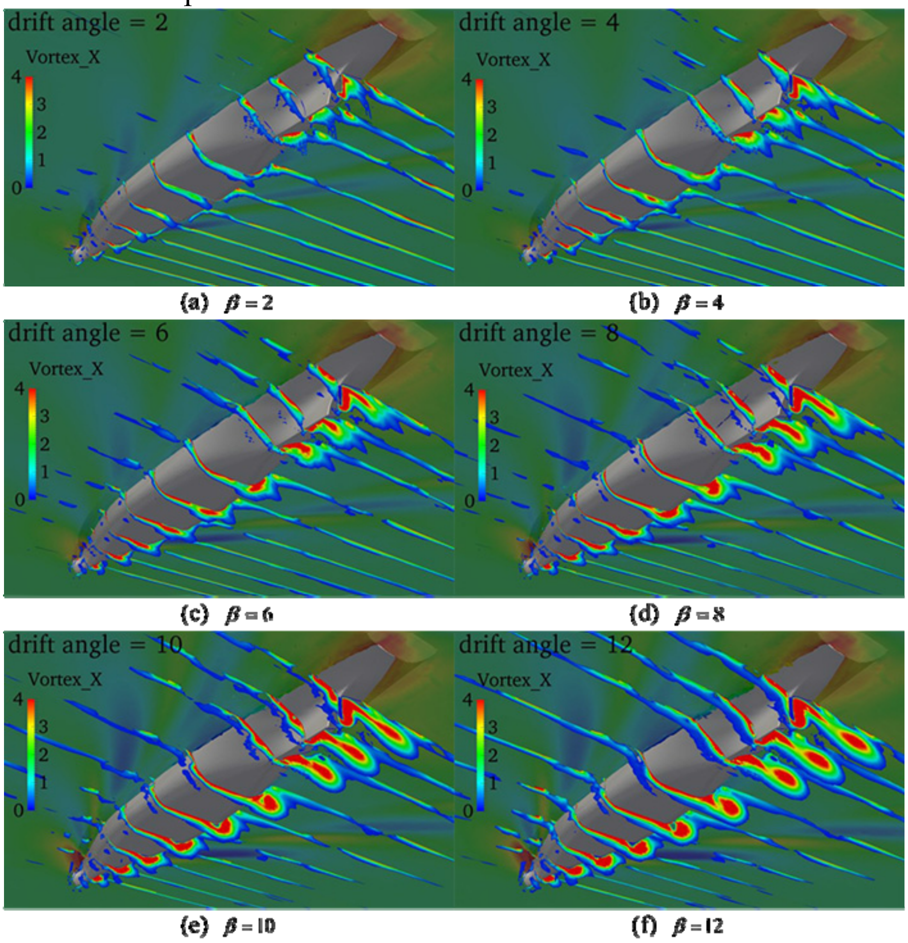


Figure 6: Vortices separated from ship hull with drift angles

Zha et al.[16] conducted numerical predictions of ship resistance in calm water with emphasis on viscous wave-making resistance for 6 ship hulls. They also simulated high-speed catamaran in calm water[17], where different ship speeds were considered. The numerical results agreed very well with the measurement data. Wave making and vortex field were well predicted and further analysis of the hydrodynamic performance was discussed. Wang et al.[18] further investigated the hydrodynamic performance for a ship with different drift angles. The detailed vortices separated from the ship hull can be well resolved as shown in Figure 6. More recently, the CFD solver was applied to simulate breaking wave phenomena of high-speed surface ships[19]. The grid density and turbulence model effect on the breaking bow waves were analyzed in detail.

Ship in waves, also called seakeeping, is another key performance of ship. Based on the developed wave generation and absorption module, various ocean waves can be generated. Incorporating with the 6DoF motion module, ship motions in waves can be estimated by the developed CFD solver. Shen et al.[20] and Ye et al.[21] conducted the numerical simulations of ship motion in head waves using RANS approach. Different wave steepness and wave lengths were considered in the simulations and the predicted wave added resistance was validated by the available experimental data. More recently, Liu et al.[22] used naoe-FOAM-SJTU solver to predict more violent wave conditions for DTC ship model. The computations were carried out for the benchmark case, where the ship model was free to heave, pitch and roll, in oblique waves. Dynamic overset grid was adopted to handle with the large ship motions. Strong wave slamming and large ship motions can be observed as shown in Figure 7. In addition, mean drift forces and moments on the ship hull can be well predicted compared with the available experimental data.

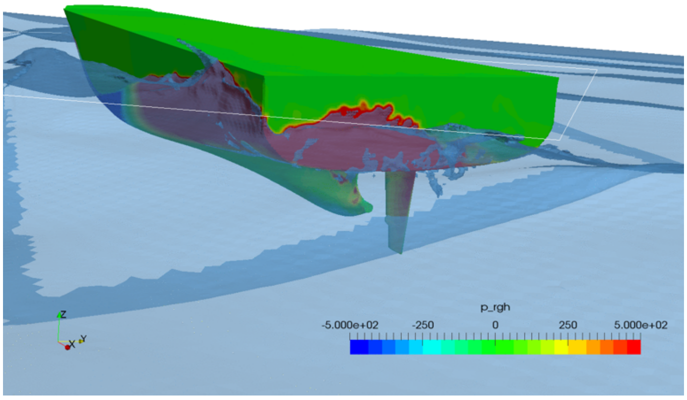


Figure 7: Slamming on ship hull in rough sea states

Despite the simulations of ship flows with bare hull model, free running ship with complex ship hull-propeller-rudder interaction has also been investigated based on the developed overset grid module associated with full 6DoF motion with a hierarchy of bodies. Shen et al.[2] performed numerical computations of ship self-propulsion and zigzag maneuver of KCS ship in calm water, and the predicted self-propulsion parameters as well as maneuvering parameters were validated by the available experimental results. Wang et al.[23] carried out the self-propulsion simulation of a twin-screw fully appended ship model and extends to the simulation of turning circle maneuver. Wang et al.[24,25] further extended the present naoe-FOAM-SJTU solver to simulate ship maneuvering in waves (shown in Figure 8) and the numerical results showed that the solver is suitable and reliable in predicting the performance of ship maneuvering in waves.

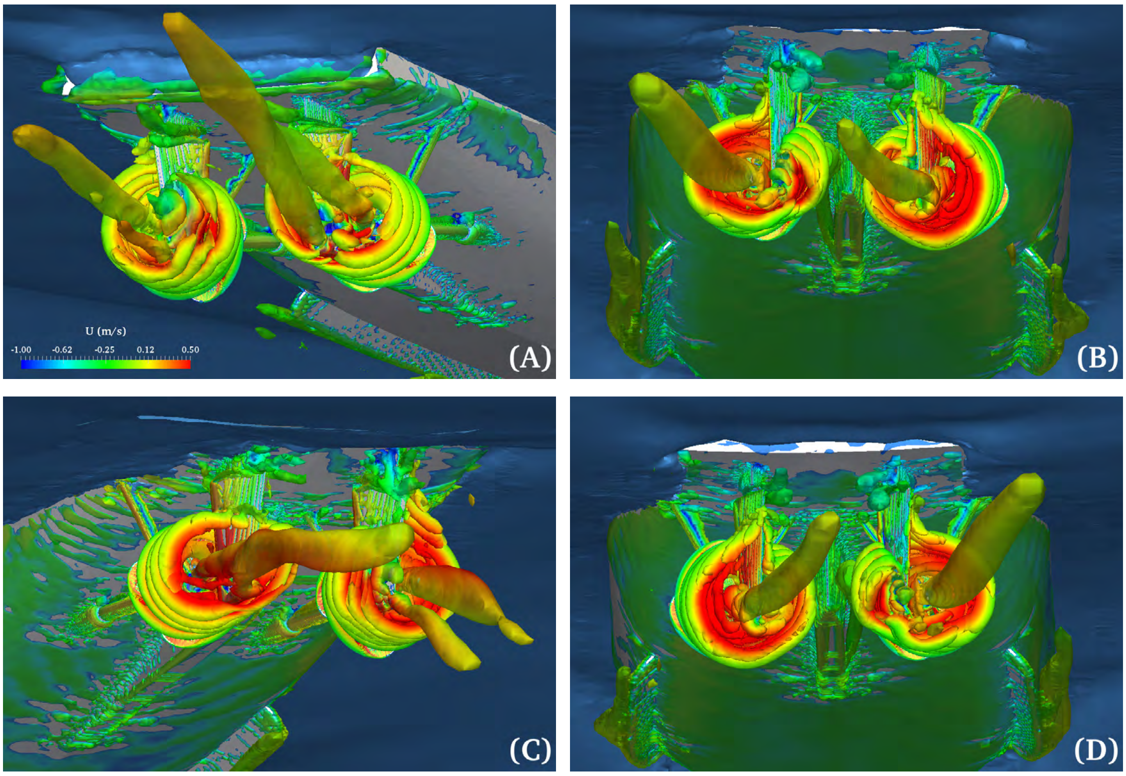
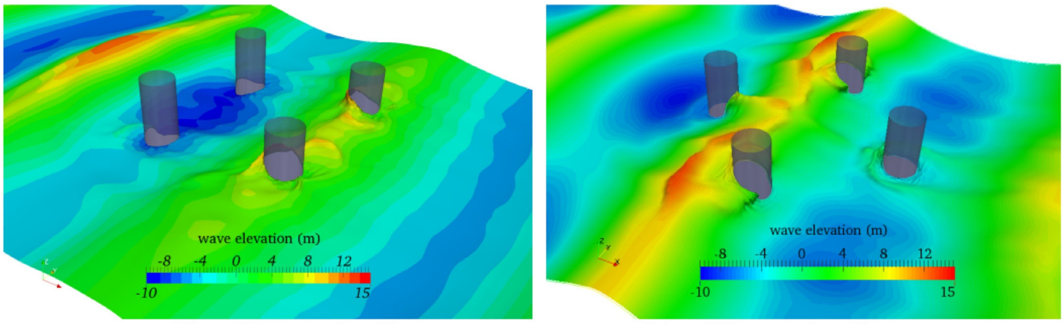


Figure 8: Iso-surfaces of Q=100 colored with axial velocity for the zigzag maneuver in waves

Apart from the investigations of ship advancing in calm water, seakeeping, propulsion and maneuvering, naoe-FOAM-SJTU solver has also been applied to estimate the performance of energy save device (ESD), cavitation, multi-ship interactions, and so on. With the upgrade of the present solver, more and more complex ship flows can be numerically studied.

3.2 Ocean engineering flows

Ocean engineering flows includes various engineering problems for offshore platforms both fixed and floating. The developed naoe-FOAM-SJTU solver has also been applied to the simulation of various ocean engineering flows. Based on the wave generation and absorption module, wave-structure interaction can be simulated. For fixed structures, wave run-up is very important for the safe deck design. Cao and Wan[10] presented benchmark simulations of wave run-up on single cylinder and four cylinders using the current solver as shown in Figure 9. Different wave periods and wave heights were studied and wave run-up heights around the cylinders were recorded with virtual wave probes and compared with experimental data. They concluded that naoe-FOAM-SJTU is capable of dealing with wave run-up problems with good accuracy. Incorporating with the 6DoF motion module, naoe-FOAM-SJTU solver can predict wave-induced motions of floating platforms. Liu and Wan[12] conducted numerical investigations of the motion response of a triple-hulled offshore observation platform with different incident waves. Time histories of motions and loads under different wave conditions were compared and analyzed.



(a) 0° wave heading (b) 45° wave heading

Figure 9: Wave run-up simulation of multi-cylinders

Based on mooring system module, coupled analysis of floating platform and mooring lines can be performed. Wang and Wan[26] carried out coupled analysis of a floating pier and its mooring system in regular waves. The multicomponent mooring lines were modelled by dynamic analysis Lumped Mass method (LMM). Motion response were compared with that obtained by the static analysis method. The results showed that dynamic analysis is necessary for coupling analysis between floating platform and mooring lines.

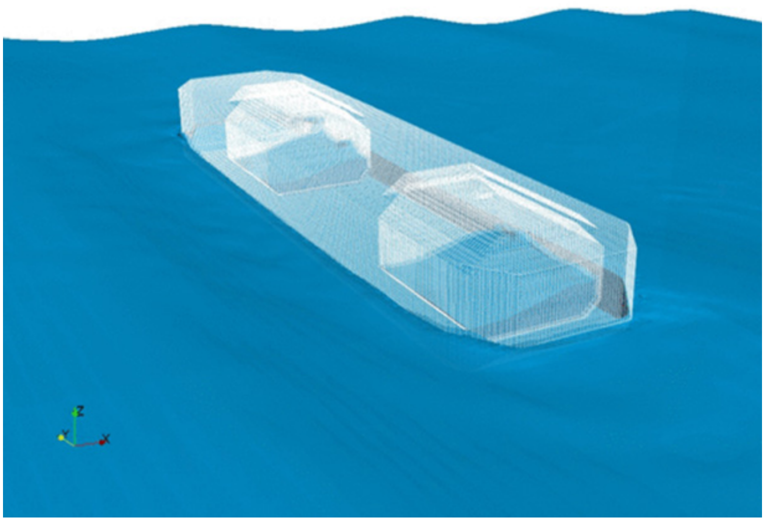


Figure 10: Instantaneous wave profile of FPSO with sloshing tanks

Zhuang and Wan[27] studied the motion response of a single-mooring FPSO using overset grid and mooring system module. The predicted natural periods for heave decay test were in good agreement with experiment. Motions and mooring forces were further analyzed. Xia and Wan[28] investigated the wave evolution and hydrodynamic characteristics of a floating platform in shallow water with submerged terrain near island. The Response Amplitude Operators (RAOs) of the platform in regular waves were in good agreement with experimental data. Further wave evolution and breaking process over the submerged terrain were also depicted and analyzed. The naoe-FOAM-SJTU solver can also perform coupled analysis of motion response of an FPSO with sloshing LNG tanks in waves. Zhuang and Wan[13] performed such simulations in which the external wave flow and internal tank sloshing were solved simultaneously. Figure 10 presents the complex flows inside the tank and the wave profile around the FPSO.

The present solver has also been applied to simulate the vortex-induced motions (VIM) of submersible platforms and Spar type platforms under sea currents. By using the mooring system module, 6DoF motion module and the high Re turbulence model, the complex viscous flows around floating platforms can be solved. The Detached-Eddy Simulation (DES) can predict massively separated flow at relatively low cost and was adopted by naoe-FOAM-SJTU to predict VIM. Zhao et al.[14] simulated the VIM of a paired-column semi-submersible by using the naoe-FOAM-SJTU solver. The “lock-in” phenomena were captured. Synchronization vortex shedding patterns between upstream columns are observed in the “lock-in” range. The transverse motion response and zero crossing period are in good agreement with experiment. Figure 11 illustrates the 3D vortical structures of the semi-submersible platform under sea currents.

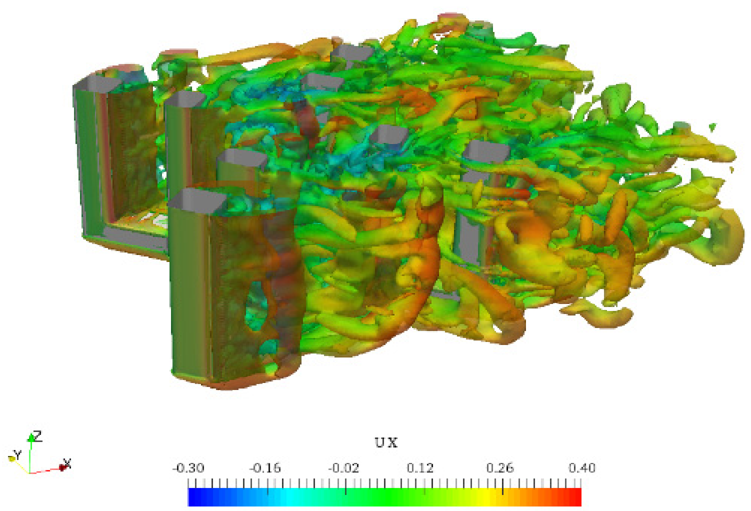


Figure 11: Vortical structure around semi-submersible platform

Other typical ocean engineering flows, such as vortex-induced vibration (VIV) of marine risers, multi floating body interactions, can also be simulated using naoe-FOAM-SJTU. Due to the length limitation, they are not presented here.

4 CONCLUSIONS

In the present paper, the development of main modules in naoe-FOAM-SJTU solver including wave generation and absorption, mooring system, 6DoF motion and overset grid are introduced in detail. The developed modules are used to simulate complex ship flows and ocean engineering flows. Then, extensive applications are discussed focusing on complex flows in ship and ocean engineering. It is concluded that with the development of specified modules in OpenFOAM, the present naoe-FOAM-SJTU solver can well resolve the complex ship and ocean engineering flows.

Future development of naoe-FOAM-SJTU solver will focus on two parts, one is the improvement of existing modules and another one is the adding more modules for ship and ocean engineering flows. Efficiency and accuracy will be the two key issues for the improvement of the present modules. More modules, including coupling strategy between potential flow and viscous flow, ship optimization design, are considered to extend the ability of naoe-FOAM-SJTU in engineering applications.

ACKNOWLEDGEMENTS

This work is supported by the National Natural Science Foundation of China (51879159, 51490675, 11432009, 51579145), Chang Jiang Scholars Program (T2014099), Shanghai Excellent Academic Leaders Program (17XD1402300), Program for Professor of Special Appointment (Eastern Scholar) at Shanghai Institutions of Higher Learning (2013022), Innovative Special Project of Numerical Tank of Ministry of Industry and Information Technology of China (2016-23/09) and Lloyd’s Register Foundation for doctoral student, to which the authors are most grateful.

REFERENCES

[1] Shen, Z., Cao, H., Ye, H., Wan, D.C. *The manual of CFD solver for ship and ocean engineering flows: naoe-FOAM-SJTU*, Shanghai Jiao Tong University, (2012).

[2] Shen, Z., Wan, D.C., Carrica, P.M. Dynamic overset grids in OpenFOAM with application to KCS self-propulsion and maneuvering. *Ocean Eng.* **108**:287–306, (2015),.

[3] Jasak, H. OpenFOAM: Open source CFD in research and industry. *Int. J. Nav. Archit. Ocean Eng.*, **1**:89–94, (2009).

[4] Jacobsen, N.G., Fuhrman, D.R., Fredsøe, J. A wave generation toolbox for the open-source CFD library: OpenFoam®. *Int. J. Numer. Methods Fluids*, **70**:1073–1088, (2012).

[5] Higuera, P., Lara, J.L., Losada, I.J. Realistic wave generation and active wave absorption for Navier–Stokes models: Application to OpenFOAM®. *Coast. Eng.* **71**:102–118, (2013).

[6] Higuera, P., Lara, J.L., Losada, I.J. Simulating coastal engineering processes with OpenFOAM®. *Coast. Eng.* **71:**119–134, (2013).

[7] Cao, H., Wan, D.C. Development of Multidirectional Nonlinear Numerical Wave Tank by naoe-FOAM-SJTU Solver. *Int. J. Ocean Syst. Eng.* **4**:52–59, (2014).

[8] Cao, H., Wan, D. C. RANS-VOF solver for solitary wave run-up on a circular cylinder. *China Ocean Eng.* **29**:183–196, (2015).

[9] Shen, Z., Wan, D.C. An irregular wave generating approach based on naoe-FOAM-SJTU solver. *China Ocean Eng.* **30**:177–192, (2016).
[10] Cao, H., Wan, D.C. Benchmark computations of wave run-up on single cylinder and four cylinders by naoe-FOAM-SJTU solver. *Appl. Ocean Res.* **65**:327–337, (2017).
[11] Noack, R.W., Boger, D.A., Kunz, R.F., Carrica, P.M. Suggar++: An improved general overset grid assembly capability. In Proceedings of the Proceedings of the 19th AIAA Computational Fluid Dynamics Conference, San Antonio TX, pp. 22–25, (2009).
[12] Liu, Y., Wan, D.C. Numerical simulation of motion response of an offshore observation platform in waves. *J. Mar. Sci. Appl.* **12**:89–97, (2013).
[13] Zhuang, Y., Wan, D.C. Numerical Study on Ship Motion Fully Coupled with LNG Tank Sloshing in CFD Method. *Int. J. Comput. Methods*, 1840022, (2017).
[14] Zhao, W., Zou, L., Wan, D.C., Hu, Z. Numerical investigation of vortex-induced motions of a paired-column semi-submersible in currents. *Ocean Eng.* **164**:272–283, (2018).
[15] Wang, J., Zhao, W., Wan, D.C. Development of naoe-FOAM-SJTU solver based on OpenFOAM for marine hydrodynamics. *J. Hydrodyn.* **31**:1–20, (2019).
[16] Zha, R., Ye, H., Shen, Z., Wan, D.C. Numerical study of viscous wave-making resistance of ship navigation in still water. *J. Mar. Sci. Appl.*, **13**:158–166, (2014).
[17] Zha, R., Ye, H., Shen, Z., Wan, D.C. Numerical computations of resistance of high speed catamaran in calm water. *J. Hydrodyn.*, **26**:930–938, (2015).
[18] Wang, J., Liu, X., Wan, D.C. Numerical Simulation of an Oblique Towed Ship by naoe-FOAM-SJTU Solver. In Proceedings of the 25th International Offshore and Polar Engineering Conference, Big Island, Hawaii, USA, (2015).
[19] Wang, J., Ren, Z., Wan, D.C. RANS and DDES Computations of High Speed KRISO Container Ship. In Proceedings of the 32nd Symposium on Naval Hydrodynamics, Hamburg, Germany, (2018).
[20] Shen, Z., Wan, D.C. RANS computations of added resistance and motions of a ship in head waves. *Int. J. Offshore Polar Eng.*, **23**:264–271, (2013).
[21] Ye, H., Shen, Z., Wan, D.C. Numerical prediction of added resistance and vertical ship motions in regular head waves. *J. Mar. Sci. Appl.*, **11**:410–416, (2012).
[22] Liu, C., Wang, J., Wan, D.C. CFD Computation of Wave Forces and Motions of DTC Ship in Oblique Waves. *Int. J. Offshore Polar Eng.* **28**: 154–163, (2018).
[23] Wang, J., Zhao, W., Wan, D.C. Free Maneuvering Simulation of ONR Tumblehome Using Overset Grid Method in naoe-FOAM-SJTU Solver. In Proceedings of the 31th Symposium on Naval Hydrodynamics, Monterey, USA, (2016).
[24] Wang, J., Zou, L., Wan, D.C. CFD simulations of free running ship under course keeping control. *Ocean Eng.*, **141**:450–464, (2017).
[25] Wang, J., Zou, L., Wan, D.C. Numerical simulations of zigzag maneuver of free running ship in waves by RANS-Overset grid method. *Ocean Eng.*, **162**:55–79, (2018).
[26] Wang, J., Wan, D.C. Dynamic coupling analysis of the mooring system and floating pier in the South China Sea. *Chin. J. Hydrodyn.*, **30**:180–186, (2015).
[27] Zhuang, Y., Wan, D.C. Numerical study of single point mooring system FPSO based on overset grids. *J. Jiangsu Univ. Sci. Technol. Nat. Sci. Ed.*, **31**:574–578, (2017).
[28] Xia, K., Wan, D.C. Numerical investigation of motion response of floating platform near submerged terrain. *The Ocean Eng.*, **36**:10–17, (2018).