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Research Article

Numerical Method to Simulate Self-Propulsion of Aframax Tanker in Irregular Waves

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With the implement of ship energy efficiency design index (EEDI), computational fluid dynamics (CFD) technique has become an effective method to predict the ship performance and further guide the designers to optimize hull lines. However, due to the complexity of the propeller-hull interactions and the ship's complex motions in waves, accurately predicting the speed-power performance of a self-propelled ship in actual seaway remains a challenge. In the present work, firstly, the resistance and self-propulsion experiments of Aframax model in waves are carried out at FORCE towing tank. Then, the CFD model and method are adopted to investigate the resistance and thrust under the conditions of regular and irregular waves in a three-dimensional numerical wave tank created by commercial software Star-CCM+. Therein, Reynolds-Averaged Navier–Stokes (RANS) equations and k-ε turbulent models were used for modeling the turbulent flow, and volume of fluid (VOF) method was applied to track the location and shape of transit-free surface. Based on the numerical method, the added resistance caused by regular waves was firstly investigated, and the self-propulsion of propeller in irregular waves was further performed. Furthermore, in order to simulate the rotation of the propeller, both the sliding mesh technique and overset mesh technique were discussed. Finally, compared with the experimental data, the numerical solutions have been validated, which shows potential to provide theoretical guidance and technical support for the self-propulsion performance of Aframax tanker in waves.

1. Introduction

The speed-power performance and oil consumption under ship operation condition have been the focus research with the implement of ship energy efficiency design index (EEDI). This tendency poses great challenges for ship designers. Fortunately, with the rapid development of numerical analysis and computer technology, computational fluid dynamics (CFD) technique is now frequently adopted to predict the ship performance, and further guide designers to optimize hull lines. Furthermore, in the evaluation of different designs, self-propulsion simulation is undoubtedly a direct and effective way for judgment.

Through years of practice, the simulation of self-propulsion in calm waters has been well developed. However, it is difficult to predict the speed-power performance in actual seaway, as a result of the complex ship's motions in waves and the propeller-hull interaction. Thus, the prediction of the speed and power performance in seaway has always been the focus of academic research. The analyses of the ship's speed and power problem mainly involve two issues: first, the added resistance caused by sea waves; second, the propulsion performance in waves. The added resistance problem has been widely researched through both experimental and numerical methods by using the potential flow method and recently the CFD method. From the experimental viewpoint, added resistances were measured and analyzed by Gerritsma and Beukelman [1]; Fujii and Takahashi [2]; Journee [3]; Guo and Steen [4]; and Lee et al. [5]. Based on the potential flow theory, there are two major approaches including the far-field method and near-field method. In terms of the momentum conservation, the far-field method is established and first introduced [1, 6–8], and Liu et al. [9] made further study of the calculation of the added resistance based on the far-field method. Furthermore, near-field method is another approach, which directly integrates the second-order fluid pressure over the wetted surface. Havelock [10]; Faltinsen et al. [11]; Salvesen [12]; Kim et al. [13, 14]; and Seo et al. [15] conducted the research in this area. With the advance of computing technology, using the CFD methods, to predict the added resistance becomes a very active field of research. It has advantages over potential methods as it can deal with large-amplitude ship motions and with nonlinear flow phenomena such as breaking waves and green water, without explicit approximation and empirical values [16]. Guo and Steen [4] studied on added resistance of KVLCC2 in short waves and discussed Faltinsen's asymptotic formula. Park et al. [17] calculated the added resistance of the original KVLCC2 hull and its modified hull forms and compared it with linear results.

While the added resistance is calculated through the abovementioned approaches, the speed and power performance can be predicted based on the assumption that the propeller characteristics and the self-propulsion factors in waves are identical to those in still water. Although this method has certain accuracy and less time consumption, the results are approximate, and it is difficult to consider the interaction between hull and appendages. In order to reduce deviations, the technique for simulating self-propulsion in waves by using CFD solvers is currently put forward. Carrica et al. [18] simulated the fully appended ONR tumblehome model DTMB 5613 with moving rudders and rotating propellers in following regular waves with the in-house code CFD Ship-Iowa v4.5. Shen and Carrica [19] validated the overset code in OpenFOAM and found the high accuracy and flexibility of predictions of ship motions and forces in regular head waves. Wang and Wan [20] investigated the self-propulsion in regular waves of the fully appended ONR Tumblehome ship by the in-house CFD solver NAOE = -FOAM-SJTU. It is a great challenge to combine the complexity of the ship's motions in waves and the propeller's rotation, actually few studies have been carried out in both regular and irregular waves conditions. In view of the previous studies, the regular waves are often the focus of researchers. There are two possible explanations, one is that the experiment data is abundant and the other is more conclusions can be deduced by spectral analysis. However, the study of irregular waves is rarely mentioned. It may be due to the lack of available experiment data, as it is well known that the test in irregular wave condition is more expensive than that in the traditional regular waves. Besides, the irregular waves are described by superimposing a series of regular wave components. Neither the grid size nor time step should be small enough to improve the convergence, which increases the difficulty of simulation. However, it is indeed necessary to carry out the research for self-propulsion in irregular waves because it reflects the actual characteristics of ship performance in seaway, which also makes the judgment between different hull lines more scientific and reasonable. Recently, some researchers began to study the maneuverability of ship in irregular waves. Sprenger et al. [21] discussed the seakeeping and maneuverability of the KVLCC2 tanker, the Duisburg Test Case (DTC) container ship, and RoPax ferry based on the experimental model tests. For the abovementioned KVLCC2 ship and DTC container ship, Shigunov et al. [22] further studied the maneuverability of ships in waves by numerical simulation methods. However, the related research studies on the self-propulsion performance (especially about thrust and torque of the propeller) for various kinds of ships in irregular waves are still scarce.

In the present paper, an Aframax tanker is taken as the research objective, which has strong practicability and gets extensive favor of the ship owner. Firstly, the experiments of the Aframax model in regular and irregular waves were performed. Then, added resistance and self-propulsion performance of the experimental model were measured. Secondly, a three-dimensional numerical wave tank was created by commercial software Star-CCM+. On this basis, the numerical simulations of the added resistance in regular waves and self-propulsion performance in irregular waves for an Aframax tanker were discussed. Therein, prior to the calculation, the calibrations of generating and absorbing waves in the VOF model were investigated. Then, the convergence test was performed to obtain an optimum mesh based on the computational precision and efficiency. Finally, in order to simulate the propeller rotation, both sliding mesh technique and overset mesh technique were utilized and discussed. Meanwhile, the added resistance in regular waves and the thrust and torque of the propeller in irregular waves were numerically calculated and compared with the experimental measurements.

2. Experiments of an Aframax Model in Regular and Irregular Waves

The research model is a type of Aframax tanker, which comes from the Average Freight Rate Assessment (AFRA) system. Due to few restrictions of sea routes and ports, the Aframax tankers get extensive favor of the ship owner. The scale ratio of experiments is 37.273, and the main information and geometrical model of this vessel can be referred in Table 1 and Figure 1.

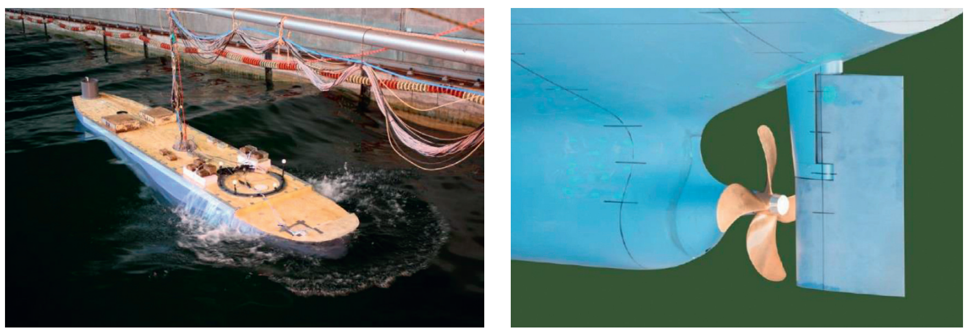
In the resistance test of the hull model in regular waves, the model was towed at the speed corresponding to the Froude number (F_n) 0.15 in a regular wave with 0.053 m wave amplitude and 2 s wave period. Therein, the total model resistance was measured and combined with the mean resistance in calm waters to calculate the nondimensional added resistance σ_{aw} as defined in the following:

$$\sigma_{aw} = \frac{R_w - R_0}{\rho g \zeta_a^2 B^2 / L_{pp}}, \tag{1}$$

where R_w and R_0 represent the mean resistance of the ship in regular waves and calm waters and ζ_a is the wave height. Thus, the experimental σ_{aw} of the Aframax model can be obtained as 5.48, which is used to verify the numerical solution in Table 2 of Section 3.2.

Table 1: Main particulars.

Hull			Propeller		
Item	Unit	Value	Item	Unit	Value
L_{pp}	m	6.57	Z	—	4
B	m	1.18	D (diameter)	m	0.22
D (draft)	m	0.41	Rotation direction	—	Right handed
K_{xx}	m	0.41	$(P/D)_{0.75R}$	—	0.759
K_{yy}	m	1.55	A_D/A_0	—	0.40
K_{zz}	m	1.55			
Froude no.	—	0.15			



(a) (b)

Figure 1: (a) Aframax tanker and (b) propeller model in the experiments.

Table 2: Comparison of nondimensional-added resistance versus different time steps.

Time step	σ_{aw} (−)	Diff. (%)
0.004	5.17	—
0.002	5.26	1.74%
0.001	5.27	0.19%

In the self-propulsion test of the hull model in irregular waves, the Aframax model can sail forward by the propeller and be free in all motions and then is connected only through loose safety lines. Instrumentation cables were connected vertically above the model to prevent any type of pulling forces. Motions of the model were monitored through the use of the Pro reflex camera to track the system. The ship model is driven in the water at basically stable speed, at each speed the propeller loading is systematically varied by suitable adjustment of propeller revolutions. Additionally, to the thrust from the propeller, the model is pulled with a loading FD, the towing force. The Pierson–Moskowitz Spectrum with significant wave height H_s 0.054 m and peak period T_p 1.31 s is taken in the self-propulsion test, which is corresponding to a general wave condition of H_s 2 m and T_p 8 s on the practical sea route from the statistical data. The irregular wave pattern in the experiment is generated based on the FORCE technology standard procedure. And prior to the actual tests, the waves to be used in the tests are calibrated. During the calibration, a wave probe was mounted in the middle of the tank. Here, the time histories of ship speed, revolution speed, thrust, and torque of the propeller can be shown in Figure 2. Therein, the average speed is 1.249 m/s and the ship speed has small variation within 5%. Furthermore, the revolution speed, thrust, and torque of the propeller change around 550.17 rpm, 40.52 N, and 1.009 Nm, which are compared with the numerical results in Table 3 of Section 3.2.

3. Numerical Results and Discussion

3.1. Numerical Models and Boundary Conditions. The present numerical simulations in this paper were created by using the commercial solver Star-CCM + based on CFD theory. Therein, Reynolds-Averaged Navier–Stokes (RANS) equations and SST k-ω model were applied to model the turbulent flow, which were discretized by the implicit unsteady method. Then, the VOF Waves model is taken to simulate surface gravity waves on an air-water interface by use of wave-making technique. The artificial wave damping is introduced to avoid the undesirable effect of the reflect waves from the outlet boundaries, which is applied by adding a resistance term to the equation for w- velocity [23]. Furthermore, the DFBI (Dynamic Fluid Body Interaction) model is utilized to simulate 6 DOF motion of the Aframax tanker. The geometries of the hull and propeller were created and shown in Figure 3.

For the Aframax test in the regular and irregular waves, the computational domain contains background region, hull region, and propeller rotating region. Therein, the background region extends 1.0 L_{pp} from the stem to the inlet, 3.0 L_{pp} from the stern to the outlet including damping zones

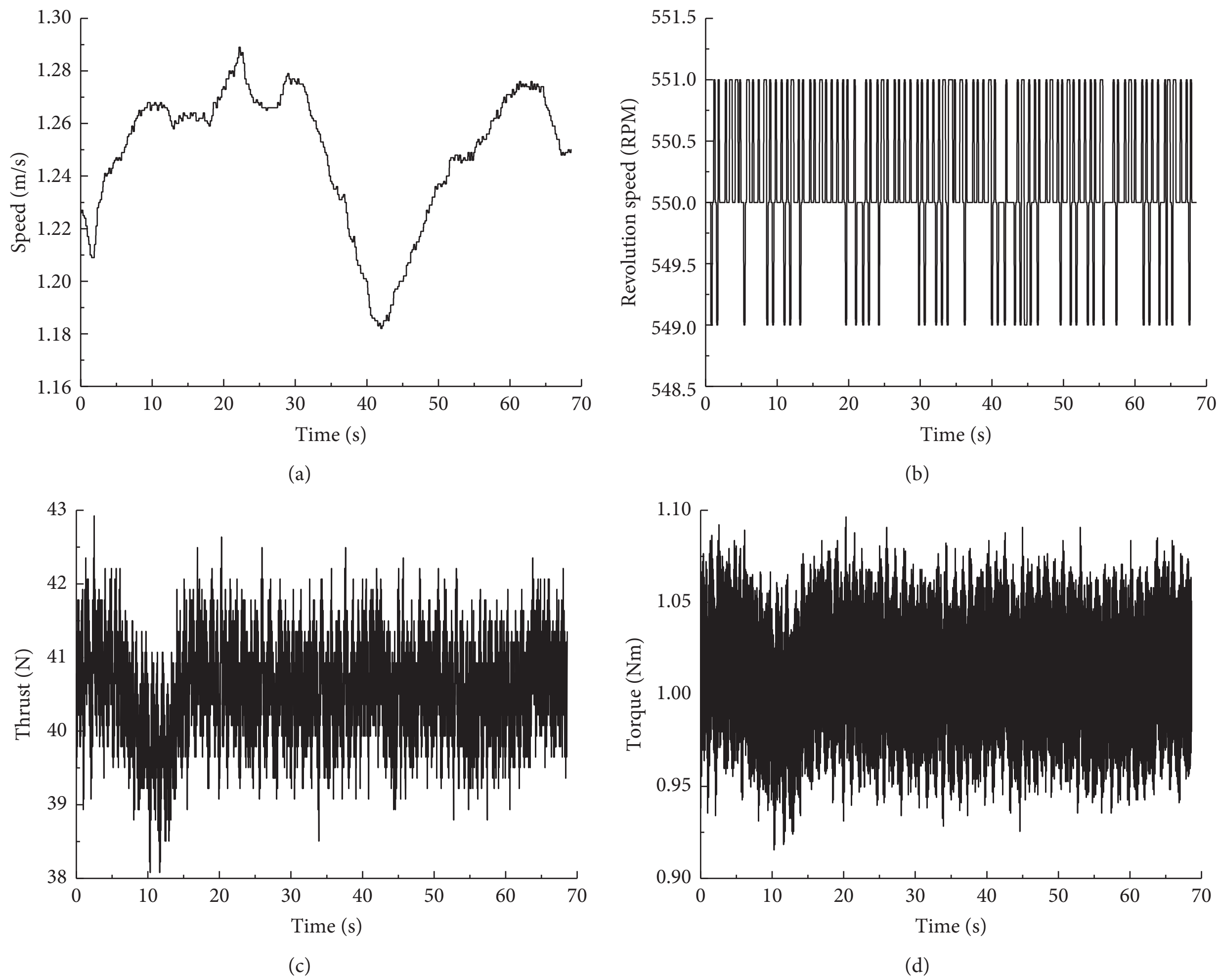


Figure 2: Time histories of self-propulsion performance for the Aframax model. (a) Ship speed. (b) Revolution speed of the propeller. (c) Thrust of the propeller. (d) Torque of the propeller.

Table 3: Comparisons of added resistance of the Aframax model in regular waves.

Method	σ_{aw}	Diff. (%)
Experimental result	5.48	—
Numerical solution (1.05 million)	5.14	6.20%
Numerical solution (2.88 million)	5.26	4.02%
Numerical solution (7.54 million)	5.36	2.19%

Figure 3: Numerical geometries of the (a) hull and (b) propeller.

with length of about 1.0 L_{pp}, 2.0 L_{pp} to the side, 1.0 L_{pp} above, and 2.0 L_{pp} below the undisturbed free surface. The background grid is fixed in the earth-fixed coordinate. To refine the wave region, there are 20 cells per wave height and 80 per wave length. The ratio ensures that the mesh on the free surface is not particular "narrow." Therein, the half computational domain and boundary conditions together with the meshes can be referred as Figure 4. Then, the relative whole computational domain is used for the self-propulsion simulation.

3.2. Numerical Mesh Scheme. In the numerical simulation on test cases of regular and irregular waves, the overset grid technique was taken to handle the large-amplitude motion of ship in waves. Therein, the hull region moves with the ship model and communicates with the background region. The dimensions of the hull region are 1.2 L_{pp} in x-direction, 0.5 L_{pp} in y-direction, and 0.3 L_{pp} in z-direction, which ensures to cover the range of ship's motion in waves. Furthermore, at least 3 cells that are required to couple the overset and background regions refers to cell count in the direction normal to the boundary. In addition, local meshes were refined on the hull region, especially for the bow and stern regions, where hull geometry shows large gradients. The overset gird scheme of the computational domain is shown in Figure 5.

Furthermore, in the test case of irregular wave, the propeller domain follows the ship and should rotate at a certain speed. Therefore, there are two different ways to simulate the propeller rotation, overset method and sliding method. Considering the sliding method cost less, both two methods were applied and investigated. It is noteworthy that due to the close proximity between hull and rudder an appropriate size of rotation region should be chosen. In this simulation, the rotating part is a cylinder, which extends 0.2 propeller diameters in axial direction and 1.25 diameters in the radial direction.

3.3. Numerical Solutions and Discussion

3.3.1. Convergence Analysis on Numerical Mesh and Time Step. Here, the grid convergence about the overset mesh of the resistance in regular wave is described. The parameters of the regular wave are the same as the experimental condition with 0.053 m wave amplitude and 2 s wave period. Then, three sizes of girds are discussed in the grid convergence tests. The coarse and fine mesh systems are derived by reduction and increasing cell numbers by the ratio $\sqrt{2}$ for three directions and the details of girds are illustrated in Table 4. Then, the nondimensional added resistances versus different meshes with time step 0.002 s were simulated and listed in Table 5. Therein, Diff. (%) is defined as the relative deviation of nondimensional added resistances between two mesh schemes, for example, the value of Diff. (%) 1.90 means |5.36–5.26|/5.26. Then, by means of the grid scheme of 2.88 million, the sensitivity of time step is discussed. The nondimensional added resistances versus different time steps were simulated and listed in Table 2. Therein, Diff. (%) is defined as the relative deviation of nondimensional added resistances between two time steps.

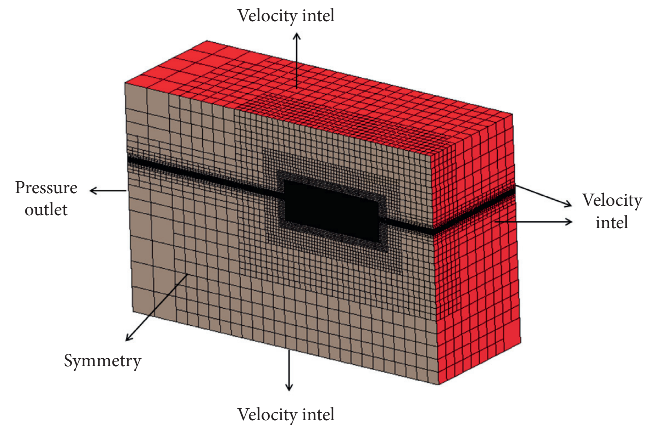


Figure 4: Boundary condition and grids.

From the Tables 5 and 2, it can be found that with the numerical mesh increasing or the time step decreasing, the relative difference Diff. (%) of numerical solutions σ_{aw} gradually decreases, which can verify that the numerical methods of this paper to calculate the ship resistance in waves have the convergence of numerical grid and time step in a certain extent.

Furthermore, in the self-propulsion case, the rotation of the propeller can be handled by two grid schemes of the sliding method and overset method. By the sensitivity analysis as mentioned above, the numerical method of this paper to simulate the thrust and torque of the propeller also has the convergence of grid and time step. According to the calculation precision and time cost, the overset grid scheme in irregular wave is selected as 6.44 million and the relative sliding grid method is 6.26 million for the whole computational domain of self-propulsion case. Therein, the total numbers of computational grids generated by both methods are shown in Table 6 and Figure 6 in detail. From the figure, it can be found that the difference of two mesh methods is the propeller grids and refinement regions behind the propeller. Moreover, through the sensitivity analysis, the time step can be chosen as 0.0015 s.

3.3.2. Numerical Results of Wave Making and Absorbing Performance. For the numerical wave tank of this paper, the wave profile for the case of the regular wave generated by the present method can be shown in Figure 7(a). It could be clearly observed that due to the artificial damping, waves decay quickly in the damping zone and become flat water on the outlet boundary. Then, the time histories of wave heights are illustrated in Figure 7(b). The location of monitor is about 1.0 L_{pp} from the inlet. From the figure, it can be seen the wave elevations between theory and numerical solution are agreement with each other, which shows the accuracy of regular wave-making and absorbing techniques of the present numerical method.

Furthermore, by means of the numerical method, time history of wave elevation at about 1.0 L_{pp} from the inlet is

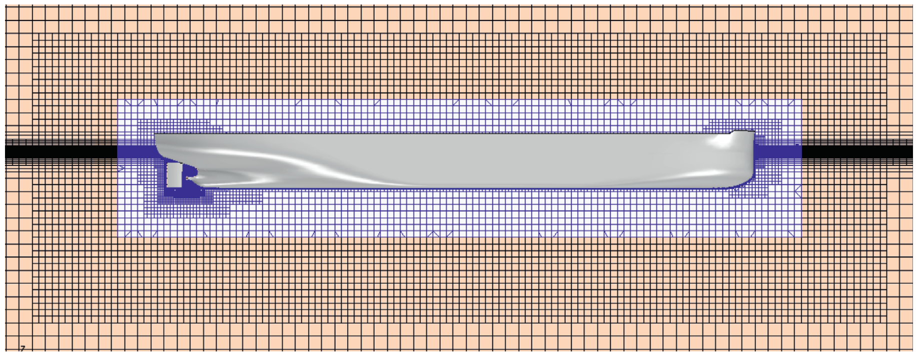


Figure 5: Overset gird scheme of the computational domain.

Table 4: Grid size for convergence tests in the regular case.

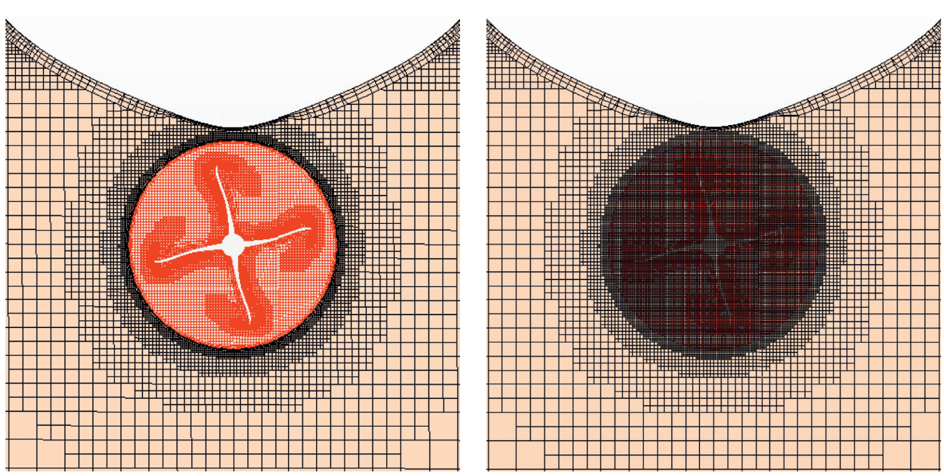
Grid scheme	Hull	Background	Total
Coarse	0.34 million	0.72 million	1.05 million
Medium	0.89 million	1.98 million	2.88 million
Fine	2.48 million	5.05 million	7.54 million

Table 5: Comparison of nondimensional-added resistance versus different meshes.

Grid scheme	σ_{aw} (−)	Diff. (%)
Coarse	5.14	—
Medium	5.26	2.33
Fine	5.36	1.90

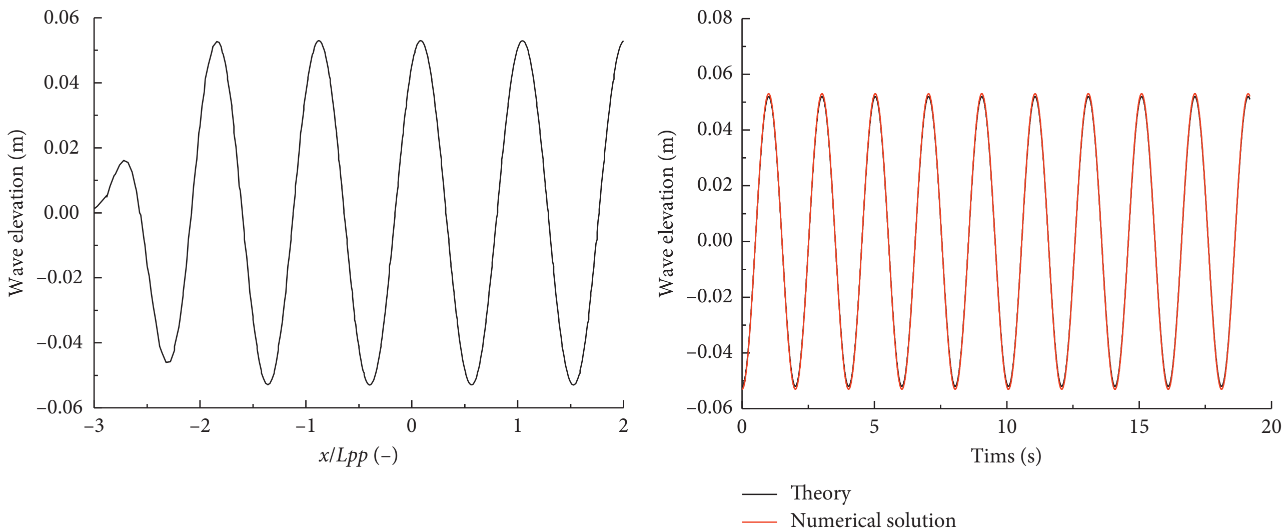
Table 6: Mesh information of the sliding method and overset method.

Region	Sliding method	Overset method
Background	3.95 million	3.95 million
Hull	1.79 million	1.99 million
Propeller	0.51 million	0.49 million
Total	6.26 million	6.44 million



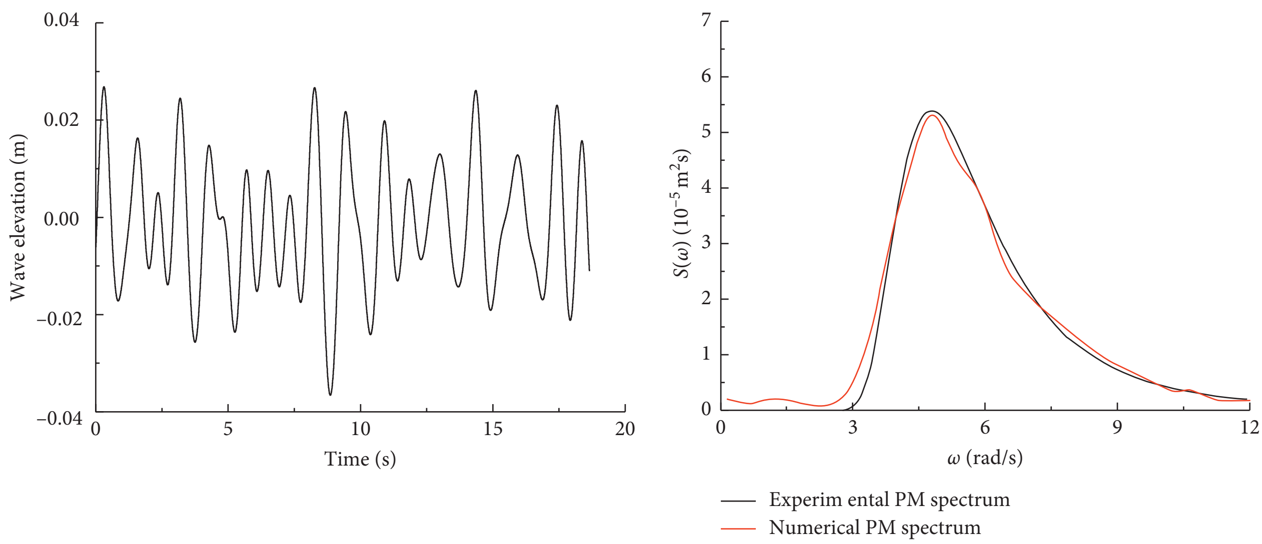
(a) (b)

Figure 6: Comparison of the grids in the propeller region versus two methods. (a) Sliding method. (b) Overset method.



(a) (b)

FIGURE 7: Wave elevation of the regular wave. (a) Wave profile along x-distance. (b) Time histories of wave elevation.



(a) (b)

FIGURE 8: Wave elevation and spectrum of irregular wave by the numerical method. (a) Time history at 1.0 L_{pp} from inlet (b) Comparison of wave spectrum.

shown in Figure 8(a). On this basis, the Fast Fourier Transform is applied on the time-domain data to obtain the spectral response in Figure 8(b). It can be found that the wave spectrum of numerical solution is close to the theoretical data, which can validate the accuracy of the numerical method for irregular waves.

3.3.3. Discussion on Ship Resistance and Propulsion Performance in Waves. For the test case of regular waves, by means of the present numerical method, the wave contour including regular waves and ship waves can be better numerically simulated, as shown in Figure 9. Furthermore, the added resistance of the Aframax model in regular waves can be simulated and listed in Table 3. Therein, Diff. (%) is defined as the relative deviation of nondimensional added resistances between numerical solution and experimental result. It can be found that the computational result is lower than experimental result with the relative difference about 4%, which can show the accuracy of the numerical method to simulate the Aframax model in regular waves.

Furthermore, for the test case of irregular waves, from the time histories of self-propulsion performance in Figure 2, the average value of ship speed 1.249 m/s is selected as flow velocity to simulate the ship speed in the numerical model. Besides, the rate of propeller revolution

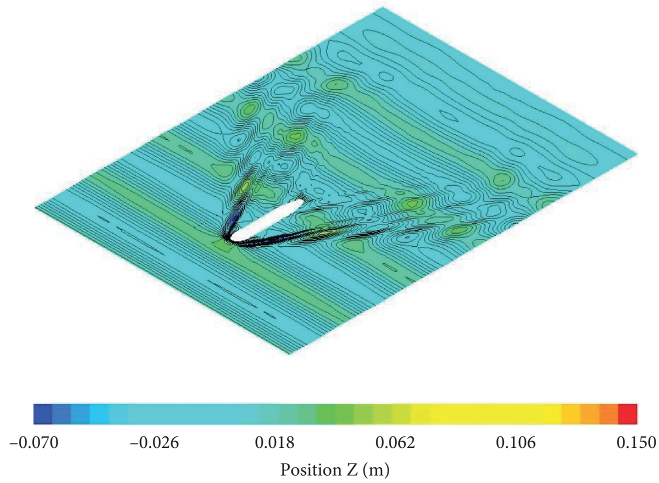


Figure 9: Wave contour of regular waves and ship waves for the Aframax model.

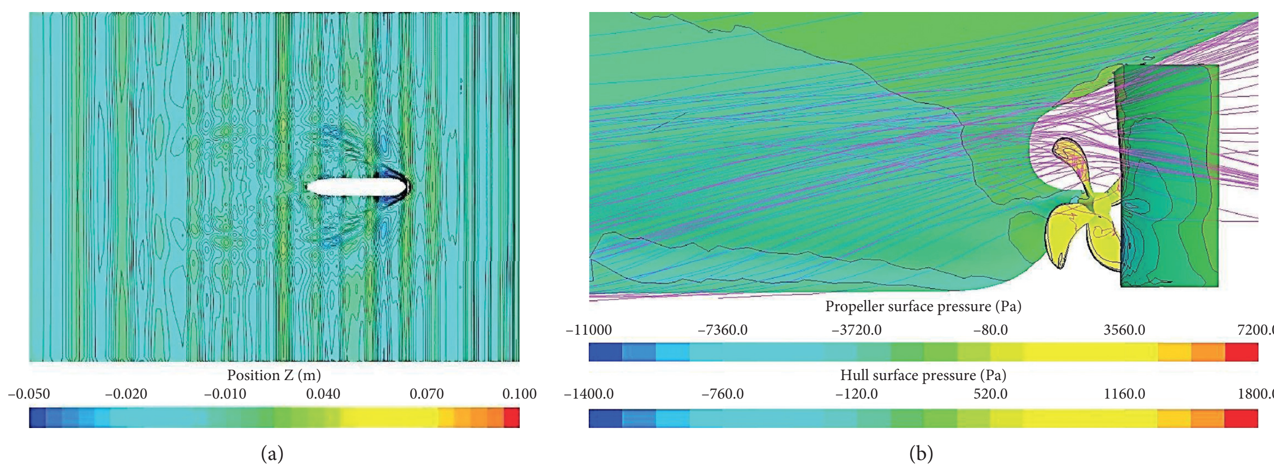


Figure 10: Simulation on fluid field of the Aframax model in irregular wave. (a) Wave contour (b) Streamline.

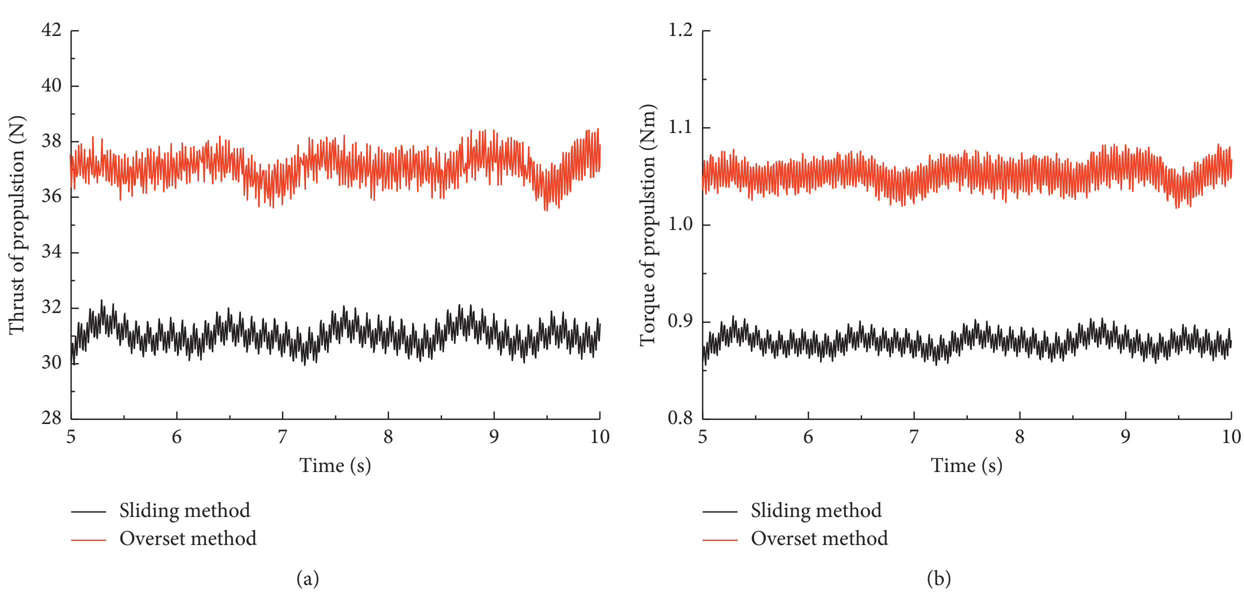


Figure 11: Time histories of self-propulsion performance of the Aframax model. (a) Thrust (b) Torque.

Table 7: Comparison of thrust and torque versus different methods.

	Experimental data	Sliding method	Overset method
Thrust (N)	40.52	31.02	37.16
Diff. (%)	—	23.45	8.29
Torque (nm)	1.008	0.879	1.009
Diff. (%)	—	12.80	0.10

was set as fixed to 550.17 rates per minute (RPM), which was same as the average revolution speed. By the present numerical method with time step 0.0015 s, the wave contour and streamline around the Aframax model can be better numerically simulated and shown in Figure 10. Furthermore, the thrust and torque of the propeller can be achieved and then the numerical results during 5~10 s are shown in Figure 11. On this basis, the statistics value versus different methods can be obtained and listed in Table 3. Therein, Diff. (%) is defined as the relative deviation of thrust and torque between numerical solution and experimental result.

From Figure 11 and Table 7, it can be found that the predicted thrust and torque by the numerical method are lower than the experimental results. In contrast of the two methods, the results in the overset method are coincided well with the measurements, with the relative error 8.29% for propeller thrust and 0.10% for torque. Furthermore, the time consumption of the overset method in this case is approximately 120 hours by 20 processors, which is 1.15 times more than the sliding method. However, the sliding method in this case seems not accurate enough to be utilized to simulate the propeller rotating with respect to the motion state of the Aframax model in irregular waves. The reason may be that when the ship model is sailing in waves, its motion attitude will change significantly at two adjacent moments. In the scheme of sliding grid, the interface should move with the ship motion, which can cause a significant variation of the interface position with time advancing and then result in the relative large deviation of data transfer between the inner and outer domains. Oppositely, the scheme of overlapping grids can solve this problem very well.

4. Conclusions

In the present study, the self-propulsion performance of a practical Average Freight Rate Assessment (Aframax) tanker in waves was studied by numerical and experimental methods. The performance parameters of the added resistance of hull in regular waves, the thrust and torque of the propeller in irregular waves are measured at FORCE towing tank. Furthermore, the CFD numerical method and models were created to analyze the propulsion performance of the Aframax model. Some conclusions can be drawn as follows:

(1) The study of mesh sensibility shown that the numerical methods of this paper have grid convergence. Furthermore, compared with the experimental data, the numerical nondimensional-added resistance had 4.02% relative error and the numerical thrust and torque of the propeller for the overset mesh were 8.29% and 0.10% respectively, which shown the accuracy and feasibility of numerical method in this paper to simulate the Aframax model in regular and irregular waves.

(2) For the two mesh schemes of sliding and overset methods to study the rotational propeller, the time consumption of the overset method in this case was approximately 120 hours by 20 processors, which is slightly greater than the sliding method. However, compared with the experimental data, the relative error of thrust for the overset method 8.29% was far less than the sliding method 23.45%, and the relative error of torque for the overset method 0.10% was also far less than the sliding method 12.80%. Therefore, the numerical method with the overset mesh in this paper was reasonable and effective to simulate the propulsion performance of the Aframax tanker in waves.

Nomenclature

B: Beam (m)
D: Propeller diameter (m)
g: Acceleration of gravity (m/s^2)
K_{xx}: Transverse radius of inertia (m)
K_{zz}: Vertical radius of inertia (m)
R_w: Mean resistance in waves (N)
T_P: Peak wave period (s)
ζa: Wave height (-)
ω: Wave frequency (rad/s)
d: Draft (m)
F_n: Froude number (-)
H_s: Significant wave height (m)
K_{yy}: Longitudinal radius of inertia (m)
L_{PP}: Length between perpendiculars (m)
R_0: Mean resistance in calm water (N)
Z: Number of blades (-)
σ_{aw}: Nondimensional-added resistance (-)
ρ: Water density (kg/m^3).

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References

[1] J. Gerritsma and W. Beukelman, "Analysis of the resistance increase in waves of a fast cargo ship," *International Shipbuilding Progress*, vol. 19, no. 217, pp. 285–293, 1972.

[2] H. Fujii and T. Takahashi, "Experimental study on the resistance increase of a ship in regular oblique waves," in *Proceedings of the of 14th ITTC*, vol. 4, pp. 351–360, Ottawa, Canada, September 1975.

[3] J. M. J. Journee, *Experiments and Calculations on Four Wigley Hull Forms*, Faculty of Mechanical Engineering and Marine Technology, Society of Naval Architects and Marine Engineers, Jersey, NY, USA, 1992.

[4] B.-J. Guo and S. Steen, "Evaluation of added resistance of KVLCC2 in short waves," *Journal of Hydrodynamics*, vol. 23, no. 6, pp. 709–722, 2011.

[5] J. H. Lee, M. G. Seo, D. M. Park et al., "Study on the effects of hull form on added resistance," in *Proceedings of the 12th International Symposium on Practical Design of Ships and Other Floating Structures*, pp. 329–337, Changwon, Korea, October 2013.

[6] H. Maruo, "The drift of a Body floating on waves," *Journal of Ship Research*, vol. 4, no. 1, pp. 2–15, 1978.

[7] J. N. Newman, "The drift force and moment on ships in waves," *Journal of Ship Research*, vol. 11, no. 1, 1967.

[8] N. Salvesen, "Added resistance of ships in waves," *Journal of Hydronautics*, vol. 12, no. 1, pp. 24–34, 1978.

[9] S. Liu, A. Papanikolaou, and G. Zaraphonitis, "Prediction of added resistance of ships in waves," *Ocean Engineering*, vol. 38, no. 4, pp. 641–650, 2011.

[10] T. H. Havelock, "The resistance of a ship among waves," *Proceedings of the Royal Society of London. Series A—Mathematical and Physical Sciences*, vol. 161, no. 906, pp. 299–308, 1937.

[11] O. M. Faltinsen, "Prediction of resistance and propulsion of a ship in a seaway," in *Proceedings of the 13th symposium on naval hydrodynamics*, Tokyo, Japan, October 1980.

[12] N. Salvesen, E. O. Tuck, and O. Faltinsen, "Ship motions and sea loads," *Trans. of Society of Naval Architects and Marine Engineers*, vol. 78, no. 8, pp. 250–287, 1970.

[13] K.-H. Kim and Y. Kim, "Numerical study on added resistance of ships by using a time-domain Rankine panel method," *Ocean Engineering*, vol. 38, no. 13, pp. 1357–1367, 2011.

[14] K. H. Kim, M. G. Seo, and Y. Kim, "Numerical analysis on added resistance of ships," *International Journal of Offshore and Polar Engineering*, vol. 22, no. 1, 2012.

[15] M.-G. Seo, K.-K. Yang, D.-M. Park, and Y. Kim, "Numerical analysis of added resistance on ships in short waves," *Ocean Engineering*, vol. 87, pp. 97–110, 2014.

[16] M. Kim, O. Hizir, O. Turan, and A. Incecik, "Numerical studies on added resistance and motions of KVLCC2 in head seas for various ship speeds," *Ocean Engineering*, vol. 140, pp. 466–476, 2017.

[17] D.-M. Park, M.-G. Seo, J. Lee, K.-K. Yang, and Y. Kim, "Systematic experimental and numerical analyses on added resistance in waves," *Journal of the Society of Naval Architects of Korea*, vol. 51, no. 6, pp. 459–479, 2014.

[18] P. M. Carrica, H. Sadat-Hosseini, and F. Stern, "CFD analysis of broaching for a model surface combatant with explicit simulation of moving rudders and rotating propellers," *Computers & Fluids*, vol. 53, pp. 117–132, 2012.

[19] Z. Shen, P. M. Carrica, and D. C. Wan, "Ship motions of KCS in head waves with rotating propeller using overset grid method," in *Proceedings of the 33rd International Conference on Ocean, Offshore and Arctic Engineering*, San Francisco, CA, USA, American Society of Mechanical Engineers.

[20] J. H. Wang and D. C. Wan, "Investigations of self-propulsion in waves of fully appended ONR tumblehome model," *Applied Mathematics & Mechanics*, vol. 37, no. 12, pp. 1345–1358, 2016.

[21] F. Sprenger, A. Maron, G. Delefortrie et al., "Experimental studies on seakeeping and maneuverability of ships in adverse weather conditions," *Journal of Ship Research*, vol. 61, no. 3, pp. 131–152, 2017.

[22] V. Shigunov, O. el Moctar, A. Papanikolaou, R. Potthoff, and R. Liu, "International benchmark study on numerical simulation methods for prediction of manoeuvrability of ships in waves," *Ocean Engineering*, vol. 165, pp. 365–385, 2018.

[23] J. Choi and S. B. Yoon, "Numerical simulations using momentum source wave-maker applied to RANS equation model," *Coastal Engineering*, vol. 56, no. 10, pp. 1043–1060, 2009.