Proceedings of the Thirty-third (2023) International Ocean and Polar Engineering Conference **www.isope.org**
Ottawa, Canada, June 19-23, 2023

ISBN 978-1-880653-80-7; ISSN 1098-6189

Study of Self-Propulsion Performance of a Single-Screw Ship in Waves Based on Improved Propeller Body Force Model

*Jianhua Wang[1], Wentao Wang[1,2], Decheng Wan[1]**

[1] Computational Marine Hydrodynamics Lab (CMHL), School of Naval Architecture, Ocean and Civil Engineering
Shanghai Jiao Tong University, Shanghai, China
[2] China Ship Scientific Research Center, Wuxi, China
*Corresponding Author

ABSTRACT

So far, self-propulsion simulation using fully discretized approach by modelling all moving components, especially for the rotating propellers, is very time consuming. It is very important to find a more efficient approach to evaluate the hydrodynamic performance with acceptable accuracy. In this paper, an improved blade element momentum theory (BEMT) propeller body force model is proposed to predict the propulsion performance considering hull-propeller-rudder interaction. The single-screw KRISO Container Ship (KCS) under head wave is simulated by in-house CFD solver naoe-FOAM-SJTU. Dynamic overset grid method is used to deal with the large ship motion in waves, while the improved body force model is utilized to calculate the propeller performance. Predicted results, i.e., ship motions, thrust and torque in waves, are compared with discretized propeller results and the experimental data. The results showed that the proposed propeller body force model is suitable and reliable in predicting the self-propulsion performance of ship sailing in waves.

KEY WORDS: Propeller body force model, self-propulsion, overset grid method, hull-propeller interaction in waves

INTRODUCTION

The performance of free running ship in waves is very complicated due to the complex hull-propeller-rudder interactions under large amplitude 6DOF motions. Therefore, the prediction of self-propelled ship in waves has been a widely concerned issue in the research field of ship hydrodynamics. Previous studies are mostly using the fully discretized approach based on dynamic overset grid method. This approach was firstly introduced to ship and ocean engineering for CFD simulations of self-propelled ships (Carrica et al., 2010; Castro et al., 2011). Wang et al., (2019a) employed the same approach to study the self-propulsion behaviors under different ship speeds. Wang et al., (2017) further applied the dynamic overset grid method to simulate the free running ship in different wave headings. With the help of dynamic overset grid technique and 6DoF motion solver with a hierarchy of bodies, simulations of ship self-propulsion become very convenient.

However, fully discretized approach by modelling all moving components, especially for the rotating propellers, is very time consuming. It is very important to find a more efficient approach to evaluate the hydrodynamic performance of self-propulsion with acceptable accuracy. Body force propeller model has long been used to predict the performance of open water test and self-propulsion test. Phillips et al. (2010) carried out rudder-propeller interaction simulation based on the Uniform Thrust (UT) distribution model, HO model (Hough and Ordway, 1965), and BEMT model (Benini, 2004). The results showed that BEMT model give relatively good predictions among three models. It was also noted (Yamazaki (1977), Tokgoz (2013)) that local velocity plays an important role in BEMT propeller model. The modified body force propeller model was further applied to the simulation of hull-propeller interaction (Li et al. (2019), Feng et al. (2020a, b) and Yu et al. (2021)).

Previous studies most focused on the clam water condition or quasi-steady condition when predicting the hull-propeller interaction with body force propeller model. However, ship self-propulsion in waves has very complex interactions and the propeller performance are highly nonlinear, which means a more accurate propeller body force model is needed to conduct the simulations. The motivation of this study is to find out whether it is reliable for the numerical computations of ship self-propulsion in waves based on body force model and to study the wave effects on the propulsion performance. In the present paper, an improved BEMT body-force model is proposed to predict the performance of ship self-propulsion in waves. The results are compared with fully discretized model to examine the accuracy of propeller body force model.

The outline of this paper goes as follows: the numerical approach including discretized model and body force model are presented in the second section; the simulation designs, including the geometry model, test conditions and grid distribution are described in the third section; the simulation results and discussions are presented in the fourth section; finally, conclusions from the present study are drawn.

NUMERICAL APPROACH

Governing Equations

Numerical computations are performed with the CFD solver naoe-FOAM-SJTU (Shen et al., 2015; Wang et al., 2019b), which is developed on the open-source platform OpenFOAM. The CFD solver calculates the Reynolds-averaged Navier-Stokes (RANS) equations for unsteady turbulent flows. The unsteady RANS equations are presented as a mass conservation equation and a momentum conservation equation:

$$\nabla \cdot \boldsymbol{U} = 0 \tag{1}$$

$$\frac{\partial \rho \boldsymbol{U}}{\partial t} + \nabla \cdot (\rho \boldsymbol{U}\boldsymbol{U}) = -\nabla p - \rho \mathbf{g} + \nabla \cdot (\mu \nabla \mathbf{U}) + (f_\varepsilon)_i \tag{2}$$

where p is the pressure, ρ is the density, $\boldsymbol{U}$ is flow velocity, μ is the viscosity coefficient, $\boldsymbol{g}$ is the gravity acceleration, $(f_\varepsilon)_i$ is the body-force source term, which will be activated when using body force model.

The turbulence is modeled by a blended $k-\omega / k-\varepsilon$ shear stress transport (Menter et al., 2003) turbulence model and wall functions are used in the near wall region. Volume of Fluid (VOF) approach with bounded compression technique (Berberović et al., 2009) is applied to capture free surface. Wave generation and absorption is based on the in-house wavemaker module (Cao et al., 2014).

Finite volume method (FVM) with unstructured grids is applied to discretize the computational domain. The pressure-implicit split-operator (PISO) algorithm is used to solve the RANS equations. Built-in numerical schemes in OpenFOAM are used to solve the partial differential equations (PDE). An implicit Euler scheme is used for temporal discretization. Second order TVD scheme is used to discretize the convection term, while a central differencing scheme is applied for diffusion terms. Van Leer scheme is used to discretize the convection term for VOF equation.

The present CFD solver has been extensively validated on various ship hydrodynamic cases, e.g., ship resistance (Zha et al., 2014), seakeeping (Shen and Wan, 2013), self-propulsion (Shen et al., 2015; Wang et al., 2019a) and maneuvering (Wang et al., 2017; 2018). Only main features are introduced herein, more detailed information can be found in the references mentioned above.

Discretized Propeller Model

The discretized propeller model (DP) or actual propeller (AP) is based on the 3D propeller geometry to generate the propeller boundary grid. By directly involving the propeller boundary, most of the flow details can be simulated. The key to the application of the discretized propeller model is to deal with the grid motion of rotating propellers. The naoe-FOAM-SJTU solver has dynamic overset grid capability and a full 6DoF motion solver with a hierarchy of bodies. The overset meshes are independent of each other and each mesh can move without any constraints (as shown in Fig. 1), making it easy to directly simulate ship self-propulsion in waves with rotating propellers. Details of the overset grid module implementation in OpenFOAM can be found in Shen et al., (2015). In the present study, the geometries are decomposed into several overlapping grids, which can be used to direct simulate ship self-propulsion in waves.

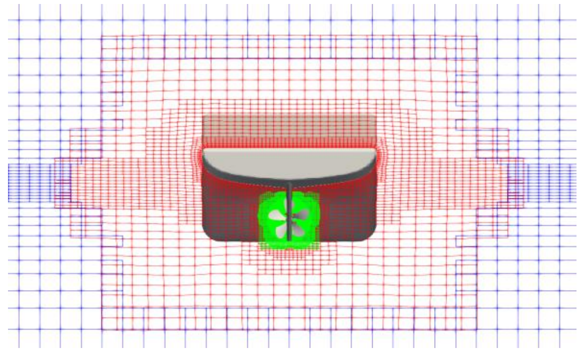


Fig. 1 Discretized propeller model

Body Force Propeller Model

In the present paper, an improved BEMT body force propeller model is applied to represent the effect of rotating propeller behind ship hull. The region of body-force is an envelope region formed by the projection region of a series of excitation points. In this paper, the distribution of the actuating points is designed as a disc (as shown in Fig. 2), corresponding to the large surface ratio of the marine propeller. The body force model is achieved by establish the relationship between the local velocity and the inflow velocity of the blade element under the action of the source term, which is very important in the calculation for the instantaneous wake flow condition under ship large motion in waves. The detailed information of the improved body force model can be found in Wang et al. (2022).

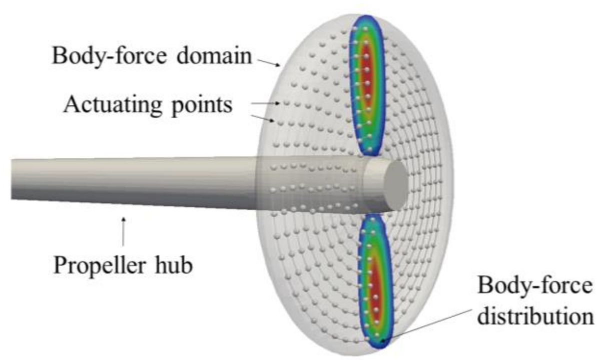


Fig. 2 Diagram of body force propeller model

SIMULATION SETUP

Geometry Model

In this paper, the benchmark ship model KCS and the SVP1193 propeller model are selected for the ship self-propulsion in wave simulation at model scale. This model has been widely used for the CFD calculation and extensive experiment data are available for CFD validation. The 3D geometry model of KCS ship appended with propeller and rudder is shown in Fig. 3. The main particulars of KCS model and SVP 1193 propeller model are listed in Table 1 and Table 2, respectively.

Fig. 3 Geometry model of KCS with propeller and rudder

Table 1. Main particulars of KCS model

Main particulars	symbol	Model scale
Scale factor	λ	52.667
Length between perpendiculars	L_{pp}(m)	4.3671
Length of waterline	L_{wL}(m)	4.4141
Beam of waterline	B_{wL}(m)	0.6114
Draft	T(m)	0.2051
Displacement	Δ (m^2)	0.3562
Block coefficient	C_B(m)	0.6505
Longitudinal center of buoyancy, fwd+	LCB(%L_{PP})	-1.48
Vertical center of gravity (from keel)	KG(m)	0.0669
Longitudinal momentum inertia	I_{zz}/L_{pp}	0.25

Table 2. Main particulars of SVP 1193 model

Main particulars	symbol	Model scale
Diameter	D(m)	0.15
Pitch ratio	$P_{0.7}/D$	1.00
Area ratio	A_e/A_0	0.70
Hub ratio	d_h/D	0.227
Number of blades	Z	5
Rotation	-	Right hand

Grid Distributions

There are three-part grids to directly simulate the self-propulsion in actual propeller case, i.e., hull grid, propeller grid and background grid, while only two-part grid is applied in the simulation of body force case. The computational domain with boundary setup is shown in Fig. 4.

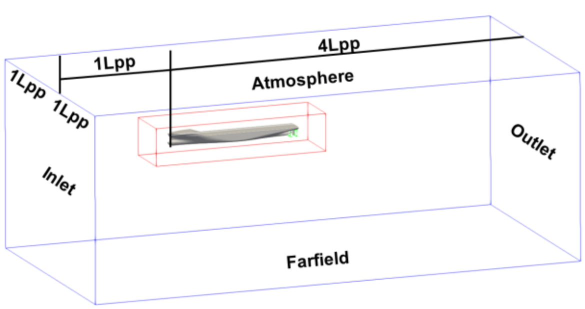


Fig. 4 Computational domain and boundary condition

Grid distribution for the actual propeller case and body force case are shown in Fig. 5 and Fig. 6, respectively. Since propeller grid is no longer needed in the body force case, the total grid number for the body force propeller simulation is 2.53 million, while 3.85 million cells are needed in actual propeller case.

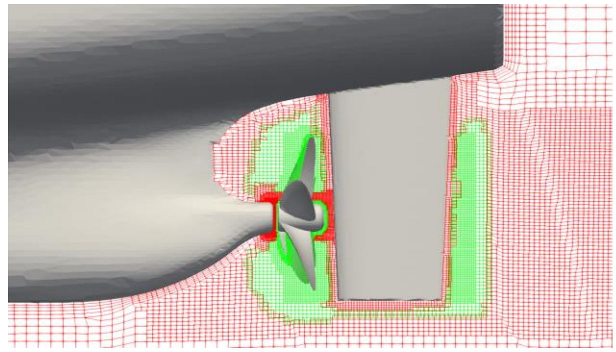


Fig. 5 Local grid distribution for actual propeller case

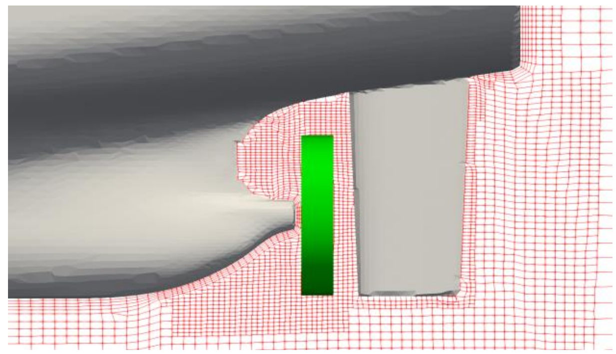


Fig. 6 Local grid distribution for body force propeller case

Test Conditions

The numerical simulations followed the setup of ship model test performed at FORCE (Otzen et al., 2008), and the available experimental data can be used to validate the CFD results. The single-screw ship is advancing at constant speed of $U = 1.701\, m/s$ with corresponding $Fr = 0.26$ and $Re = 6.82 \times 10^6$. The rudder is fixed with ship hull and the propeller is rotating at constant RPS. Head wave condition is adopted in the test with the wave heigh $H = 0.084m$, wave period $T = 1.78s$, H/λ =1/60, corresponding to $\lambda/L_{pp} = 1.15$. In this case, the encountering frequency is 0.91 Hz, which is close to the natural frequency of heave and pitch motion 0.91 Hz. As a result, the motion response can be very large and is suitable to study the motion behaviors in waves.

NUMERICAL SIMULATIONS

All the calculations are conducted on the HPC cluster in Computational Marine Hydrodynamics Lab (CMHL), Shanghai Jiao Tong University. Each node consists of 2 CPUs with 20 cores per node and 64GB accessible memory (Intel Xeon E5-2680v2 @2.8 GHz). 40 processors are assigned to calculate the ship self-propulsion computation in both actual propeller and body force propeller case. The time step was set to $\Delta t = 0.0002s$ in actual propeller simulations, which corresponds to approximately 1.0 degrees of propeller rotation per time step under self-propulsion condition. And time step of $\Delta t = 0.001s$ is used in the body force calculations. It costs approximately 99.8 hours of clock time to complete the self-propulsion computations of actual propeller case, while only 7.3 hours of clock time is needed in the body force calculations. The body force model can be more efficient in the numerical computation of self-propulsion in waves.

Motions

Fig. 7 shows the comparisons of time histories of heave and pitch motion between actual propeller model and body force model. It can be found that the present body force model results show well agreement with actual propeller results. The numerical results of ship motion response are also compared with measurement data. The quantality comparison of transfer function of heave and pitch motion with experimental results is listed in Table 3.

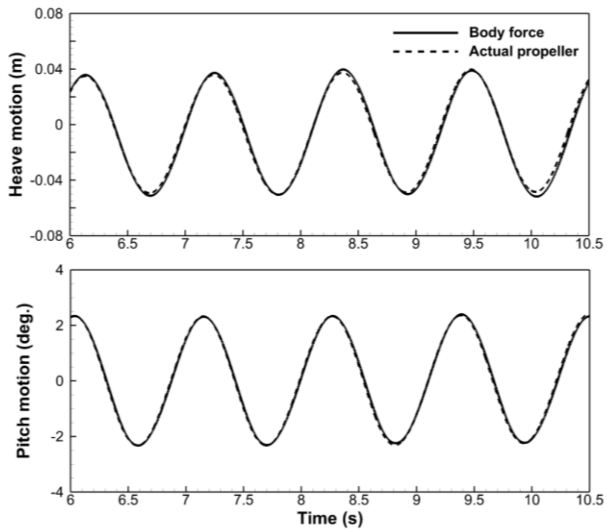


Fig. 7 Comparisons of time histories of heave and pitch motions

The transfer function (TF) of heave motion and pitch motion is listed as follows:

$$TF_3 = \frac{x_{3_1}}{a} \tag{3}$$

$$TF_5 = \frac{x_{5_1}}{ak} \tag{4}$$

where TF_3 and TF_5 represents the transfer function of heave motion and pitch motion, respectively. x_{3_1} and x_{5_1} denotes the first-order amplitude after FS expansion of heave and pitch motion. It can be seen that the present body force model and actual propeller model can all give good predictions of the ship heave motion in waves, where body force model error is 3.62% comparing with the actual propeller error 0.73%. It was reported in the measurement that obvious wave dissipation was observed, which may be the reason why large discrepancy for the pitch motion is occurred.

Table 3. Comparison of transfer function between CFD and EFD

	TF_3	TF_5
EFD	0.988	0.695
Body force	1.023	0.748
Error	3.62%	7.62%
Actual propeller	0.995	0.747
Error	0.73%	7.48%

Fig. 8 shows four typical time instants of free surface elevation and ship motion in one wave period. It can be noted that when ship bow encountering wave trough, the bow will out of water (as shown in time instance a and d). On the contrary, the ship bow will go downward when experiencing wave crest (as shown in time instance b and c). Breaking bow waves can also be observed when bow experience wave crest. The motion behaviors are consistent with the trend in Fig. 7.

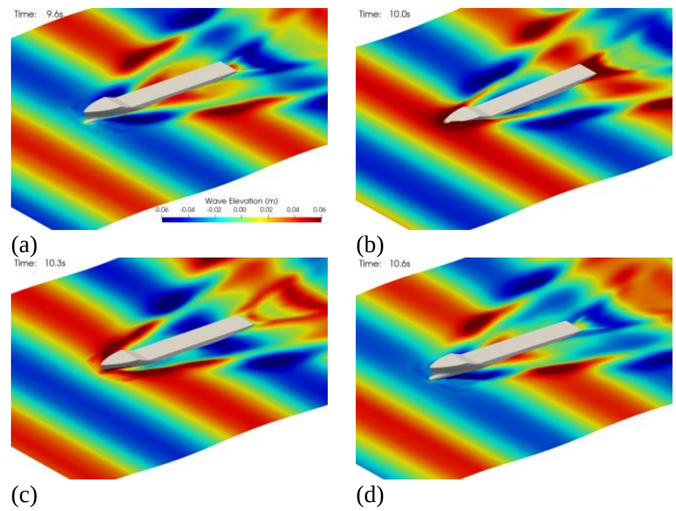


Fig. 8 Snapshots of free surface and ship motion in one wave period

Propulsion Performance

The rotating propeller behind ship hull will experience un-uniform wake flows and the nonuniformity is more complicated when the ship hull has large 6DoF motion in waves. As shown in Fig. 7 and Fig. 8, the pitch and heave motion are time varying and the propulsion forces will change corresponding to the motion response. Fig. 9 demonstrates the time histories of instantaneous thrust and torque during ship self-propulsion in waves. It is very clear that both the body force propeller model and the actual propeller model can predict the wave effects on propulsion performance. The present body force model can well predict the thrust and torque variations, while some under-estimations can be observed when comparing with actual propeller results.

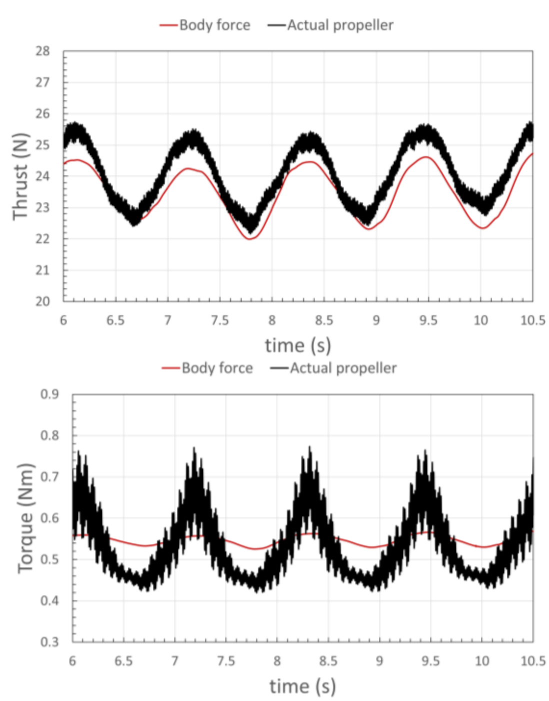


Fig. 9 Comparisons of the time histories of the thrust and torque during ship self-propulsion in waves

Fig. 10 presents the enlarged view of the thrust and torque comparisons. It is obvious that the overlapping shadows shown in Fig.9 are the high-frequency fluctuations, which are equal to the frequency of 5-bladed propeller rotating rate. This phenomenon proved that the present body-force model can only predict the wave effects on the mean propulsion forces, while the actual propeller model can give more detailed information around the rotating propellers. But in general, the body force propeller model can be an efficient approach to study the hydrodynamic performance of ship self-propulsion in waves.

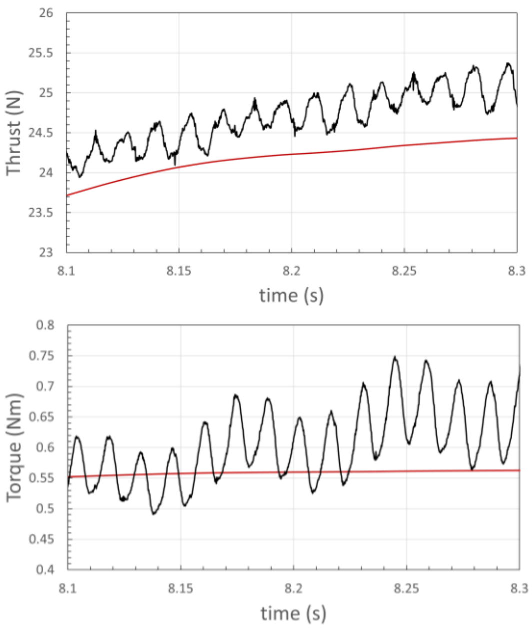


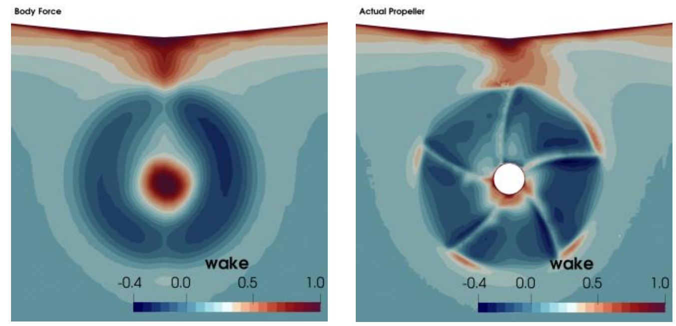
Fig. 10 Local view of the comparison of thrust and torque between body force model and actual propeller

Table 4 gives the comparison of mean thrust and torque data between present numerical results and experiment results. Both approaches can well predict the thrust with error up to 3.23%, while the torque is under-estimated to a larger discrepancy. Since the numerical approach can not well model the friction characters in the shaft and the measurement facilities for this very high-frequency data can not record all the information, the reasons for the deviation should be further studied.

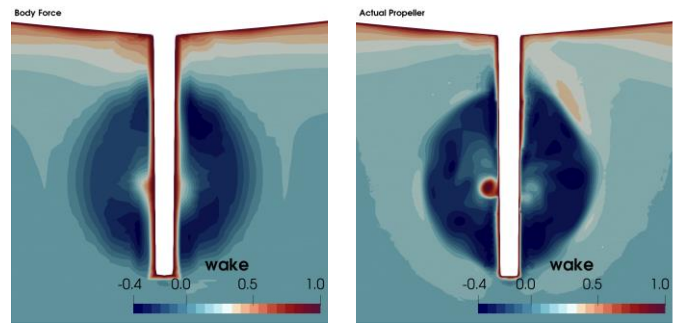
Table 4. Comparison of mean thrust and torque between CFD and EFD

	Thrust (N)	Torque (Nm)
EFD	24.251	0.595
Body force	23.468	0.547
Error	-3.23%	-8.04%
Actual propeller	24.063	0.539
Error	-0.78%	-9.41%

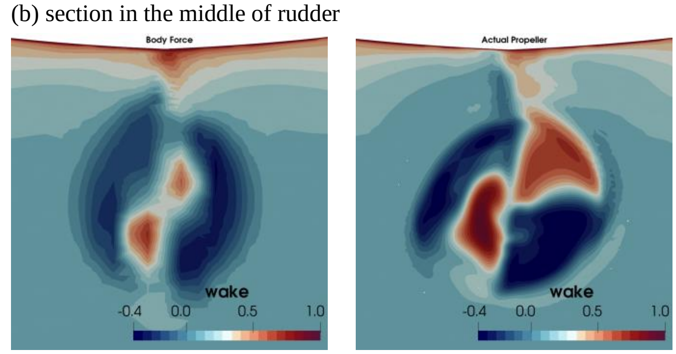
In order to explain the propulsion performance as shown in Fig. 9 and Fig. 10, wake flows at different sections are presented in Fig. 11. All the figures are colored by wake fraction $w = (U - U_A)/U$. It should be noted that all the wake flows are represented by the instantaneous flow at the same time. It can be seen that the wake flows are highly non-uniform, and the wake distribution in body force model are also asymmetry. The dark blue color shown in the propeller disk region means the water are accelerated due to the rotating motion of propeller. Both results show similar distribution for the wake flow, even for the local distribution of the asymmetric phenomenon. The hub effects can also be observed in section b. The asymmetric behavior of local wake flows can be captured by body force model even in the downstream side after rudder (as shown in section c). However, the body force can only give a mean trend of the wake flow, which explains the smoother curves shown in Fig. 9 and Fig. 10. Actual propeller can give more detailed information around rotating propellers.



(a) section behind propeller disk



(b) section in the middle of rudder



(c) section after rudder

Fig. 11 Wake flow distribution at different sections (left: body force model, right: actual propeller)

Fig. 12 illustrates the vortical structures (represented by iso-surface of Q=150) around ship hull and propellers in both actual propeller case and body force case. It shows that all the flow characters are almost the same in the front region except the vortices around propeller and rudder in the stern region. Fig. 13 shows the enlarged view of the vortical structures around propeller in both actual propeller case and the body force case. The main difference is the tip vortex around propeller. The reason for the emergence of tip vortex is that the pressure gradient before and after the propeller makes the fluid near the tip flow back from pressure-side to suction-side, so the intensity of the tip vortex is related to the pressure gradient. For the actual propeller case, the pressure gradient occurs on the surface of blades, and there is no obvious pressure gradient in the gap between the blades. Therefore, the tip vortex is concentrated in the tip and migrate downward with the wake, forming five independent spiral structures as shown in Fig. 13. However, for the body-force model, the pressure gradient occurs in the whole propeller plane, so the tip vortex appears a continuous ring structure. Meanwhile, the pressure force per unit area is smaller in the body-force case, so the tip vortex intensity is weaker than that of the actual propeller case. In addition, the body force model can predict the propeller hub vortices. The vortices distribution around propeller and rudder are also consistent to the wake flow performance shown in Fig. 11.

Fig. 12 Vortical structures around ship hull (upper: actual propeller, lower: body force propeller)

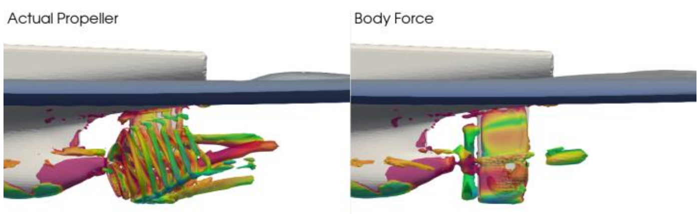


Fig. 13 Enlarged view of vortical structures around propeller

CONCLUSIONS

This paper presents the numerical simulations of ship self-propulsion in waves using both fully discretized propeller model and body force propeller model. KCS ship model is used for all the numerical simulations. Comparing with actual propeller results and experimental data, the present improved body force propeller model can give good predictions of the hydrodynamic performance of ship self-propulsion in waves. For ship motions, body force model results match very well with the actual propeller results. For propulsion performance, body force propeller model can predict the wave effects on the time variations of thrust and torque. The mean thrust is under-estimated by 3.23% and 0.78% for body force model and actual propeller model, respectively. Through the comparisons of ship motion and propulsion forces, the improved body force propeller model is proved to be reliable and efficient in predicting the performance of ship self-propulsion in waves. The wake flow in different sections also indicate that the propeller body force model can give relatively mean flow behaviors of ship self-propulsion in waves, while actual propeller can give more detailed information of flow characters.

ACKNOWLEDGEMENTS

This work was supported by the National Natural Science Foundation of China (52131102), and the National Key Research and Development Program of China (2019YFB1704200), to which the authors are most grateful.

REFERENCES

Benini, E (2004). “Significance of blade element theory in performance prediction of marine propellers.,” *Ocean Eng*, 31(8-9), 957-974.

Berberović, E, van Hinsberg, N, Jakirlić, S, Roisman, I, Tropea, C (2009). “Drop impact onto a liquid layer of finite thickness dynamics of the cavity evolution.” *Phys Rev E*, 79 (3), 36306.

Cao, H, and Wan, DC (2014). “Development of Multidirectional Nonlinear Numerical Wave Tank by naoe-FOAM-SJTU Solver,” *Int J Ocean Sys Eng*, 4(1), 52-59.

Carrica, PM, Castro, AM, Stern, F (2010). “Self-propulsion computations using a speed controller and a discretized propeller with dynamic overset grids,” *J Mar Sci Technol*, 15, 316–330.

Castro, AM, Carrica, PM, Stern, F (2011). “Full scale self-propulsion computations using discretized propeller for the KRISO container ship KCS,” *Comput Fluids*, 51, 35–47.

Feng, D, Yu, J, He, R, Zhang, Z, and Wang, X (2020a). “Free running computations of KCS with different propulsion models,” *Ocean Eng*, 214, 107563.

Feng, D, Yu, J, He, R, Zhang, Z, and Wang, X (2020b). “Improved body force propulsion model for ship propeller simulation,” *Appl Ocean Res*, 104, 102328.

Hough, G, and Ordway, D (1965). “The generalized actuator disk,” *Dev Theor Appl Mech*, 2, 317–336.

Li, Z, Yu, J, Feng, D, Jiang, K, and Zhou, Y (2019). “Research on the Improved Body-Force Method Based on Viscous Flow,” *Proc 38th International Conference on Ocean, Offshore and Arctic Engineering*, OMAE, Glasgow, Scotland, UK.

Menter, FR, Kuntz, M, and Langtry, R (2003). “Ten years of industrial experience with the SST turbulence model,” *Turbul Heat Mass Transf*, 4(1), 625–632.

Otzen, JF, Simonsen, CD (2008) “Uncertainty assessment for KCS resistance and propulsion tests in waves,” *ONRIII187 01, Lyngby, Denmark, FORCE Technology*.

Phillips, AB, Turnock, SR, and Furlong, M (2009). “Evaluation of manoeuvring coefficients of a self-propelled ship using a blade element momentum propeller model coupled to a Reynolds averaged Navier Stokes flow solver,” *Ocean Eng*, 36(15–16), 1217–1225.

Phillips, AB, Turnock, SR, and Furlong, M (2010). “Accurate Capture of Propeller-Rudder Interaction using a Coupled Blade Element Momentum-RANS Approach,” *Ship Technol Res*, 57(2), 128–139.

Shen, Z, and Wan, DC (2013). “RANS computations of added resistance and motions of a ship in head waves,” *Int J Offshore Polar Eng*, 23(04), 264–271.

Shen, Z, Wan, DC, and Carrica, PM (2015). “Dynamic overset grids in OpenFOAM with application to KCS self-propulsion and maneuvering,” *Ocean Eng*, 108, 287–306.

Tokgoz, E, Win, YN, Kuroda, K and Toda, Y (2014). “A New Method to Predict the Propeller Body-force Distribution for Modeling the Propeller in Viscous CFD Code without Potential Flow Code,” *J Japan Society Naval Architects and Ocean Eng*, 19, 1-7.

Wang, J, Zhao, W, and Wan, DC (2019a). “Simulations of Self-Propelled Fully Appended Ship Model at Different Speeds,” *Int J Comput Methods,* 2019, 16(5), 1840015.

Wang, J, Zhao, W, and Wan, DC (2019b). “Development of naoe-FOAM-SJTU solver based on OpenFOAM for marine hydrodynamics,” *J Hydrodyn*, 31(1), 1-20.

Wang, J, Zou, L, and Wan, DC (2017). “CFD simulations of free running ship under course keeping control,” *Ocean Eng*, 141, 450–464.

Wang, J, Zou, L, and Wan, DC (2018). “Numerical Simulations of Zigzag Maneuver of Free Running Ship in Waves by RANS-Overset Grid Method,” *Ocean Eng*, 162: 55-79.

Wang, M, Wan, DC, and Wang J (2022). “An improved BEMT model based on agent actuating disk with application to ship self-propulsion simulation," *Ocean Eng*, 266: 112787.

Yamazaki, R (1977). "On the propulsion theory of ships on still water (improved theoretical method)," *In: Memoirs of The Kyushu University, Faculty of Engineering*, 1, 65–88, 34.

Yu, J, Yao, C, Liu, L, Zhang, Z and Feng, D (2021). "Assessment of full-scale KCS free running simulation with body-force models," Ocean Eng, 237, 109570.

Zha, R, Ye, H, Shen, Z, and Wan, DC (2014). "Numerical study of viscous wave-making resistance of ship navigation in still water," *J Mar Sci Appl*, 13(2), 158–166.