Numerical investigation of open water performance of hybrid CRP podded propulsion system

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Abstract

Hybrid CRP podded propulsion system inherits merits of contra-rotating propellers (CRPs) and Azipod propulsion system. Firstly it matains good maneuverability of Azipod system and will decrease carbon emission since Azipod system is powered by electricity. Secondly the rear propeller can drastically recover swirl energy wasted by the front propeller in the wake flow field. Thirdly the pressure magnitude suffered by the two propellers is reduced dramatically, therefore the hybrid CRP podded propulsion system can relieve undesired cavitating and vibrating level compared with single propeller . In this paper, the hybrid system is composed of a CRPs a streamlined pod. Based on CFD (Computational Fluid Dynamics) technology with RANS function, k-ω SST turbulence model and sliding mesh method, the hybrid CRP podded propulsion system is simulated at different advance coefficients. Predicting results show that the Azipod propulsion system has little influence on the front propeller while the latter is strongly affected by the former. K_T and $10K_Q$ have 8 small periods when propeller rotates 180 degrees and their fluctuating amplitude is very small under considered axial spacing between the propeller centerlines. The efficiency is 3.5% higher than single propeller, the rear pod shape should be optimized to reduce its drag force. As the spacing increases to some extent, K_T and $10K_Q$ become smaller while efficiency almost keeps constant. Wake flow field information such as velocity distribution and vorticity structure reflect complex interactions between front propeller and Azipod propulsion system.

Keywords: Hybrid CRP podded propulsion system, sliding mesh method, open water performance

Introduction

Nowadays in order to reduce costs of ship operation, cargo carriers such as container ships, are designed to be more bigger and faster, then propeller needs larger radius and suffers more heavier weight and load. This may lead to serious non-uniform wake flow and undesirable cavitation and propeller vibration which will greatly deteriorate propulsion efficiency. In the past decades, majority of vehicles are propelled by traditional screw propeller with one shaft linked to main engine, on one hand, low efficiency of this propulsion way under heavy load condition consumes large quantity of fuel oil, on the other hand, the limitation of engine power cannot supply sufficient thrust to propel larger ships. Every year all kind of ships will discharge large amount of pollution gas, report from IMO points out that in 2009, shipping industry all over the world discharged 96.5 million tons of carbon dioxide and this data will be increased to 153 million tons in 2030. In order to promote development of “Green ship”, IMO puts forward three indexes , namely EEDI (Energy Efficiency Design Index), EEOI (Energy Efficiency Operational Index), SEEMP (Ship Energy Efficiency Management Plan) to regulate ship design and operation. Ship design with lower energy consuming, higher propulsion efficiency and better cavitation performance has turn to be an international tendency.

Contra-rotating propellers (CRPs) , as figure 1 shows, is composed of two conventional propellers which rotate axially in reverse direction. Compared with single propeller, CRPs has better propulsion efficiency and energy-saving effect. However complexity of shaft system and high costs of installation and maintenance limit its further development. Then hybrid CRP podded propulsion system was put forward and applied widely in recent years. Hybrid CRP podded propulsion system, as figure 2 shows, inherit merits of CRPs and Azipod propulsion system. Firstly it maintains good maneuverability of Azipod system and will decrease carbon emission since Azipod system is powered by electricity. Secondly the rear propeller can drastically recover swirl energy wasted by the front propeller in the wake flow field. Thirdly the pressure magnitude suffered by the front and Azipod system decreases dramatically compared to single propeller, therefore, the hybrid CRP podded propulsion system can relieve undesired cavitation and vibrating level to obtain higher propulsion efficiency.

Figure 1. CRPs configuration

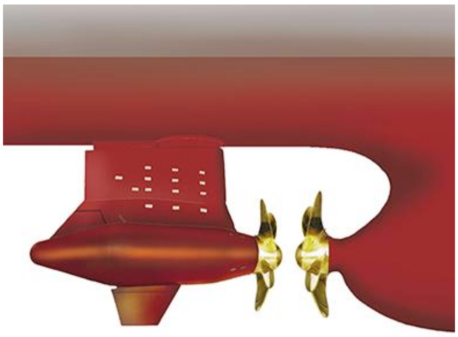


Figure 2. Hybrid CRP podded system

Azipod propulsion system[1] was firstly put forward and applied by ABB with great success in 1999 and then in 2002 hybrid CRP podded propulsion system[2] was developed based on previous work. In 2001, Samsung Heavy Industry Co. Ltd[3]. and ABB agreed to develop a Ultra Large Container Vessel (ULCC) with the hybrid CRP podded propulsion system, later Samsung Ship Model Basin carried model tests for ULCC with single screw, twin screw, and hybrid CRP podded propulsion system, and finally hybrid CRP podded propulsion system was proven to the most efficient propulsion system for carrier with this type and size, power savings to twin screw were about 9% and to single screw were 5%. Sheng et al. (2012)[4] performed open water experiment of hybrid CRP podded propulsion system in cavitation tunnel and the experimental data were compared with results predicted by CFD. Both model test and numerical model were proven to be reliable and credible.

Open water performance and interactions between front propeller and the rear Azipod propulsion system are critical issues in initial design period of hybrid CRP podded propulsion system. Up to now, there three main methods, model test in cavitation tunnel, lifting surface theory and CFD technology, have been widely used to propeller design. Model test has relatively high accuracy, however high cost of model building, experimental devices and long experimental period limit its popular application in ordinary people, meanwhile experimental result is sensitive to accuracy of detection instruments. Lifting surface theory has high computing efficiency, but for ignorance of viscosity, it rely on much experience to rectify model. Yang et al. (1991,1992) [5][6] investigated the steady and unsteady performance of contra-rotating propellers by lifting surface theory. Owing to the great progress in numerical algorithms and supercomputer, the applications of CFD technology are advancing rapidly in the fields of ship hydrodynamics. Because CFD technology is based on actual fluid control functions (Navier-Stokes equations) which take the viscosity and rotation into account, thus it can correctly model nonlinear wake deformation and flow separation due to heavy loading. Up to now, MRF (Multiple Reference Frame) method, overset mesh method, and sliding mesh method are the three main techniques dealing with propeller' rotation. MRF method can only be used to solve steady problems, in other words, dynamic flow field cannot be obtained. Though this method has high efficiency, its precision is not so good as overset mesh method and sliding mesh method. Overset mesh method has been extensively applied to handle problems that have multiple moving objects with many degrees of freedom. Different grids will exchange their information through an interpolating code named SUGGAR++(Noack et al., 2009） [7]on the overlapping area. At sacrifice of relatively large of computing resources, this method will guarantee high accuracy. Shen, et al (2012)[8] carried out KCS self-propulsion and maneuvering by CFD solver naoe-FOAM-SJTU with overset mesh technique, predicted results agree well with their experimental data. Comparing with MRF and overset mesh method, sliding mesh method keeps equal precision as overset mesh method, but its computing efficiency is greatly improved since this method only needs interpolation between overlapping faces of rotational region and static region. Wu et al (2016) [9]compared accuracy and computing efficiency of those three method applied to numerical prediction of open-water performance of single propeller. Based on sliding mesh method, Zhou (2014) [10]investigated unsteady flow around wind turbines with different blades numbers. Wang, et at (2012)[11] studied two sets of CRPs' open-water performance developed by David W Taylor Naval Ship R&D Center using CFD method, numerical predicted results agree well with their experimental counterparts, furthermore, he investigated CRPs' periodical unsteady thrust and torque in detail. In the present work, CFD technology by solving RANS functions and k-ω model which has been widely used to predict hydrodynamics of propeller with higher computing accuracy and efficiency is used.

Numerical methods

Governing equations

In present work, fluid is assumed to be incompressible, RANS functions including mass and momentum conservation equations are listed as follow:

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

$$\frac{\partial}{\partial t}(u_i) + \frac{\partial}{\partial x_j}(u_i u_j) = -\frac{\partial p}{\partial x_j} + \frac{1}{\mathrm{Re}}\frac{\partial}{\partial x_j}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) + \frac{\partial}{\partial x_j}\left(-\overline{u_i' u_j'}\right) \tag{2}$$

Where u_i are averages of velocity components in three directions; j (=1, 2, 3) means different direction; R_e is Reynolds number; $-\overline{u_i' u_j'}$ are Reynolds stress.

Turbulence model

In order to solve RANS functions, turbulence model is introduced to model Reynolds stress. k-ω SST[5](Shear Stress Transport) was put forward by Menter in 2003, k-ω turbulence model is effective near wall surface while in the far field, k-ε turbulence model become effective. k-ω SST has been widely used in research of hydrodynamics of navel architectures.

Sliding mesh method

Sliding mesh method is typically competent to solve unsteady problems in industries, such as propeller, pump, turbine and so on. It has higher accuracy and computing efficiency because fluid information is transferred only at overlapping area in a simple interpolation way. As can be seen in figure 5, the whole computing zone is divided into three zones, two of them surround the front and rear propellers respectively and they will rotate synchronously with propeller. The residual big zone is kept static. Interpolation will be done at overlapping area based on weight factor. In figure 3, blue surface and red surface are named master surface slave surface respectively. The contribution master cell 1 makes to slave cell 1 is measured by the weight factor which is defined by how much overlapping area master cell 1 accounts .

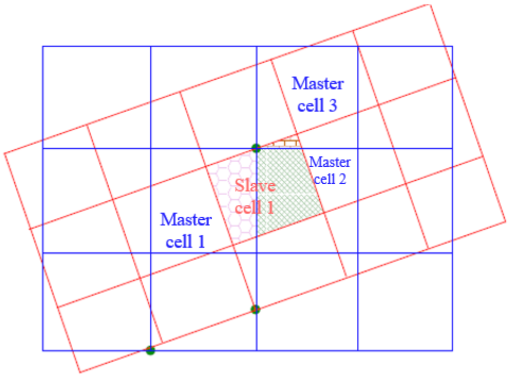


Figure 3. Diagram of overlapping area

Geometry, grid and test conditions

Geometry

In the present work, the hybrid CRP podded propulsion system is composed of a CRPs model and a streamlined pod model. The CRPs model was developed by Miller[1] in David W Taylor Naval Ship R&D Center in 1976. As Table 1 shows, DTMB3686 works as front propeller and DTMB3687A as the rear propeller. Both propellers own 4 blades and diameter of the latter is slightly smaller than the former owing to shrinking effect of wake flow field. Azipod propulsion system is composed of the rear propeller and a streamlined pod who not only stows motor but also works as rudder.

Table 1. Main parameters of CRPs

Items	DTMB3686	DTMB3687A
Diameter/mm	305.2	299.1
Blade number	4	4
$(P/D)_{0.7R}$	1.291	1.326
Disc ratio	0.303	0.324
Direction	Left	right
Airfoil	NACA66mod	NACA66mod

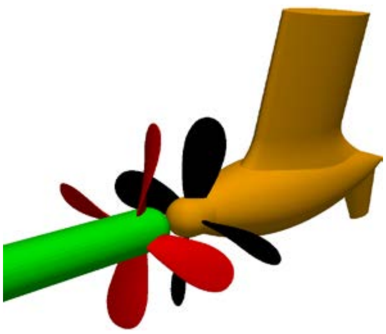


Figure 4. Hybrid CRP podded propulsion system

Grid distribution and test conditions

Grid generation is a crucial but very tough work. In present work, firstly the background grid is generated by ANSYS ICEM CFD , it is quite convenient to generate structured grid by creating ‘O block’ . Secondly background grid is imported to OpenFOAM, one of its grid generation application, named snappyHexMesh will delete cells in the bodies, move boundary to the surfaces and add boundary layers sequentially. Thirdly, another application, named topoSet, will be used to create two rotational zones that surround the front and the rear propeller and sliding mesh faces will be constructed by topology technology. The final grid zone and grids are displayed in figure 5 and figure 6. Total grid number is 2.9 million where 2.6 million is gathered around propeller blades in order to capture important flow features. Y^+ is chosen to be 40 which is required to be more than 30 if wall functions is applied.

Open water performance validation of contra-rotating propellers is carried out at different advance coefficients. They are 0.7, 0.8, 0.9, 1.0, 1.1 which can be achieved by altering inflow velocity while keeping rotation rate constant (12 rps). Time step is settled to be 1.1574e-4s so that propeller will rotate with 1 degree, this small time step will improve computing accuracy of unsteady forces suffered by propeller. In order to investigate influence of axial spacing between the propeller centerlines on hydrodynamics of hybrid CRP podded propulsion system, three distances, 0.343 D_F, 0.543 D_F, 0.743 D_F are going to be taken into consideration at advance coefficient 0.9.

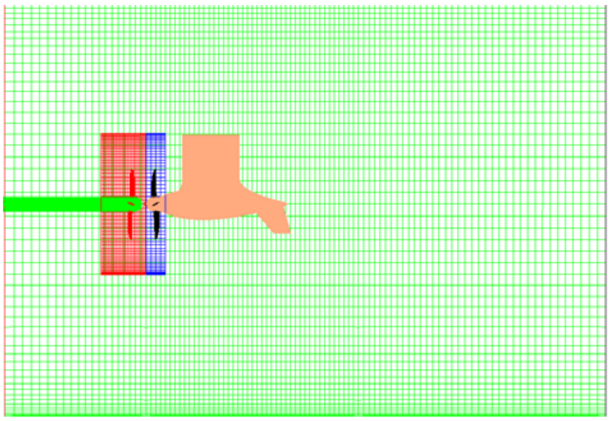


Figure 5. Grids allocation

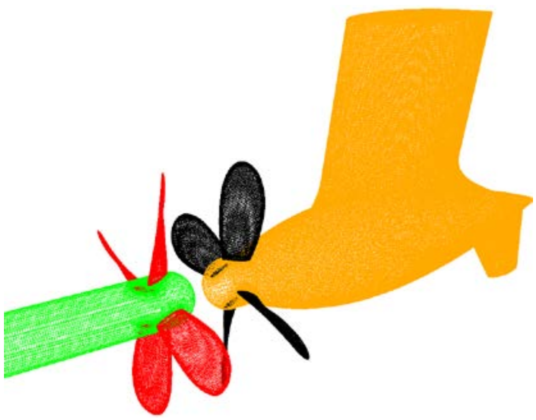


Figure 6. Grids of the model

Simulation results and analysis

Hybrid CRP podded propulsion system is composed of a CRPs and a streamlined pod, model test of this CRPs was carried out by Miller (1976)[13] at David W Taylor Naval Ship R&D Center, open water performance validation of CRPs will help verify whether numerical methods and numerical model in present work is correct. Then open water performance of hybrid CRP podded propulsion system is analyzed in detail including interactions between front propeller and Azipod propulsion system, influence of axial spacing between the propeller centerlines.

Open water performance validation of contra-rotating propellers

Some important hydrodynamic coefficients should be defined to measure open water performance of hybrid CRP podded propulsion system, they are listed as follow:

$$J = \frac{U_0}{nD_F} \tag{3}$$

$$K_T = \frac{T_F + T_P}{\rho n^2 D_F^{4}} \tag{4}$$

$$K_Q = \frac{Q_F + Q_P}{\rho n^2 D_F^{5}} \tag{5}$$

$$\eta_0 = \frac{JK_T}{2\pi K_Q} \tag{6}$$

Where U_0 is inflow velocity, T_F, Q_F, T_P, Q_P are thrust coefficient and torque coefficient of the front propeller and Azipod propulsion system respectively, D_F, n are diameter and rotation rate of front propeller.

Figure 7 shows open water performance of CRPs, predicting results agree well with their experimental counterparts, errors of thrust coefficient and torque coefficient are about 2%, 3.6% respectively which are slightly higher than experimental data, errors of efficiency is -1.6% which is slightly lower than experimental data. In general, numerical model and algorithms in present work are reliable and credible. Now, a streamlined pod will be added to CRPs as hybrid CRP podded propulsion system.

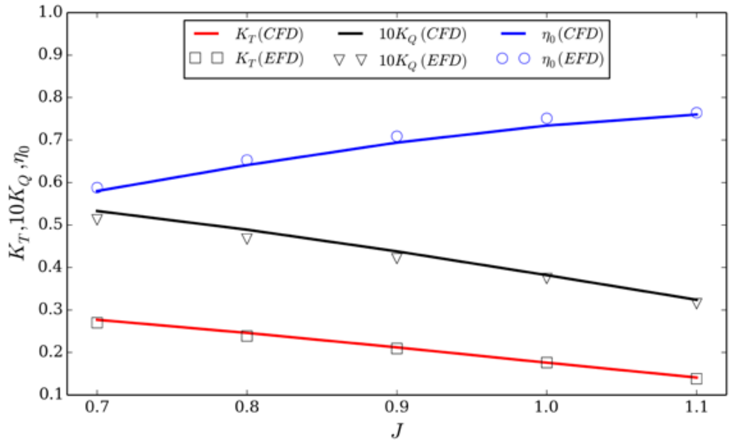


Figure 7. Open water performance of CRPs

Open water performance of hybrid CRP podded propulsion system

Interactions between front propeller and Azipod propulsion system are critical issues of hybrid CRP podded propulsion system, in present work, computing results of this propulsion system are compared with computing open water results of single propeller and Azipod propulsion system. Figure 8 shows that the Azipod propulsion system has little effect on the front propeller. As can be seen in figure 10(a) and figure 10(b), owing to the reason that blockage effect induced by the rear pod counteracts suction effect induced by the rear propeller, flow fields around single propeller and the front propeller show no obvious difference. However Figure 9 shows that hydrodynamic coefficients of the Azipod propulsion system are greatly affected by the front propeller. As can be seen in Figure 10(b) and Figure 10(c), inflow velocity before Azipod propeller has been dramatically boosted by the front propeller, thrust and torque of the Azipod propulsion system are reduced obviously typically at high advance coefficients.

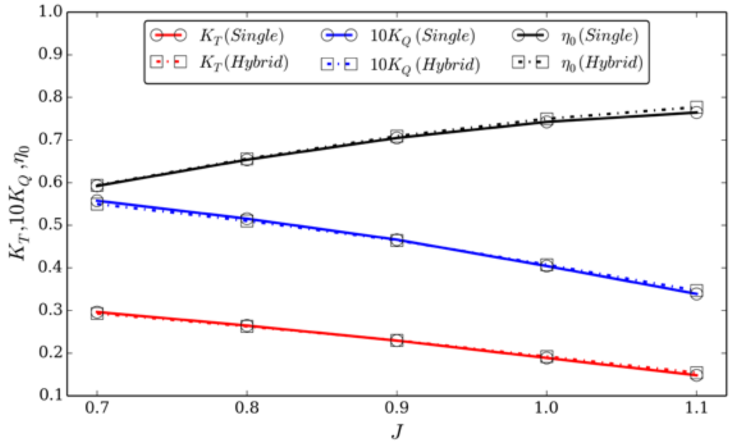


Figure 8. Effect of the podded propeller on the front

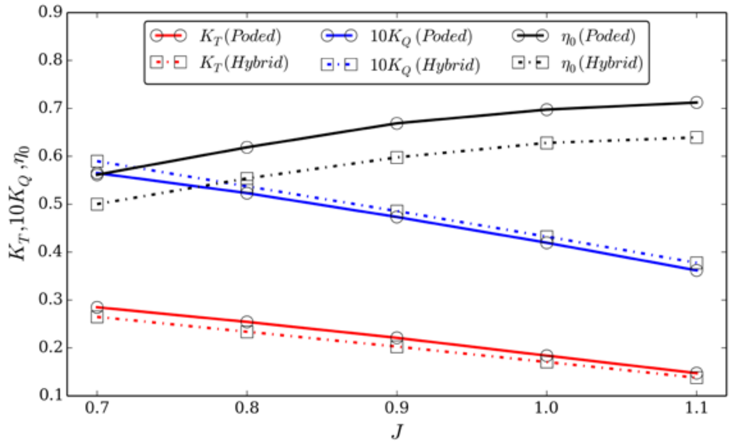
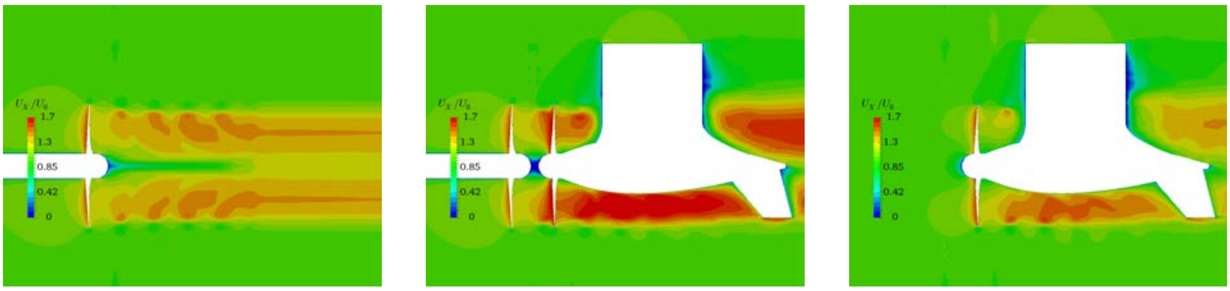


Figure 9. Effect of the front propeller on the podded propeller



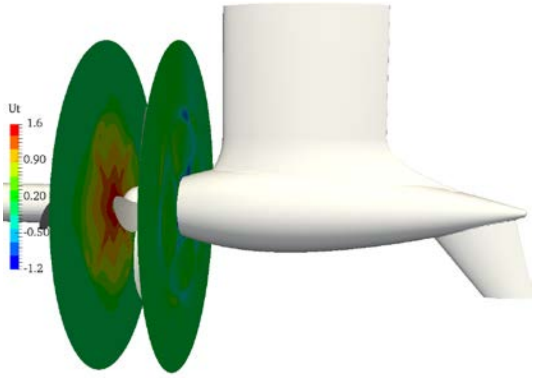
(a) Single propeller

(b) Hybrid CRP podded propulsion system

(c) Azipod propulsion system

Figure 10. Axial velocity distribution

Figure 11 shows that tangential velocity can be obviously utilized by the rear propeller which means hybrid CRP podded propulsion system could obtain better energy-saving effect than single propeller. Meanwhile, Figure 12 shows that the rear propeller will intensify magnitude of axial velocity. At last, rudder performance will be improved with smaller tangential velocity but higher axial velocity, on the other hand, reverse rotating direction of the front and rear propeller lead to minimum unbalanced torque suffered by this hybrid system, it will improve curse-keep performance of torpedo.



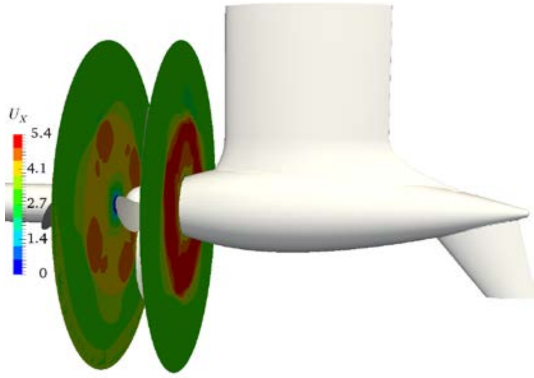
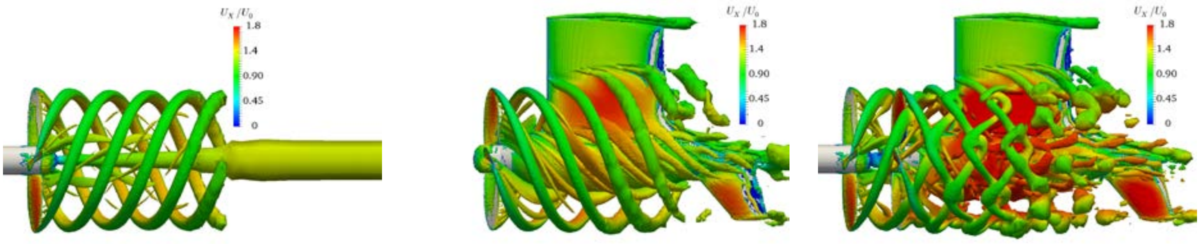


Figure 11. Tangential velocity distribution **Figure 12. Axial velocity distribution**

Figure 13 displays vortex structure of those three types of propulsion when Q is equal to 200. All of them are colored by U_X/U_0 where U_X , U_0 are axial velocity and inflow velocity respectively. Both vortex structures of Azipod propulsion system and hybrid CRP podded propulsion system will climb up when they encounter the rear pod , it is induced by the blockage effect of pod who functions as a rudder. Meanwhile axial velocity will be boosted around convex surface of pod. After comparison of figure 13(b) and figure 13(c), it's easy to find that vortex structure of hybrid CRP podded owes small tangential velocity in wake flow field, in other words, the rear propeller recovers swirl energy induced by the front propeller.



(a) Single propeller **(b) Azipod propulsion system** **(c) Hybrid CRP podded propulsion system**

Figure 13. Vortex structure distribution

In the period of designing hybrid CRP podded propulsion system, much more attention should be paid to unsteady forces, because large amplitude of fluctuation may induce ship vibration and serious noise. Figure 14 shows time history of unsteady forces suffered by front propeller and Azipod propulsion system, where 'Front', 'Azipod' mean the front propeller and Azipod propulsion system of hybrid CRP podded propulsion system respectively. Owing to the interaction between front propeller and the Azipod propulsion system, both K_T and $10K_Q$ have 8 small periods when propeller rotate 180 degrees which is related to blade numbers and blade number ratio, on the other hand, fluctuating amplitude is very small when axial spacing between the propeller centerlines is $0.343D_F$. it means that hybrid CRP podded propulsion system will not suffer obvious unsteady forces under a certain spacing where Azipod propulsion system could rotate normally.

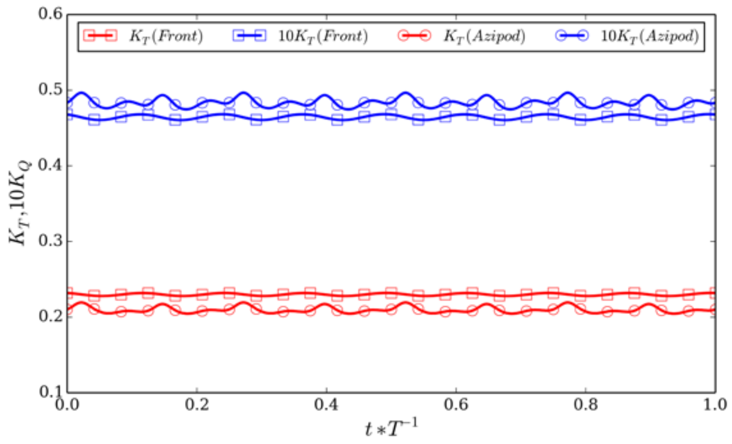


Figure 14. Unsteady forces suffered by front propeller and Azipod system

In table 2, three types of propulsion are compared under the condition that they could approximately produce equal thrust. Efficiency of CRPs is 10% higher than single propeller while efficiency of hybrid CRP podded propulsion system is 3.5% higher than single propeller for the reason that the rear pod unit will produce drag force. In future work, pod unit shape should be optimized to improve propulsion efficiency.

Table 2. Comparison of efficiency among three types of propulsion

Propulsion manner	T(N)	Q(N·M)	η_0
Single propeller	529.12	30.31	0.630
CRPs	529.91	33.41	0.694
Hybrid CRP podded propulsion system	540.00	36.24	0.652

Effects of spacing between propeller centerlines

The question of whether and how the spacing between propeller centerlines affects hydrodynamics of hybrid CRP podded propulsion system is also investigated in detail. Figure 15 shows that with the spacing increasing, K_T, $10K_Q$ will decrease to some extent while η_0 almost keeps constant. Figure 16 displays axial velocity distribution at different spacing of propeller centerlines, where U_0, U_X are inflow velocity and axial velocity in flow field respectively. It could be found that with the spacing becoming larger, inflow velocity near leading edge before the rear propeller will become larger to some extent typically. As Wang et al[14]. (2016) pointed out, the smaller spacing, the better energy-saving effect can be obtained.

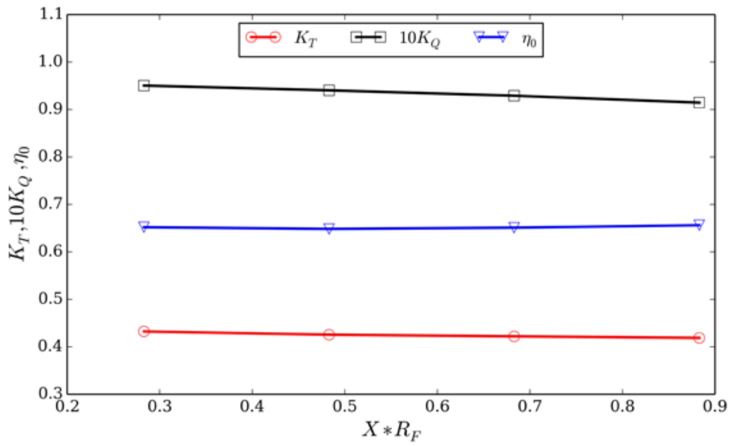
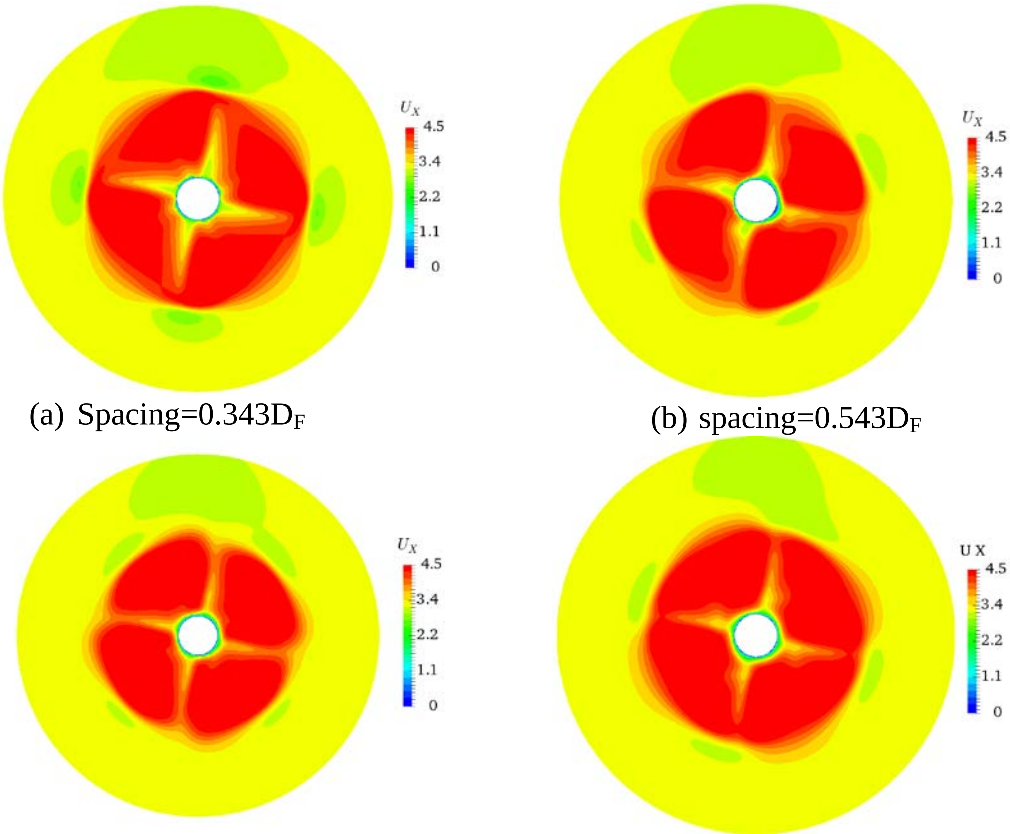


Figure 15. hydrodynamic coefficients at different spacing



(a) Spacing=0.343D_F

(b) spacing=0.543D_F

(c) Spacing=0.743D_F

(d) Spacing=0.943D_F

Figure 16. Axial velocity distribution before rear propeller at different spacing of propeller centerlines

Conclusions

This paper investigates open water performance of hybrid CRP podded propulsion system by CFD software, OpenFOAM. Based on analysis of hydrodynamics and wake flow field information, some useful conclusions can be draw as follow:

1) Predicting results of open water performance of CRPs agree well with their experimental counterparts, it proves that numerical methods and numerical models in present work are reliable and creditable.
2) The Azipod propulsion system has little influence on the front propeller, because suction effect of the rear propeller is counteracted by blockage effect of the rear pod, while Azipod propulsion system is greatly affected by the front propeller, thrust and torque will decrease because its inflow velocity has been boosted by front propeller by a large scale.
3) Magnitude of tangential velocity in wake flow field is reduced dramatically which means hybrid CRP podded propulsion system could obtain better energy-saving performance than single propeller.
4) Efficiency of hybrid CRP podded propulsion system is 3.5% higher than single propeller, the rear pod shape, which will produce drag force, should be optimized in future work.
5) With the spacing between propeller centerlines increasing, K_T, $10K_Q$ of the front propeller almost keep constant, while for the Azipod propulsion system, they will be reduced gradually, however η_0 of the hybrid CRP podded propulsion system changes slightly.

Future wok will focus on optimization of pod shape and investigation of power ratio influence on hydrodynamics of hybrid CRP podded propulsion system.

Acknowledgements

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