Numerical investigation of wake equalizing duct by using double-model theory

Tao Sun, Chonghong Yin, Decheng Wan*

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

ABSTRACT: In the paper, the wake equalizing duct (WED) is investigated by CFD-based method coupled with double-model theory. All the computations are carried out by our in-house CFD solver naoe-FOAM-SJTU, which is developed on the open source platform OpenFOAM and mainly composed of a dynamic overset grid module and a full 6DoF motion module. Finally, simulation results, wake field and vortex at stern are provided and energy saving effect of WED is investigated.

KEY WORDS: wake equalizing duct; double-model theory; JBC; naoe-FOAM-SJTU solver

INTRODUCTION

With more attention paid to environmental protection, the International Marine Organization(IMO) makes strict restriction for saving energy and reducing emission of ships. There are various methods to satisfy the demands of IMO for ships saving device. In recent years, energy saving device for ships has drawn more and more attention from science and technology workers due to its low cost and remarkable effect for reducing fuel consuming and environmental pollution. Among varieties of energy saving devices, wake equalizing duct is widely applied to merchant ships widely because of its simple structure, convenient installation and low cost[1,2]. Wake equalizing duct is fitted at stern before propeller, the general function of it is set to improve uniformity of propeller's inflow field, thus homogenizing the wake and improving hull efficiency. Also, the wake equalizing duct can accelerate the flow by means of the lift created by the aero-foil shape of the duct cross-section. Usually, the wake equalizing duct(WED) has a good energy saving effect of 3% to 7%, and cost can be recovered in 6 months.

In recent decades, CFD method has experienced rapid growing capability which can present reliable simulations of ship resistance and propulsion. For forced self-propulsion simulations with energy saving devices, CFD studies usually ignore the effect of free surface because the wave resistance is quite small under condition of ship sailing at low velocity in calm water[3]. So the paper will use CFD method to investigate the energy saving effect of WED by using double-model theory, which will not take free surface into account. Before the numerical computations are begun, the verification and validation method is applied to control numerical and modeling errors according to the benchmark case of forced self-propulsion JBC in Tokyo 2015 CFD Workshop, in which condition free surface is taken into account and experiment data is presented. After the verification and validation[4], we can take off freesurface from the computation domain and grid arrangement of the benchmark case and start the computation using double-model method, which will guarantee the reliability of the following simulation.

The CFD solver employed in the paper is naoe-FOAM-SJTU[5,6,7], which is developed on the open source platform OpenFOAM. Mainly consisting of a dynamic overset grid module and a full 6DoF motion module with a hierarchy of bodies, the solver can numerically simulate the self-propulsion of ship accurately[8,9]. The main frame of the paper goes as follows: first, a brief introduction is given; and the second section presents the computational overview, including the geometry model, test conditions, verification & validation, grid distribution; then comes the simulation results and analysis section.

COMPUTATIONAL OVERVIEW

Geometry model

Numerical simulation in the present work is carried out for JBC equipped with and without WED under condition of forced self-propulsion without considering free surface. The geometry models of JBC, WED are respectively shown in Fig.1, Fig.2, and the principle geometric characteristics are listed in Table 1.

(a) Overall view

(b) JBC without WED

(c) JBC with WED

Fig.1 Geometry model of JBC

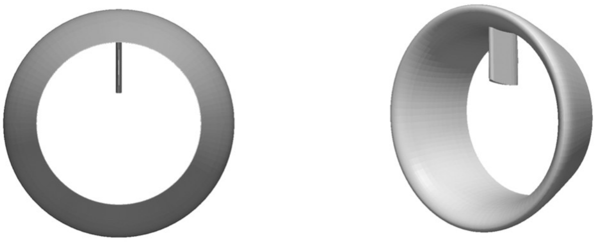


Fig.2 Geometry model of wake equalizing duct

Table 1 The principle characteristics of JBC

Main particulars	Full scale	Model scale
L_{PP} (m)	280	7
L_{WL} (m)	285	7.125
B_{WL} (m)	45	1.125
D (m)	25	0.625
T (m)	16.5	0.4125
∇ (m^3)	178369.9	2.7870
$S_{0\_w/oESD}$ (m^2)	19556.1	12.2226
S_{0_wESD} (m^2)	19633.9	12.2706
C_B	0.858	0.858
LCB	2.5475	2.5475
x/L_{PP}	0.985714	0.985714
$-z/L_{PP}$	-0.0404214	-0.0404214
—	clockwise	clockwise

Test conditions

JBC models are performed at $Re=7.46\times10^6$ and $Fr=0.142$, corresponding to a velocity of 1.179 m/s. The water density is 998.2 kg/m^3 and the kinematic viscosity is 1.107×10^{-6} m^2/s. The value of gravitational acceleration is 9.80 m/s^2. In the simulation process, JBC is set to sail at the forced self-propulsion point supplied by the TOKYO 2015 CFD Workshop in calm water.

Table 2 The forced self-propulsion point of JBC

case	n(r/s)	V(m/s)
JBC W/O WED	7.8	1.179
JBC W WED	7.5	1.179

Verification and Validation

Currently, verification and validation tend to be useful for quantifying numerical and modeling errors in CFD computations. Proceeded by verification, validation is a process that controlling the numerical solution against the appropriate experimental data, in order to reveal the error and uncertainty from both numerical and modelling deficiencies.

The validation is according to the benchmark case in Tokyo 2015 CFD Workshop, in which condition free surface is taken into account.

Table 3 Grid convergence study for JBC

Parameter		JBC without WED				JBC with WED			
		EFD	V&V study			EFD	V&V study		
			Coarse	Medium	Fine		Coarse	Medium	Fine
$C_T\times10^3$	Value	4.811	5.372	4.697	4.261	4.762	5.248	4.551	4.596
	E%D	/	-11.66	4.238	3.949	/	-10.21	4.427	3.486
$C_F\times10^3$	Value	/	3.046	2.819	2.869	/	3.004	2.504	2.548
$C_P\times10^3$	Value	/	1.576	1.463	1.489	/	1.393	1.141	1.161
K_T	Value	0.217	0.237	0.223	0.222	0.233	0.253	0.241	0.239
	E%D	/	-9.217	-2.765	-2.304	/	-8.584	-3.433	-2.575
K_Q	Value	0.0279	0.0296	0.0287	0.0285	0.0295	0.0311	0.0304	0.0299
	E%D	/	-6.093	-2.867	-2.151	/	-5.424	-3.051	-1.356

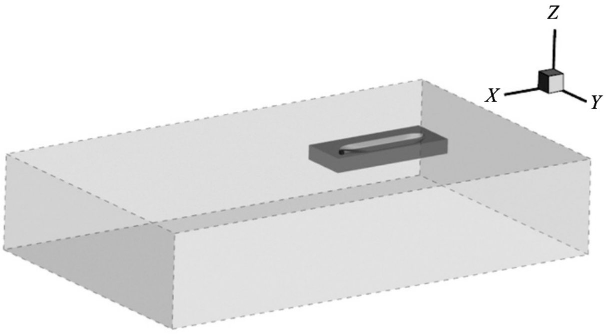
The medium grid is applied in the paper. The total resistance coefficients from CFD computation have error about 4.5% compared with the experimental data. For low-speed JBC without and with WED, the friction resistance dominates. As a kind of fat ship, JBC sailing at low speed is numerically computed well by naoe-FOAM-SJTU. We will take off the free surface from the computation domain and grid arrangement according to the double-model theory in the next step.

Overset grid distribution

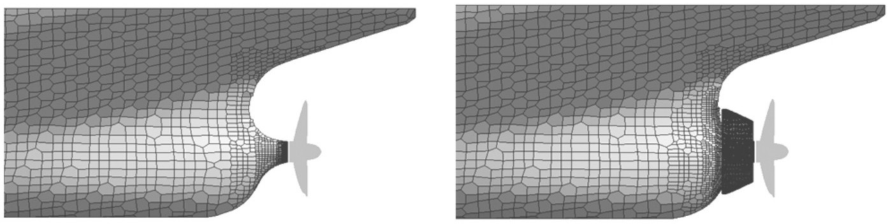
The space coordinate range is determined as $-1.0L_{pp}<x<4.0L_{pp}$, $-1.5L_{pp}<y<1.5L_{pp}$, $-1.0L_{pp}<z<0$. The mesh is generated by *SnappyHexMesh*, an automatic mesh generation tool provided by OpenFOAM. This tool generates mesh based on Cartesian grids by splitting hexahedral cells, resulting in unstructured octree-hexahedral grids. In the present study, the computational domain is divided into three parts: one for background grid, one for grid around ship hull, one for grid around propeller. The background-hull-propeller system is combined using overset assembly at runtime. Fig.3 shows the overset grid distribution for each component. The summary of overset component grids is listed in Table 4.

Table 4 Grid sizes of overset component grids

Grid size	Hull	Propeller	Background	Total
JBC W/O ESD	1.29×10^6	1.94×10^6	0.27×10^6	3.50×10^6
JBC W ESD	1.51×10^6	1.94×10^6	0.27×10^6	4.91×10^6



(a) Computational domain



(b) Grid arrangement for JBC without WED

(c) Grid arrangement for JBC with WED

Fig.3 Overset grid distribution for each components.

RESULTS

To evaluate the reliability of the code, the open-water propeller test is computed first in this paper[10]. When performing computation with discretized propellers under condition of forced self-propulsion for JBC, the time step is determined by the needs of the propeller flow, meaning that smaller time steps are needed. Two hundred time steps per propeller rotation are typically required. Time step is set to be 0.00025s in this computation.Fig.4 shows the open water results for the rotating propeller, and the numerical results agree very well with the experimental data.

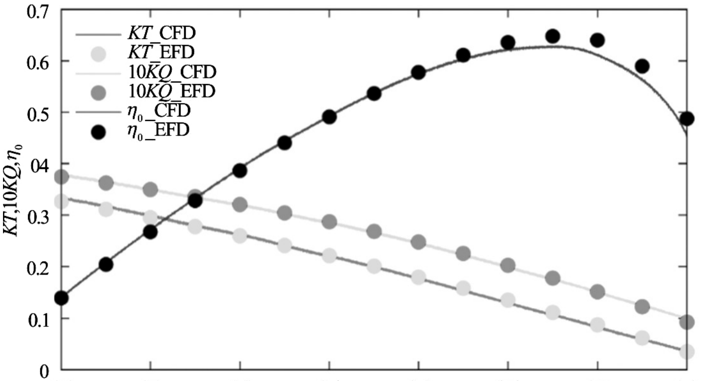


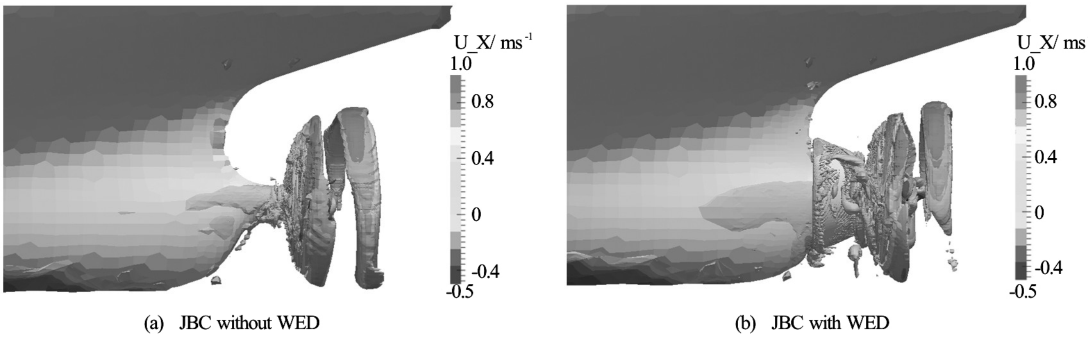
Fig.4 Open water results for propeller

The forced self-propulsion of JBC with and without WED will be numerically simulated by naoe-FOAM-SJTU. The paper will compare the results of the two cases and analysed the energy saving effect of WED. ΔE is defined by the following equation: $\Delta E(\%) = (P_{WO-ESD} - P_{W-ESD}) / P_{WO-ESD} \times 100$. Energy saving effect for forced self-propelled JBC with WED is displayed in Table 5.

Table 5 Energy saving effect of WED

JBC W/O WED			JBC W WED		
n(r/s)	Q(N·m)	2πn·Q	n(r/s)	Q(N·m)	2πn·Q
7.8	0.158	7.74	7.5	0.154	7.25

$\Delta E(\%) = (P_{WO-ESD} - P_{W-ESD}) / P_{WO-ESD} \times 100$ =(7.74-7.25)/7.74×100=6.3. Propeller power P is defined as $2\pi n \times Q$, where Q is the propeller torque. The wake equalizing duct studied in this paper show a good energy saving effect of 6.3% by CFD computation. The simulation of vortices behind the propeller is useful to evaluate the propulsion performance. Fig.5 shows the iso-surfaces of Q=100 colored with axial velocity under self-propulsion conditions and present clearly that the propeller tip vortices and hub vortex of self-propelled JBC significantly weakened after installed the energy saving device.



(a) JBC without WED (b) JBC with WED

Fig.5 Iso-surfaces of Q=100 colored according to Ux under self-propulsion

Contours of mean axial velocity at x/L_{pp}= 0.9412 and x/L_{pp}= 0.9656 are shown in Fig. 6. The former cross section is situated before the WED and the later one is situated at the gap between the propeller and the WED. The flow velocity before WED for both cases is quite the same, but the flow velocity at the gap is conspicuously different, which is smaller for JBC with WED indicating energy loss is largely reduced because the flow velocity is in the same direction with the ship.

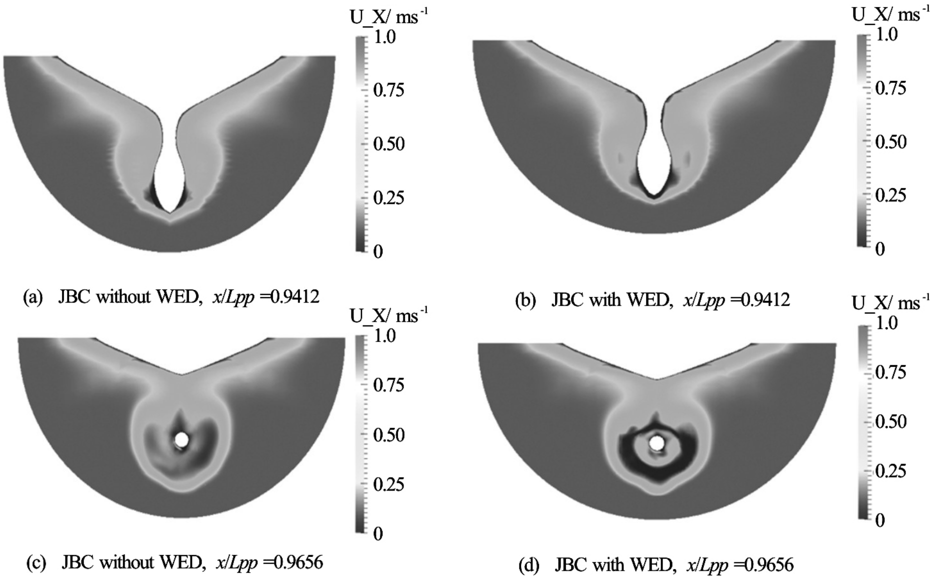


Fig.6 Wake field comparisons

CONCLUSIONS

In this paper, a numerical study is carried out for studying the effectiveness of wake equalizing duct on JBC by using double-theory method, proceeded by verification and validation considering free surface. Computations of forced self-propulsion cases with and without energy saving device are performed by the in-house multifunction solver naoe-FOAM-SJTU. The study contains the investigation for the effectiveness of energy saving device, analysis of wake field and vortex structures at stern. Some meaningful conclusions can be summarized. The wake equalizing duct studied in this paper can improve the propulsion characteristics of the JAPAN Bulk Carrier considerably. It shows a good energy saving effect of 6.3% by CFD computation.

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