Model- and Full-scale VLCC resistance prediction and flow field analysis based on IDDES method

*Chonghong Yin, Jianwei Wu and 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

With the development of CFD technology and the improvement of computing capacity, CFD is playing an increasingly important role in ship design. However, at present CFD computations of ships are typically performed in model scale due to the lack of experimental results in full-scale, and the increasingly complexity of numerical simulation at very high Reynolds numbers that RANS is hard to solve. In this paper, a RANS/DES solver for naval architecture and ocean engineering named naoe-FOAM-SJTU, which is developed from OpenFOAM, is applied to carry out the numerically simulation of model- and full-scale VLCC. For model scale computation results, we adopt the three-dimensional extrapolation method to get full-scale resistance, and also full-scale calculation is carried out by CFD method at the cruise speed directly. Results are compared with the experimental results/three-dimensional extrapolation results. The effect of surface roughness is considered in full-scale computations. Analysis results show reliability and validity of our IDDES method in ship resistance prediction. This paper also made a discussion on comparison of flow fields of model- and full-scale VLCC.

KEY WORDS: DES method; S-A IDDES method; full-scale resistance; surface roughness；OpenFOAM; naoe-FOAM-SJTU

INTRODUCTION

Prediction of ship resistance is an important task in ship design. Due to various constraints, the current forecast for ship resistance is mostly based on model tests. Model tests are generally following Froude number equal condition, but we can't guarantee equal Reynolds. Due to the scale effect, Reynolds at ship model scale (about 106 orders of magnitude) and the real scale (about 109 orders of magnitude) often have three orders of magnitude difference. A series of practical engineering experience extrapolation formula are introduced to solve the problem of scale effect, such as Froude method (two-dimensional method) and Hughes three-dimensional method, which measured from the model experiment and made a use of empirical extrapolation formula also hull roughness coefficients to get the real ship resistance. Although these methods have a strong practical in engineering, with the development of shipbuilding industry and the coming out of a variety of energy-saving devices, people are trying to find a way to give direct information of flow field under real ship scale.

With the rapid development of computer technology and numerical methods, the method of Computational Fluid Dynamic (CFD) has been increasingly developed to solve the hydrodynamic problems in recent years. The viscosity effects of fluid can be fully taken into consideration and non-linear factors can be handled precisely, especially in the conditions of high Reynolds number. Also, with the advancements of computer science and mature numerical computation methods, nowadays the efficiency and accuracy of CFD method are greatly improved. Recent years, usage of CFD method to perform full scale ship computations directly is increasing. Tahsin Tezdogan (2015) used the commercial code Star-CCM+ to perform the full scale KCS computations with the condition of head waves, also comparisons with potential flow theory and experimental data were analyzed. Pablo M. Carrica (2011) adopted the overlapping solver CFDShip-Iowa v4.5 to simulate full scale self-propelled KCS, and made a comparison analysis of model scale and full scale wake field at propeller disk.

At present stage, full scale ship resistance predictions based on CFD method are mostly based on RANS approach. But RANS method has problems in the following two aspects of the calculation of the full scale ship. On the one hand, boundary layer thickness of full scale ship at very high Reynolds number is thinner than model scale relatively, which needs to generate very thin first layer cells around hull surface to capture the viscous force, and causing greater difficulties in mesh generation. On the other hand, since the Reynolds number of full scale calculation is greater than model scale, unsteady features of fluids will be more obvious, eddy viscosity of the current conventional RANS method will be overestimated, this will ignore important vortex structures in the flow fields, the defects exist in RANS length scale will be more apparent.

In this paper, the in-house RANS/DES solver naoe-FOAM-SJTU (2012) is used to perform the computations, which is developed based on the open source code OpenFOAM. S-A IDDES (DES) model and k-ω SST (RANS) model are adopted to the numerical computations of model and full scale VLCC hull in calm water, results are compared with the three-dimensional extrapolation results from model experiment.

COMPUTATIONAL METHODS

DES Model

DES (Detached Eddy Simulation) model is one of the most common types of hybrid RANS-LES method which was first proposed by Spalart and Allmaras (1997). The general idea is to combine the advantages of both RANS and LES. More precisely, the model acts as a RANS model in attached boundary layers and turns into LES for the separated flow regions. A smooth transition is made from regions where the unsteady Reynolds-averaged equations are solved to those where a standard LES is performed. The switching between two models depends on the local grid-resolution.

The original DES utilizes the Spalart-Allmaras (S-A) RANS model for small turbulence scale region close to a wall and uses the SGS model for other small turbulence scale region that is away from the wall. The model is switched by means of a limiter, which compares the distance to wall to the local grid-spacing. This allows a smooth transition of RANS-solved attached boundary layer to the SGS-solved separated flow region. However, this method is very dependent on the mesh quality near the wall. If the mesh is small enough to trigger the SGS model in the boundary layer while too coarse to actually support the solving of the boundary layer using LES, it cannot capture all the velocity fluctuations. Moreover the eddy viscosity will be reduced, as well as the modeled Reynolds stresses, without the introduction of resolved stresses to restore the balance. This phenomenon is called Modeled Stress Depletion (MSD). This unbalanced stresses then reduce the skin friction and lead to Grid Induced Separation (GIS).

The DES model using in this paper is one the latest revisions of the recent DES models called S-A IDDES (Improved Delayed Detached Eddy Simulation, 2008). The objective of this model is to combine the advantages of the Wall Modeled LES (WMLES), and the DDES (Delayed Detached Eddy Simulation, 2006) capabilities.

IDDES defines the sub-grid scale length limiter Δ taking the influence of wall-distance dependency, which yields:

$$\Delta = f\left\{\Delta_x, \Delta_y, \Delta_z, d_w\right\} = \min\{\max\left[C_w d_w, C_w \Delta_{\max}, \Delta_{wn}\right], \Delta_{\max}\} \quad (1)$$

If the inlet condition contains unsteady turbulent flow, the WMLES is adopted; otherwise the regular DDES is used. The RANS-LES length scale of DDES branch is defined as:

$$l_{DDES} = l_{RANS} - f_d \max\left\{0, l_{RANS} - l_{LES}\right\} \quad (2)$$

DDES was designed to eliminate the odd reaction of the DES to a grid refinement beyond the limit of MSD or GIS, which introduce a second length scale to the length scale of turbulence model instead of using the LES filter. The function f_d is defined as follows:

$$f_d = 1 - \tanh(8r_d)^3 \quad (3)$$

and r_d is defined as:

$$r_d = \frac{\nu_t + \nu}{\kappa^2 d_w{}^2 \max[\sqrt{\frac{\partial U_i}{\partial x_j}\frac{\partial U_i}{\partial x_j}}; 10^{-10}]} \quad (4)$$

In contrast to the DDES branch, the WMLES branch will be activated when the inflow conditions are unsteady, contain turbulent content and have a sufficient fine grid to resolve the boundary-layer eddies. To achieve a coupling between RANS and LES, the following blended RANS-LES length scale is used:

$$l_{WMLES} = f_B(1+f_e)l_{RANS} + (1-f_B)l_{LES} \quad (5)$$

where $l_{RANS}=d_w$, $l_{LES}=C_{DES}\psi\Delta$, for S-A RANS model, the recommend C_{DES} is 0.65. ψ is the correction coefficient of IDDES Δ.

VOF method

VOF method is applied to capture the free surface in this work. This method has the advantage of being able to control numerical diffusion and can also provide high accuracy, which is suitable for the simulation of liquid sloshing. The transport equation for α is defined as follows:

$$\frac{\partial \alpha}{\partial t} + \nabla\cdot\left[\left(\boldsymbol{U} - \boldsymbol{U}_g\right)\alpha\right] + \nabla\cdot\left[\boldsymbol{U}_r(1-\alpha)\alpha\right] = 0 \quad (6)$$

where the first two terms represent the volume fraction term in continuous equation, and the last term stands for the compressible term when free surface is considered. α denotes the volume fraction which is the volume percentage of liquid in one cell. To all of the cells, the value of α varies between 0 and 1:

$$\begin{cases} \alpha = 0 & \text{air} \\ \alpha = 1 & \text{water} \\ 0 < \alpha < 1 & \text{interface} \end{cases} \quad (7)$$

with the introduction of α, ρ and μ can be defined as:

$$\rho = \alpha\rho_l + (1-\alpha)\rho_g \quad (8)$$

$$\mu = \alpha\mu_l + (1-\alpha)\mu_g \quad (9)$$

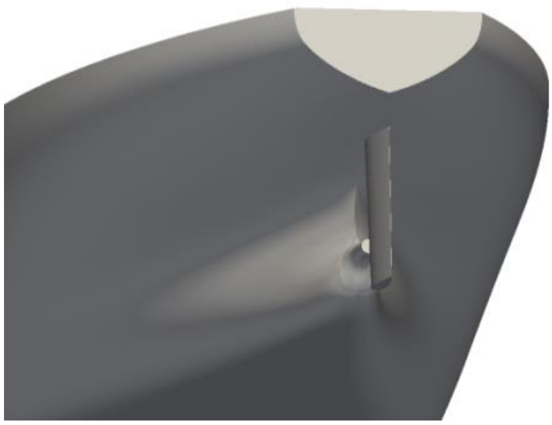
where the subscripts of g and l represent gas and liquid separately.

GEOMETRY AND MESH

Hull model

VLCC in both full scale and model scale are studied in this paper. The main dimensions and particulars are listed in Table 1, including both the full scale and the model scale. The 3D models of VLCC hull are shown in Fig. 1, including the stern and overall hull. In order to obtain a mesh with good quality, the sides of hull deck and stern plate are rounded off.

(a) Overall view



(b) View from stern

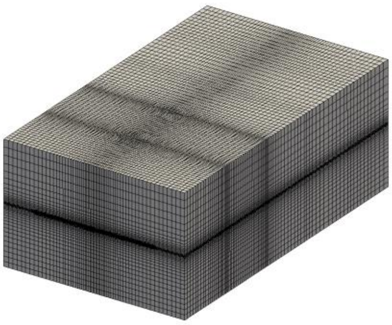
Fig. 1 VLCC model

Table 1. Principle Dimensions of VLCC

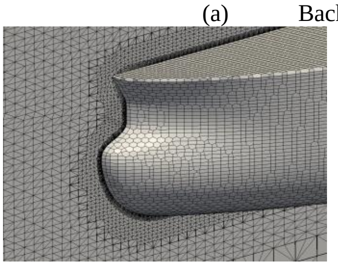
Main particulars		Full scale	Model scale
Scale	/	/	1/40
Length between perpendiculars	L_{PP} (m)	320	8
Length of waterline	L_{WL} (m)	325.992	8.1498
Draft	T (m)	20.5	0.5125
Displacement	∇ (kg)	$3.207*10^8$	5011.57
Block coefficient	C_B	0.858	0.858
Destiny	ρ (kg/m^3)	998.1	1025
Wet area	S_w	28640	17.9

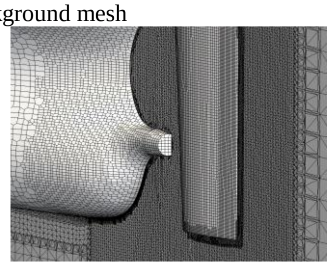
Mesh and domain

For computations in this work, space coordinate range is determined as $-1.0L_{pp}<x<4.0L_{pp}$, $-1.5L_{pp}<y<1.5L_{pp}$, $-1.0L_{pp}<z<1.0L_{pp}$. 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.



(a) Background mesh





(b) Local mesh at bow (c) Local mesh at stern

Fig. 2 Global and local mesh for full scale computation

The overall domain mesh and the details near the bow and stern are displayed in Fig.2. Background mesh is displayed in Fig. 2 (a), while local grids around bow and stern are shown in Fig. 2 (b) and (c). Total number of the grids is 4.34 million. The grids of important regions are refined to capture precisely the free surface and the wake flow field, and accurately compute the variables near wall region of the hull. The refinement domains consist of the boundary layer around the hull, the interface region, the area near bulbous bow and the rear of stern. Calculations of DES and RANS model use the same set of grid. Considering the thinner boundary layer of full scale hull, a smaller first layer thickness of boundary layer grid is used than usual model scale computation.

RESULTS AND COMPARISON

By iterative computations of enough time steps, the results of drag values and corresponding drag coefficients reach convergence. For each case, the average value of the convergent data is taken as the final result. In this paper, the resistance coefficient is defined as：

$$C = \frac{F}{0.5 * \rho S V^2} \quad (10)$$

In Eq.(10), F means the resistance. S is the area of wetted surface of the hull, and V is the sailing velocity. The corresponding coefficients can be calculated by Eq. (10), including C_t, C_f and C_p.

In this work, we adopt two different ways to forecast the resistance of full scale VLCC at cruise speed 16kn (Fr = 0.147):

1. Perform CFD computation for model scale VLCC, and adopt the three-dimensional extrapolation method to get the full scale ship resistance;
2. Carry out full scale calculation at the cruise speed directly.

For each way we use DES and RANS model at the same time. Specifically, S-A IDDES for DES model and k-ω SST for RANS.

Calculation of model scale VLCC hull is performed first. Due to the near wall calculation in S-A IDDES model is dealt with by S-A RANS model, in order to make the comparison of S-A IDDES and RANS more persuasive, we also adopt the one equation S-A model to perform the calculation. The results of all three cases using different RANS and DES models are collected in Table 2, including the values of pressure resistance coefficient, friction resistance coefficient and total resistance coefficient .The data measured by model test is provided for comparison.

Table 2. Numerical results of three turbulent models for model scale VLCC resistance computation

	C_p	C_f	C_t	R_t	*Error*
EFD	0.00098	0.00297	0.00395	59.02	—
S-A	0.00138	0.00312	0.00450	68.236	15.6%
S-AIDDES	0.00117	0.00287	0.00404	61.198	3.69%
k-ω SST	0.00124	0.00294	0.00418	63.375	7.37%

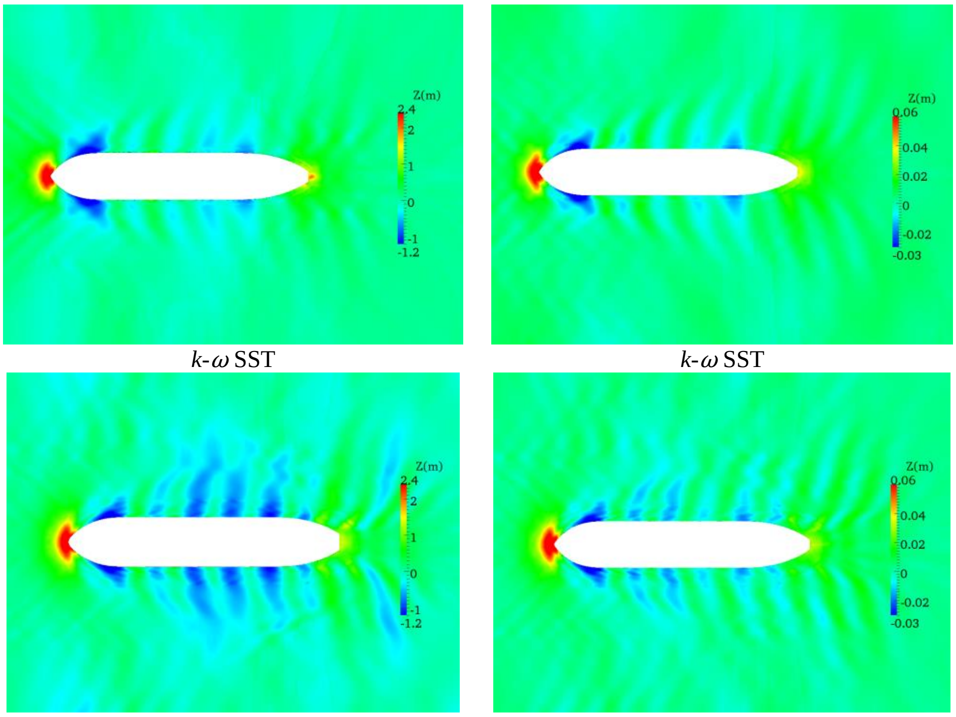
Results display in Table 2 show that calculation results of S-A model have larger errors with the experimental value, which means that as one-equation RANS model, there are certain problems for S-A model in dealing with high Reynolds turbulence conditions. Results obtained by S-A IDDES model are most close to the experimental data, especially on the calculation of pressure resistance, S-A IDDES shows relatively higher accuracy than the two RANS models, which overcome the deficiency of the S-A model effectively.

Full scale resistance calculation results and three-dimensional extrapolation results from model scale are shown in table 3 below. In the progress of three-dimensional extrapolation, shape factor 1+k and compensation coefficient Δ C_f all use the same value with model experiment.

The results show that the full scale resistances obtained by two methods are all close to the model test three-dimensional extrapolation result. Both direct calculation result and the result of the model scale extrapolation, the forecast values from S-A IDDES model are about 6% smaller than k-ω SST model relatively, also keep the consistency.

Table 3. Two prediction methods of full scale VLCC resistance compared with model test three-dimensional extrapolation

	C_{tm}	1+k	ΔC_f	C_{ts}	*Error*
EFD three-dimensional extrapolation	0.00395	1.280	0.00031	0.00221	—
S-A IDDES full scale calculation	—	—	—	0.00215	-2.71%
k-ω SST full scale calculation	—	—	—	0.00229	3.62%
S-A IDDES three-dimensional extrapolation	0.00404	1.280	0.00031	0.00217	-1.81%
k-ω SST three-dimensional extrapolation	0.00418	1.280	0.00031	0.00230	4.07%

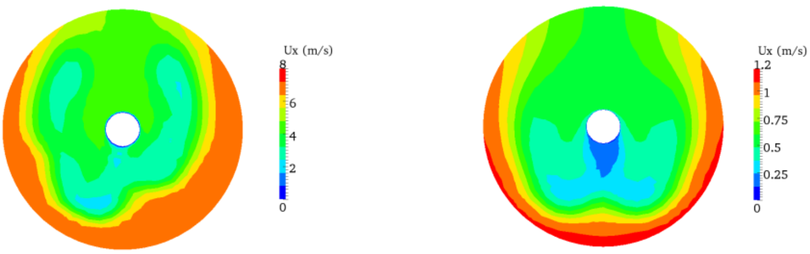


(a) Full scale (b) Model scale

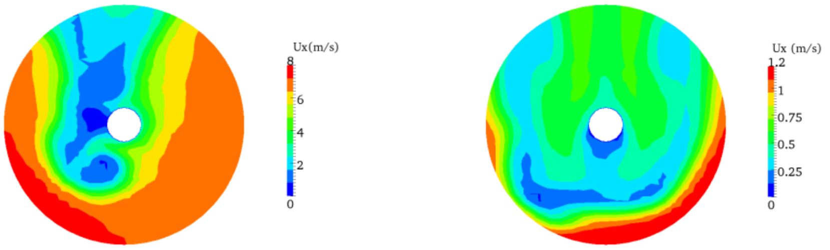
Fig.3 Comparison of free surface

The free surfaces obtained by S-A IDDES and k-ω SST models are shown in Fig. 3. For comparison, the wave range of full scale calculation is set to 40 times (the scale ratio) of the model scale. It can be seen from the comparison that the wave height of free surface for full scale VLCC is greater than model scale, this is because under the model scale Reynolds number, boundary layer thickness is opposite bigger, the viscous effect lead to a wave amplitude decrease. At the same time, it can be seen that the free surface captured by S-A IDDES model is relatively more precise than that of k-ω SST model, two wave peaks are clearly captured by S-A IDDES at stern.

Fig. 4 shows the comparison of wake fields at propeller disk. Full scale VLCC displayed a weaker wake field than the model scale, due to the relatively weaker viscosity caused by high Reynolds number. Also, unlike the symmetrical and uniform wake fields of model hull, the full scale ship wake field shows some disorder, which is affected by high Reynolds number and the viscosity decrease. Relative to k-ω SST model, S-A IDDES model obtain a more precise flow field, characteristics of unsteady flow are more obvious.



k-*ω* SST *k*-*ω* SST



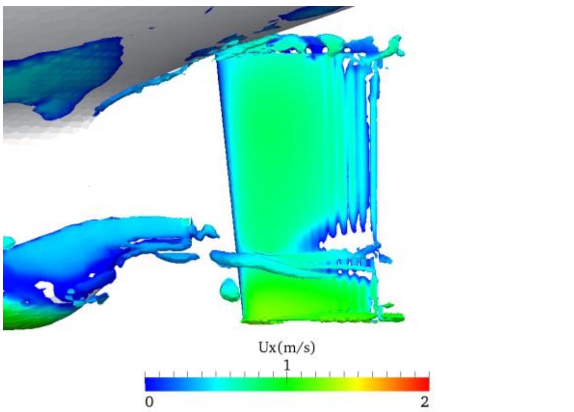
S-A IDDES
(a) Full scale

S-A IDDES
(b) Model scale

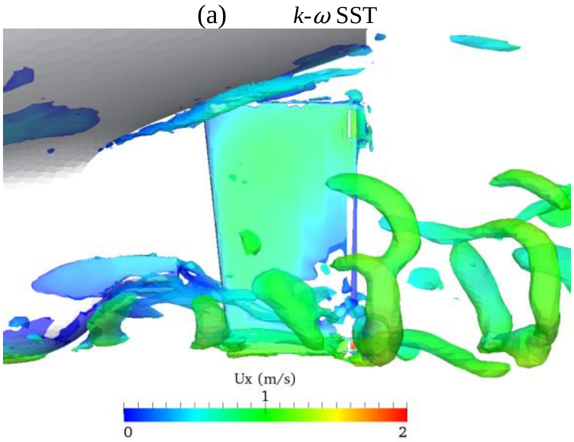
Fig.4 Comparison of wake fields at propeller disk

Fig. 5 displayed the isosurfaces of Q=50 colored according to Ux at stern. Due to the decrease of viscous effect, vortex structures of full scale VLCC are not obvious. So here only the Q isosurfaces of model hull at stern are used for comparison. Numerical results show that S-A IDDES model captures the vortex structure clearly, and also the interference of vortex by rudder at stern. But *k-ω* SST model is hardly to capture the stern vortex structure.

The RANS/LES regions during S-A IDDES full scale and model scale calculations are shown in Fig. 6. A certain range around the hull surface is calculated by RANS, away from the hull, most of the area is calculated by using the LES model. The near wall RANS calculation range of full scale calculation is narrower than model scale, due to the smaller boundary layer thickness relative to model scale.

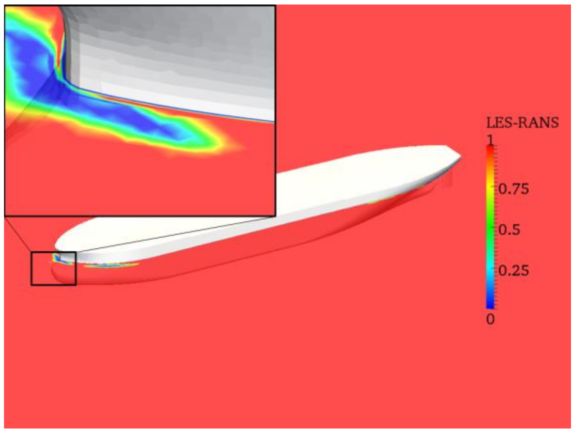


(a) *k-ω* SST

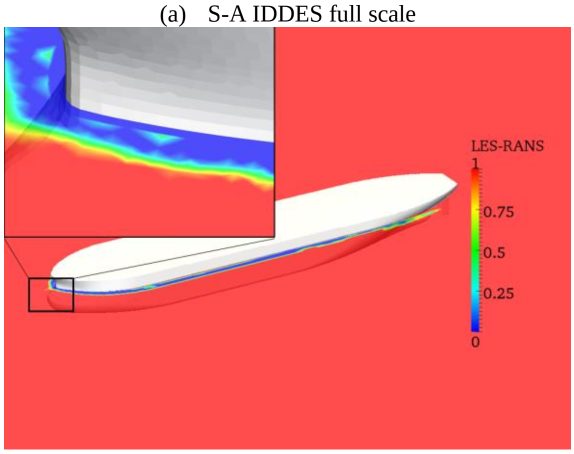


(b) S-A IDDES

Fig. 5 Isosurfaces of Q=50 colored according to Ux at stern



(a) S-A IDDES full scale



(b) S-A IDDES model scale

Fig. 6 RANS/LES region

CONCLUSIONS

In this paper, a numerical study is carried out on resistance forecast of full scale VLCC using DES and RANS model. Computations are performed by the in-house multifunction RANS/DES solver naoe-FOAM-SJTU, taking free surface into consideration. The study contains the calculation of model scale and full scale VLCC resistance components, comparison with three-dimensional extrapolation result from model test, analyses of free surface, wake fields and vortex structures at stern. Some meaningful conclusions can be summarized.

1. In the prediction of model hull resistance, DES model shows a higher accuracy relative RANS method. In the calculation of full scale VLCC, although lack the comparison with full scale experiment data, DES model captures more detailed flow field structure, also prove its reliability.

2. Due to the length scale problems for high Reynolds number,

RANS shows insufficiency in full scale ship calculations with strong unsteady turbulent flow. But DES model can make up for the defects of RANS and provide detailed flow fields information for ship design.

3. The wave height of free surface for full scale ship is greater than model scale because of the decreased viscous effect. Also, unlike the symmetrical and uniform wake fields of model hull, the full scale ship wake field shows some disorder, which is affected by high Reynolds number and the viscosity decrease.

In future work, the extensive studies including full scale DES computations of hull-propeller-rudder interactions like ship self-propulsion and maneuverability.

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REFERENCES

Tezdogann T, Demirel Y K, et al. Full-scale unsteady RANS CFD simulations of ship behavior and performance in head seas due to slow steaming [J]. *Ocean Engineering*, 97 (2015) 186–206.

Carrica P M, Castro A M, et al. Full scale self-propulsion computations using discretized propeller for the KRISO container ship KCS[J]. *Computers & Fluids*, 51 (2011) 35–47.

Shen Z R, Cao H J, Wan D C. Manual of CFD solver naoe-FOAM-SJTU[R]. Shanghai Jiaotong University, Shanghai, China, 2012.

Issa R I. Solution of the implicitly discretized fluid flow equations by operator-splitting [J]. *Journal of Computational Physics*, 1986, 62(1): 40-65.

P. Spalart, W. Jou, M. Strelets, and S. Allmaras. Comments on the feasibility of LES for wings, and on a hybrid RANS/LES approach. Advances in DNS/LES, 1, 1997.

Spalart P R, Deck S, Shur ML, et al. A new version of detached-eddy simulation, resistant to ambiguous grid densities. *Theoretical and Computational Fluid Dynamics*, 2006, 20: 181-195.

A.Travin, M.Shur, P.Spalart, et al. Improvement of delayed detached-eddy simulation for LES with wall modelling. In P.Wesseling, E.Oñate, and J. Périaux, editors, *Proceedings of the European Conference on Computational Fluid Dynamics ECCOMAS CFD* 2006, Egmond aan Zee, The Netherlands, 2006.

M.L. Shur, P.R. Spalart, M.Kh. Strelets and A.K. Travin. A hybrid RANS-LES approach with delayed-DES and wall-modeled LES capabilities, *International Journal of Heat and Fluid Flow*, 29: 1638-1649, 2008.