

Study of Effects of Model Scale and Free Surface on Maneuvering Hydrodynamics of KVLCC2 Model by CFD

Y. Han, B.S. Wu, Q.M. Miao, Z.J.Zou

China Ship Scientific Research Center Wuxi Jiangsu 214082, China

ABSTRACT: Viscous-flow-based CFD methods have been playing more and more important roles in ship maneuvering prediction. In this paper, it was preliminarily investigated whether the effect of free surface should be simulated in CFD or not. And then, the model scale effect on the hydrodynamics of MOERI Tanker KVLCC2 model test was studied by the commercial CFD code Fluent 6.2 and without free surface effect, in attempt to provide guidance for selection of model scale for towing tank tests and reference for inter-comparison of various experimental results with different scale model. It is shown that the scale effect can be neglected when the lengths of KVLCC2 model are larger than 7 meters at Froude number of 0.142 and 12 meters at Froude number of 0.064, respectively.

1 INTRODUCTION

The KRISO Very Large Crude Carrier 2 (KVLCC2) is the second variant of the MOERI tanker with more U-shaped stern frame-lines and specified as one of the benchmark ships by the 24th ITTC Maneuvering Committee. Two scale ratios of KVLCC2 model, 1:45.714 at INSEAN and 1:58 at MOERI, were chosen for model tests to provide the benchmark data for maneuvering simulation method and the results of model tests and simulation will be available on the workshop SIMMAN2008.

In recent years, China Ship Scientific Research Center has paid more and more attention to the application of viscous flow based CFD code, say Fluent, into prediction of the ship maneuverability (Yang, et al. 2006, Han et al 2007). The key point is the validation of CFD. Besides tracking advance of the international workshop SIMMAN, CSSRC has been making other effect. In 2007, oblique-towing tests of KVLCC2 bare hull model of 1: 90 was entrusted to be carried out in Shanghai Jiaotong University (SJTU) Towing tank (Wang et al, 2008). For this ship model, surface pressure distribution at different drift angles will be measured in CSSRC wind tunnel as well as the oblique towing test will be performed in CSSRC towing tank later this year. The principal dimensions of this model are shown in Tab.1

Table 1 principal dimensions of KVLCC2 hull

	$L_{pp}(m)$	$B_{wl}(m)$	$d(m)$	C_b
Full scale	320.0	58.0	20.8	0.8098
Model (1:90)	3.556	0.644	0.231	0.8098

CFD simulation will be effective and economic for evaluation of the scale effect on the hydrodynamics of a maneuvering ship model, as model test is much more time-consuming and costly for study of the model scale effects, let alone that the model scale is quite limited by the dimensions and capacity of any towing tank.

Two standard states of KVLCC2 maneuvering are assumed to be Froude number of 0.142 for deep water and Froude number of 0.064 for shallow water, respectively. For the study in this paper, the model scales are corresponding to the length-based Reynolds number range of $8 \times 10^5 \sim 2 \times 10^7$, or the ship model length range of 2.5~22 meters for $Fr=0.064$ and 1.5~13 meters

for $Fr=0.142$. Such a range can cover all the typical ship model sizes tested in towing tanks worldwide.

For sake of simplification and efficiency, the free surface effects have not been taken into consideration during the study of model scale effects by CFD. However, the free surface effects are first investigated by CFD.

2 NUMERICAL METHOD DESCRIPTION

2.1 Coordinate system and the expression of numerical results

The commonly used body-fixed coordinate frame is adopted as shown in Fig.1.

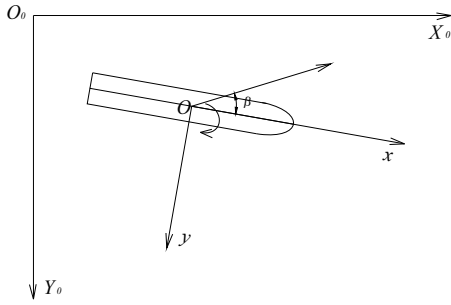


Figure 1 the reference frame of the numerical simulation

The six components of hydrodynamic forces and moments are non-dimensionalized as follows.

$$\begin{aligned}
 \text{Longitudinal force } C_x &= \frac{X}{0.5\rho V^2 L d} & \text{Lateral force } C_y &= \frac{Y}{0.5\rho V^2 L d} \\
 \text{Vertical force } C_z &= \frac{Z}{0.5\rho V^2 L d} & \text{Yawing moment } C_n &= \frac{N}{0.5\rho V^2 L^2 d} \\
 \text{Rolling moment } C_k &= \frac{K}{0.5\rho V^2 L^2 d} & \text{Pitching moment } C_m &= \frac{M}{0.5\rho V^2 L^2 d}
 \end{aligned}$$

Where V is the advance speed, L the ship model length, d the draft and ρ the water density.

2.2 Governing equations

The governing equations for incompressible, turbulent flow are the continuity equation for mass conservation and RANS equations for momentum transport.

1) Continuity equation

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \tag{1}$$

2) RANS equation

$$\rho \frac{\partial \bar{u}_i}{\partial t} + \rho \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = \rho \bar{F}_i - \frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j} \left(\mu \frac{\partial \bar{u}_i}{\partial x_j} - \rho \overline{u_i' u_j'} \right) \tag{2}$$

Where \bar{u}_i is the mean velocity component, u_i' the fluctuating velocity component, P the pressure and F the volumetric forces.

3) Turbulence model

The RNG $k-\varepsilon$ turbulence model and wall function are suitable for prediction of the maneuvering hydrodynamics of full-ship model (Yang et al, 2006). Turbulent kinetic energy (k) transport equation is

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k - \rho \varepsilon \quad (3)$$

And the equation of dissipation of turbulent energy (ε) is

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_i}(\rho \varepsilon u_i) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + C_{1\varepsilon} \frac{\varepsilon}{\kappa} G_k - C_{2\varepsilon} \rho \frac{\varepsilon^2}{\kappa} - R_\varepsilon \quad (4)$$

Where $\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}$, $G_k = -\rho \overline{u_i' u_j'} \frac{\partial u_j}{\partial x_i}$, $R_\varepsilon = \frac{C_\mu \rho \eta^3 (1 - \eta/\eta_0) \varepsilon^2}{1 + \beta \eta^3} \frac{\varepsilon^2}{k}$, $\eta = Sk/\varepsilon$

And $\eta_0, \beta, C_{1\varepsilon}, C_{2\varepsilon}, C, \sigma_k, \sigma_\varepsilon$ are the empirical constants.

The semi-empirical formulas called “wall functions” are used to bridge the viscosity-affected region between the wall and the fully-turbulent region. The use of wall functions obviates the need to modify the turbulence models to account for the presence of the wall.

Volume of Fluid (VOF) method was adopted to simulate free surface flow. For this method, α_i denotes the i th fluid volume fraction in the cell. It is used to determine the position and shape of interface. Because of the fluid is assumed to be incompressible, the conservation equation of water (or air) in the two-phase flow of waves can be written in the form of volume fraction:

$$\frac{\partial \alpha_w}{\partial t} + \vec{V} \cdot \nabla \alpha_w = 0 \quad (5)$$

In each control volume, the volume fraction of water and air should be summed to one:

$$\alpha_w + \alpha_a = 1 \quad (6)$$

Where α is volume fraction, the subscripts a and w denote air and water respectively.

2.3 Boundary condition

The computational grid of CFD is shown in Fig.2. The boundary conditions are adopted as follows.

- (a) Inlet boundary is one and half hull length ahead of bow, where velocity is prescribed for the model scale effect study, velocity and volume fraction are prescribed for the free surface effect study.
- (b) Outlet boundary is three hull lengths after stern, where pressure outlet is set for the model scale effect study; hydrostatic pressure is set for the free surface effect study.
- (c) Outer boundary is one and half hull length away from hull, where the velocity inlet boundary is applied.
- (d) Hull surface: non-slip condition is applied

2.4 Algorithm Scheme

FVM (Finite Volume Method) was used to discretize the governing equations, the second-order upwind difference scheme is utilized for the convection items and central difference scheme for the dissipation items. The velocity-pressure coupling is based on SIMPLE algorithm.

3 EFFECTS OF FREE SURFACE

The case used to investigate the effects of free surface on hydrodynamic forces is the static drift condition with the drift angle β varying from -6° to $+6^\circ$ by 2° steps in deep water at $Fr=0.142$. The model length is 3.556m (1:90). The model is fixed on even keel to neglect squat.

3.1 Grids of Computation

Multi-block structural grid is adopted in this paper, and the grid number is about 1.1 millions. The first element thickness equates to a $y^+ \sim 50$. The topology is body-fitted, $H-O$ type, H -type in longitudinal direction, O -type in transverse direction. The grids near the hull and free surface are refined. The grids on the hull surface are shown in Fig.3

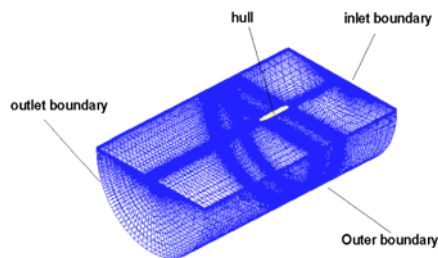


Figure 2 domain and grids of CFD simulation

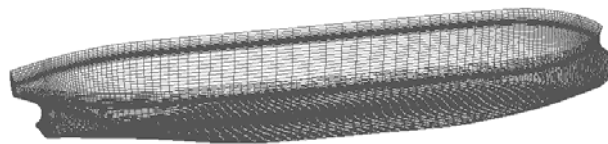


Figure 3 grids on the hull surface

3.2 Computation results and analysis

Fig.4 & Fig.5 show the hydrodynamic force and moment coefficients of CFD prediction compare with the model test by SJTU (Wang et al, 2008). It should be noted that the uncertainty analysis of the model test results of SJTU has not been available yet. So, the results present here are average value of the positive and negative drift angle, and the results of drift angle of 0 degree are set to zero in order to eliminate the possible asymmetry in model test. The results are shown in Tabs.2-3.

Tab.2 & Tab.3 show the hydrodynamic force and moment coefficients of CFD prediction for different drift angles. The yaw moment coefficients of without free surface are closer to experimental results than with free surface. The same trend is obtained by Jacquin (2006).

From the Figs.4-5 & Tabs.2-3, it can be seen that the effect of free surface is not very remarkable at $Fr=0.142$. The largest discrepancy of the results is just about 9% between with and without free surface. The difference between with and without free surface for the hydrodynamic derivative Y_v , N_v is just about 6%, which are shown in Tab.4. So it can be anticipated that the free surface effect can be neglected when study on the effect of model scale.

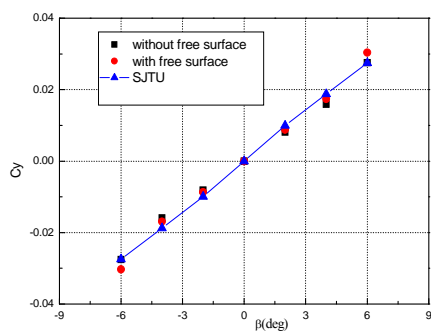


Figure 4 lateral force coefficient at $Fr=0.142$

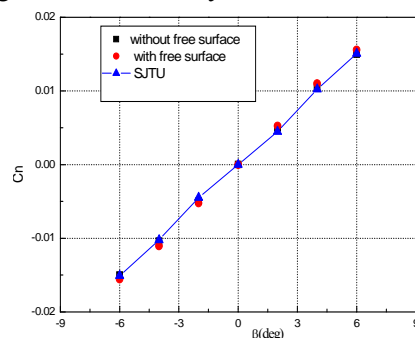


Figure 5 yaw moment coefficient at $Fr=0.142$

Table 2 the lateral force coefficients for different drift angle ($Fr=0.142$)

Drift angle	-6deg	-4deg	-2deg	0deg	2deg	4deg	6deg
Without free surface, S_{wo}	-2.756×10^{-2}	-1.591×10^{-2}	-0.812×10^{-2}	-1.035×10^{-6}	0.812×10^{-2}	1.591×10^{-2}	2.756×10^{-2}
With free surface, S_w	-3.028×10^{-2}	-1.693×10^{-2}	-0.869×10^{-2}	-1.126×10^{-6}	0.878×10^{-2}	1.741×10^{-2}	3.037×10^{-2}
SJTU*	-2.747×10^{-2}	-1.874×10^{-2}	-0.993×10^{-2}	0	0.993×10^{-2}	1.874×10^{-2}	2.747×10^{-2}
$S_w - S_{wo} / S_w$	8.98%	6.02%	6.56%	8.08%	7.52%	8.62%	9.25%

* The average value of the positive and negative drift angle of SJTU (Wang et al, 2008)

Table 3 the yaw moment coefficients for different drift angle ($Fr=0.142$)

Drift angle	-6deg	-4deg	-2deg	0deg	2deg	4deg	6deg
Without free surface, S_{wo}	-1.498×10^{-2}	-1.038×10^{-2}	-0.497×10^{-2}	1.250×10^{-6}	0.497×10^{-2}	1.036×10^{-2}	1.498×10^{-2}
With free surface, S_w	-1.554×10^{-2}	-1.105×10^{-2}	-0.525×10^{-2}	1.361×10^{-6}	0.522×10^{-2}	1.100×10^{-2}	1.557×10^{-2}
SJTU*	-1.508×10^{-2}	-1.024×10^{-2}	-0.449×10^{-2}	0	0.449×10^{-2}	1.024×10^{-2}	1.508×10^{-2}
$S_w - S_{wo} / S_w$	3.60%	6.06%	5.33%	8.16%	4.79%	5.82%	3.79%

* The average value of the positive and negative drift angle of SJTU (Wang et al, 2008)

Table 4 the hydrodynamic derivatives ($Fr=0.142$)

Hydrodynamic derivative	Y_v	N_v
Without free surface, S_{wo}	0.2518	0.1769
With free surface, S_w	0.2678	0.1897
$S_w - S_{wo} / S_w$	5.97%	6.75%

4 EFFECTS OF MODEL SCALE

The effects of model scale on manoeuvring hydrodynamic forces and moments were studied when the ship model in oblique motion with the drift angle $\beta=-4$ deg. A series of different model scale are chosen but with the same Froude number of 0.064. From the study of free surface effect, it can be seen that the effect of free surface is not very remarkable, and for sake of simplification and efficiency, the free surface effects have not been taken into consideration during the study of model scale effects by CFD.

4.1 Grids of Computation

The grid type used to study the effect of model scale is similar to the Fig.2, and the grid density is same for different model scale. The grids near the hull are refined. The grids on the hull surface are shown in Fig.6

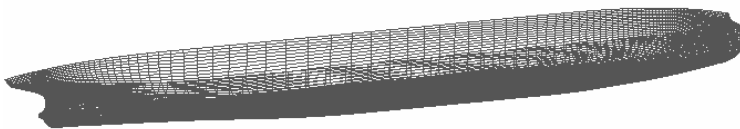


Figure 6 grids on the hull surface

4.2 Computation results and analysis

Figs7-10 shows the hydrodynamic force and moment coefficients varying with model length. Tab.6 show the hydrodynamic force and moment components for different model scale and the Reynolds number corresponding to the model length (L) for two different Froude numbers (Fr).

Referring to Figs7-10 & Tab.6, it is clear that the lateral force coefficients for different model scales differ from each other, and the discrepancy reaches 19% between the largest and smallest

model scale selected. A larger model length than 12m (for $Fr=0.064$) makes almost no difference for the lateral force coefficient.

The yaw moment presents little difference for different model scales. The discrepancy between the largest and smallest model scale is 5%.

The vertical force and pitch moment coefficients have the same trend with the yaw moment coefficient.

The roll moment coefficients of different model scale differ from each other, while the difference is small when the model length is larger than 12m (for $Fr=0.064$). The estimated static heel angle is about 0.5 degree for all the model scales selected in this paper, which are obtained through the hydrodynamic force and moment at different model scale, seeing Tab.6. So, the effect of model scale on roll can also be neglected.

Form the results mentioned above and the Tab.5, it can be anticipated that the difference of model test results of the model of 1:45.714 and the model of 1:58 will not be remarkable. The discrepancy may be just 5.11% for the lateral force coefficient, and 1.24% for the yaw moment coefficient. The difference of lateral force coefficient between the model of 1:90 and the model of 1:45.714 may be 13.32%, but just 3.64% for the yaw moment coefficient.

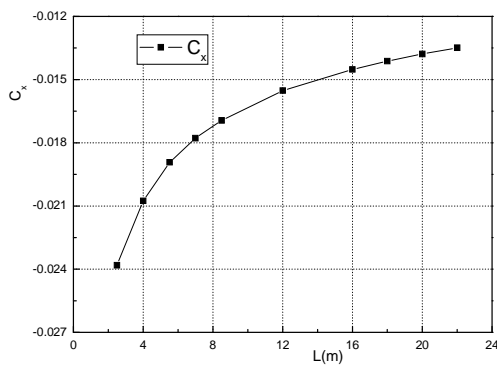


Figure7 C_x varying with model length ($Fr=0.064$)

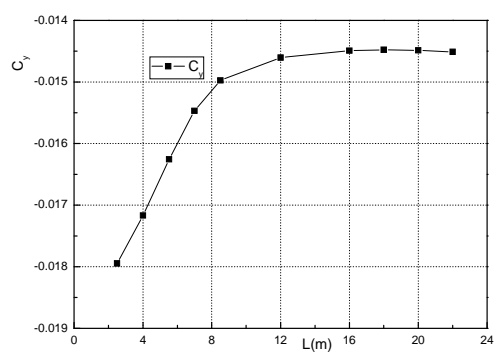


Figure8 C_y varying with model length ($Fr=0.064$)

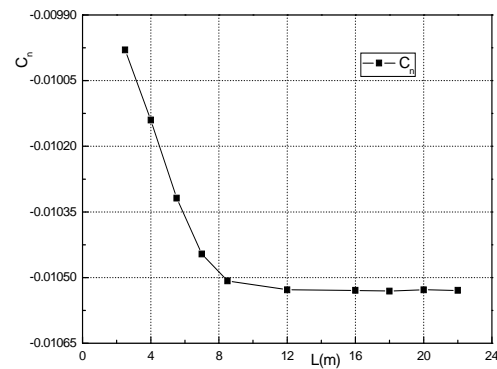


Figure9 C_n varying with model length ($Fr=0.064$)

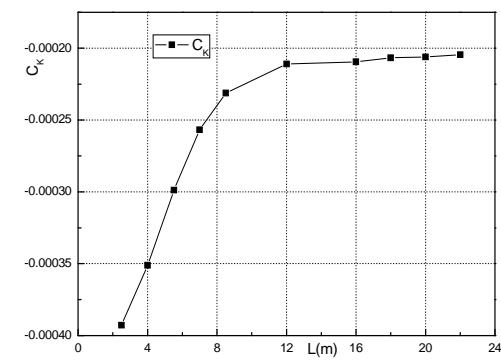


Figure10 C_k varying with model length ($Fr=0.064$)

Table 5 the hydrodynamic force and moment of three different model scales $\beta -4^\circ, Fr=0.064$

Model length(m)	3.556(1:90), S_s	5.517(1:58), S_m	7(1:45.714), S_l	$S_s - S_l / S_l$	$S_m - S_l / S_l$
$C_x \times 10^2$	-2.148	-1.893	-1.778	20.81%	6.47%
$C_y \times 10^2$	-1.753	-1.626	-1.547	13.32%	5.11%
$C_n \times 10^2$	-1.007	-1.032	-1.045	3.64%	-1.24%

Table 6 the hydrodynamic force and moment components of different model scale $\beta = -4^\circ, F_r=0.064$

$Re \times 10^{-6}$	$C_x \times 10^2$	$C_y \times 10^2$	$C_n \times 10^2$	$C_k \times 10^4$	Estimated Static heel angle ϕ ($^\circ$)	$C_z \times 10$	$C_m \times 10^2$	The model length L (m) for $F_r=0.064$	The model length L (m) for $F_r=0.142$
0.792	-2.381	-1.795	-0.998	-3.928	0.627	2.392	-3.435	2.500	1.468
1.600	-2.076	-1.717	-1.014	-3.511	0.587	2.403	-3.454	4.000	2.345
2.599	-1.893	-1.626	-1.032	-2.988	0.544	2.394	-3.469	5.517	3.241
3.731	-1.778	-1.547	-1.045	-2.568	0.512	2.412	-3.475	7.000	4.124
4.964	-1.694	-1.497	-1.051	-2.312	0.481	2.415	-3.483	8.500	4.989
8.328	-1.552	-1.460	-1.053	-2.111	0.463	2.420	-3.492	12.000	7.044
12.800	-1.452	-1.449	-1.053	-2.095	0.458	2.426	-3.500	16.000	9.381
15.300	-1.412	-1.448	-1.053	-2.068	0.458	2.428	-3.505	18.000	10.566
17.920	-1.378	-1.449	-1.053	-2.060	0.458	2.431	-3.506	20.000	11.740
20.670	-1.349	-1.451	-1.053	-2.046	0.457	2.431	-3.508	22.000	12.913

5 CONCLUSIONS

This paper presents the study of effects of model scale and free surface on maneuvering hydrodynamics by the CFD code Fluent 6.2. The effect of free surface is first investigated, and the effect is not very remarkable at small Froude number. The model scale effect on the hydrodynamics of KVLCC2 model test is studied and without free surface effect. It is shown that the scale effect is very small when the lengths of KVLCC2 model are larger than 7 meters at Froude number of 0.142 and 12 meters at Froude number of 0.064, respectively. It can be anticipated that the difference of model test results of the model of 1:45.714 and the model of 1:58 will not be remarkable. The discrepancy may be just 5.11% for the lateral force coefficient, and 1.24% for the yaw moment coefficient. The difference of lateral force coefficient between the model of 1:90 and the model of 1:45.714 may be 13.32%, but just 3.64% for the yaw moment coefficient.

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