ESTIMATION OF HYDRODYNAMIC COEFFICIENTS OF SUBMARINE WITH VARYING MIDDLE BODY LENGTH

Jinyu REN[1], Jing XU[1,*], Haibo ZHOU[2]

Maneuverability is one of the most vital sea-going performances of submarine. Although sea-trials/model tests are still the most reliable means for analysis of submarine maneuvering performance, CFD has found its way in the analysis of submarine maneuverability by providing an alternative accurate and cost-effective means of simulation of real flows. The numerical towing tank is expected to become a reality and trustworthy in near future. This work primarily explores the hydrodynamic properties of the submarine SUBOFF in three kinds of middle body lengths 3.36 m, 4.36 m, and 5.36 m. The study model setup was done using Fluent and the numerical results were compared with the experimental data. The Normal Force, Pitching Moment coefficients, and Yawing Moment were calculated for the specified middle body lengths. The results show that the model with 1.8 million cell mesh number and CO-type grid could ensure the calculation accuracy. The simulated pressure coefficient and friction coefficient on the hull were consistent with the experimental results. The Pitching moment and Normal Force also displayed reasonably good agreement with the experimental results, especially at low angels of attack, with slight deviation at high angles of attack. The Pitching moment and Normal Force increased with an increase in the length of submarine and vice versa. The Drag on the Submarine body was also increased with an increase in the Length. The proposed approach can be applied in novel submarine design and performance analysis.

Keywords: Submarine hydrodynamic; Analysis; SUBOFF; Varying middle body length

1. Introduction

Hydrodynamic computation is a critical study in the area of submarine design; hence, several researchers both home have performed an intensive investigation. Joubert R N, Cindy, and Groves N.C have conductive in-depth research on SUBOFF via experiments and calculations [1-3].Yang performed RANS simulation of viscous flow over full appended submarine and field variables validation [4]. Yu and Pan used CFD for Numerical prediction of submarine hydrodynamic coefficients [5,6]. Huang explored the Numerical

[1] Naval Architecture and Ocean Engineering, Wuhan Technical College of Communications, Wuhan 430065, China
[2] Wuhan Second Ship Design and Research Institute, Wuhan 430064, China
*Correspondence author: e-mail: 308810953@qq.com

simulation of flows over underwater axis symmetric bodies with full appendages [7]. Qiu and Liu conducted validation of numerical simulation of the fow over submarine geometries with full appendages [8,9]. Alin studied unsteady Reynolds averaged Navier Stokes and large eddy simulations via SUBOFF [10]. Coutier, Alexander B, and Pasinato H considered the effect of turbulence closure models on the vortical flow field around a prolate ellipsoid and submarine body undergoing steady drift [11-13]. Kobayashi T performed large eddy simulations for engineering applications [14].

However, the estimation of hydrodynamic coefficients for varying middle body lengths of a complete submarine has not been conducted. Herein, 3D unsteady uncompressible RANS equations were solved and one-equation Splart-Allmaras turbulence model was used. The diffusive term was discretized with second order upwind center difference scheme and the convection term was discretized using second order upwind scheme. The SIMPLE method was used for coupling of pressure and velocity. The algebraic equations after discretization were solved using Gauss-Seidel iteration approach and the AMG method was employed to accelerate the convergence. This work primarily describes the effect of variation of middle body length of submarine and full appendages on the hydrodynamic coefficients at different angles of attack and yaw. The numerical results of submarine SUBOFF can be compared with several existing experimental results.

2. Mathematical model

The governing equations for the model were the 3D incompressible RANS equations. The continuity equation and momentum equation in tensor form can be written as:

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

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial(\rho u_i u_j)}{\partial x_j} = f_i - \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] - \frac{\partial(\rho \overline{u_i' u_j'})}{\partial x_j} \tag{2}$$

where u_i means cartesian $x_i (i = 1,2,3)$ velocity components, u_i' means Fluctuating velocity components, and $\rho\overline{u_i' u_j'}$ means Reynolds stress tensor.

Reynolds stress is the impact of turbulence on the mean flow field. Herein, $k-\varepsilon$ was chosen as the turbulence model.

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho u_j k)}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right) + P_k - \rho\varepsilon \tag{3}$$

$$\frac{\partial(\rho\varepsilon)}{\partial t}+\frac{\partial(\rho u_j\varepsilon)}{\partial x_j}=\frac{\partial}{\partial x_j}\left(\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right)+\frac{\varepsilon}{k}\left(C_{\varepsilon 1}P_k-C_{\varepsilon 2}\rho\varepsilon\right) \quad (4)$$

$$P_k=\mu_t\frac{\partial u_i}{\partial x_j}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right) \quad (5)$$

$$\mu_t=C_\mu\rho\frac{k^2}{\varepsilon} \quad (6)$$

where ε is turbulent kinetic energy dissipation rate. P_k is the turbulent kinetic energy term $C_\mu=0.09,\ C_{\varepsilon 1}=1.44,\ C_{\varepsilon 2}=1.92,\ \sigma_k=1.0,\ \sigma_\varepsilon=1.30$.

3. Grid Independence Study

Herein, SUBOFF submarine model was chosen, which was designed by DARPA to build a validation database for submarine CFD analysis software. The model includes the main hull, podium round shell, wing, and propeller.

The SUBOFF Geometry Details were taken from Groves N.C. Fig. 1 shows the SUBOFF Geometry Details: Length, L = 4.36 m, Cylinder body Radius, R =0. 25 m, Sail height, h = 0.206 m, and Appendage Height=0.36 m.

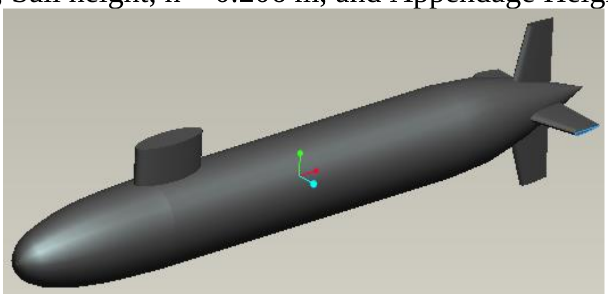

Fig. 1. Submarine SUBOFF having middle body length L+Stern Appendages + Sail on Top

This paper selects model, such as Length L-1: A Sketch of SUBOFF, Hull with Sail & Appendages, Length L=3.36 m, and Length L+1: A Sketch of SUBOFF Hull with Sail & Appendages, Length L=5.36 m.

A CFD simulation model of SUBOFF submarine with CO-type grid was developed using Fluent. In grid generation, nodes distribution and cell size were determined by the practical requirements and the resultant total cell mesh number was 1.8 million.

Figs. 2, 3, and 4 show the submarine SUBOFF model with 360 degree circumferential grid for the middle lengths of 4.36 m, 3.36 m, and 5.36 m, respectively.

Figure 5 shows the model with no-slip adiabatic wall, velocity inlet conditions, symmetry conditions, and pressure Outlet. Free stream velocity was equal with 9 m/s, while Reynolds number was equal with 3.89×10^7. Angle of attack for Normal force and Pitching Moment coefficients were -8, -4, 0, 4, and 8 degree, while Angle of attack for Yawing and Rolling Moment coefficients were -20, -10, -4, 0, 4, 10, and 20 degree. Pressure outlet was equal with 201125 Pa and Turbulence model was K-ε. The model depth in water was 10 m, near wall treatment was Standard wall Function, and Numerical scheme was second order upwind scheme.

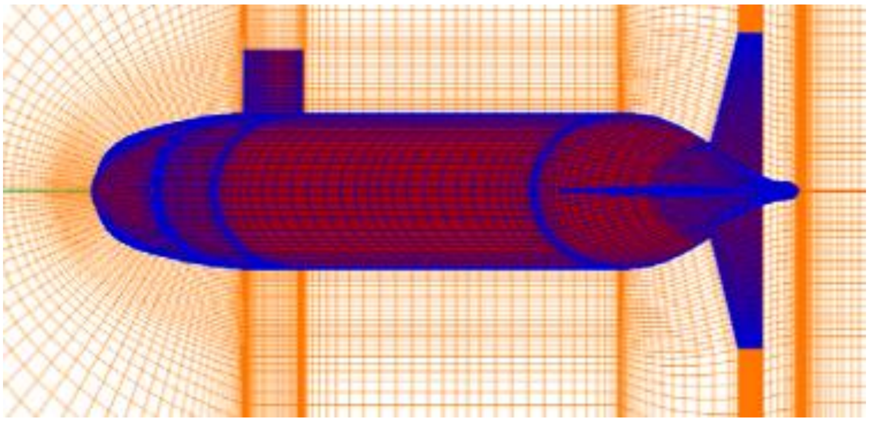

Fig. 2. Grid Model for length 4.36 m

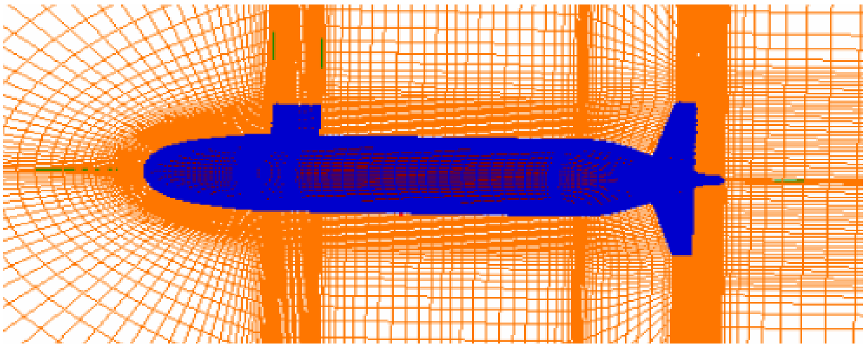

Fig. 3. Grid Model for Length 3.36 m

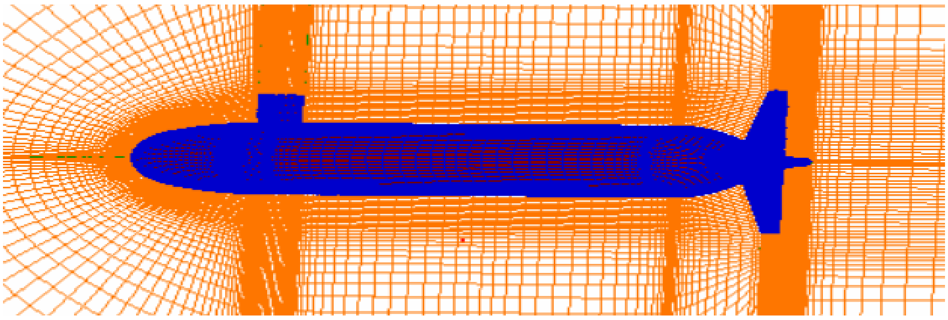

Fig. 4. Grid Model for Length 5.36 m

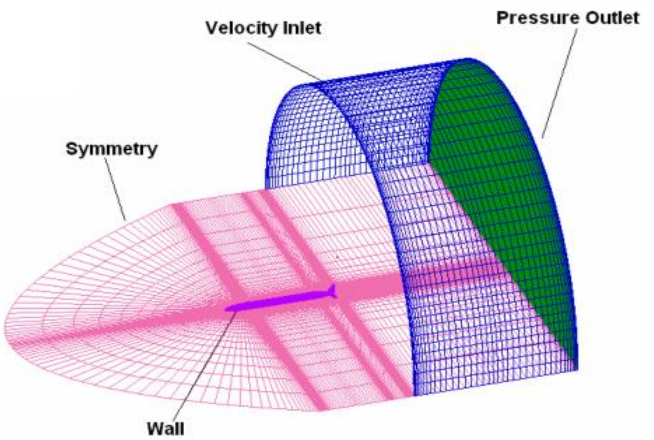

Fig. 5. Boundary Conditions for SUBOFF

4. Qualitative Results for Submarine SUBOFF

Fluent software was used to analyze the flow field qualitatively and quantitatively. The emphasis was to observe the effect of changing middle body length over the forces and moments. 3-Dimensional half-body plane was taken as the symmetry plane for analysis of normal force and pitching moment coefficients. The experimental results were taken from the thesis on steady and unsteady force and Moment Data on a SUBOFF Submarine by Cindy C.

The simulated pressure coefficient and friction coefficient on the hull are shown in Figure 6 and 7 and compared with the experimental data [2]. The simulation results are in good agreement with experimental results. It also has unanimous with the simulated results [15].

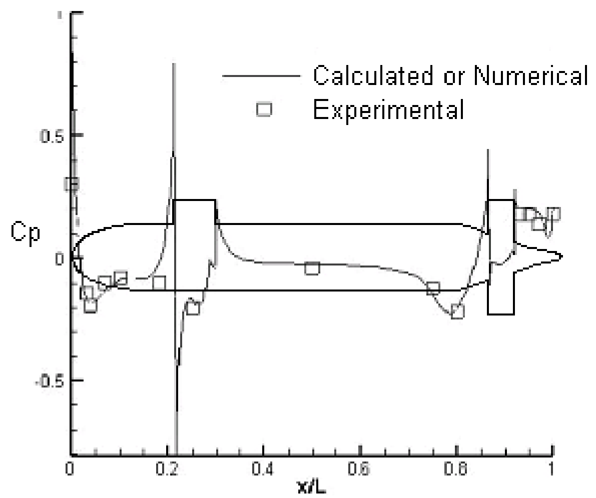

Fig. 6. Simulated pressure coefficient on the hull

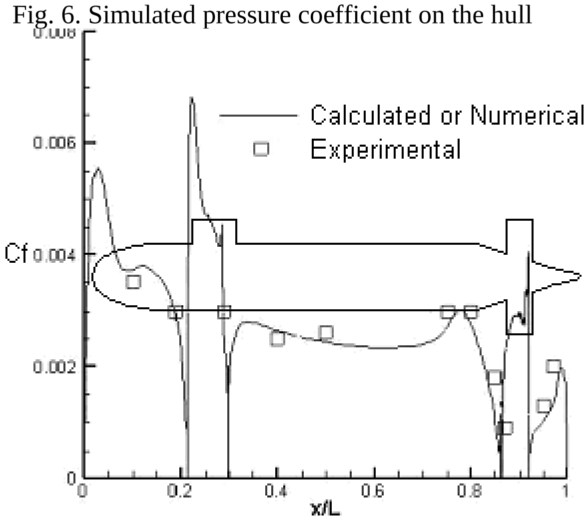

Fig. 7. Simulated friction coefficient on the hull

Figs. 8 and 9 are submarine surface stress nephogram and corresponding surface pressure value of SUBOFF submarine model at the 8 angles of attack. As observed from first upper part of the submarine, podium shell and cross around the rear wing's leading edge pressure value was big, the submarine podium shell around lateral margin and submarines to the tail pressures on flow value was small and conformed to the actual situation. Figs. 10 and Figure 11 show surface stress nephogram of SUBOFF whose lengths were 3.36 m and 5.36 m submarine model at the 8 angles of attack.

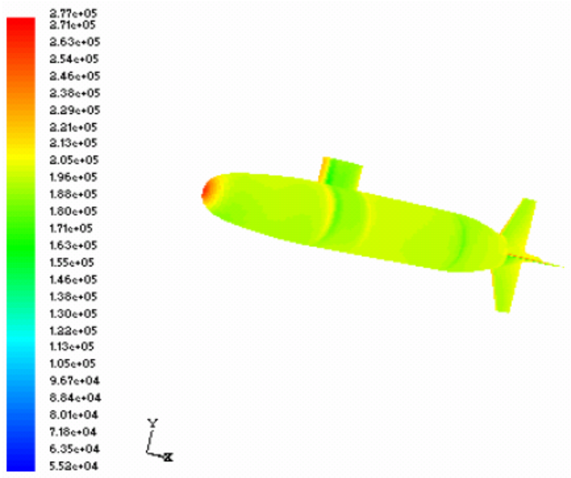

Fig. 8. Contours of pressure over the wall of SUBOFF at –8 Degree Angle of Attack.

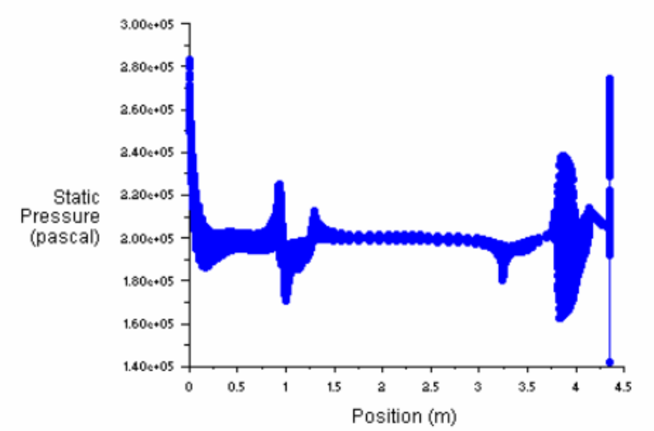

Fig. 9. XY Plot of static pressure over the wall of SUBOFF at –8 Degree Angle of Attack.

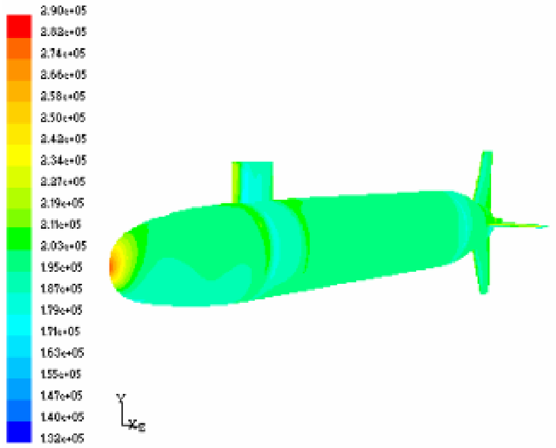

Fig. 10. Pressure Contours for Length 4.36 m at –8 degree Angle of attack.

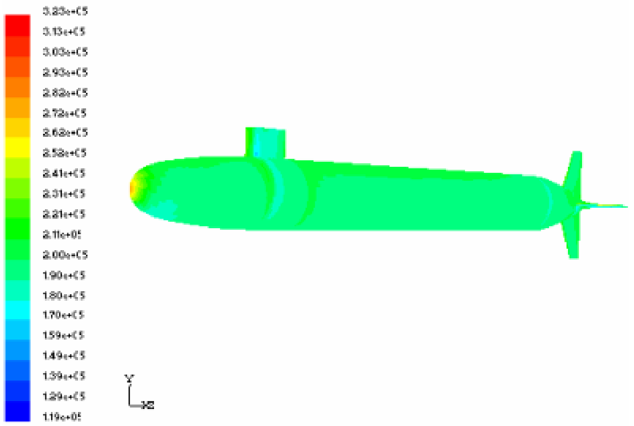

Fig. 11. Pressure Contours for length 5.36 m at –8-degree Angle of attack.

Figure 12 shows the drift angle of 4 degrees instead of submarine model submarine. We can observe that pressure on the left side of the podium was larger which conforms to the actual situation. Normal Force for Full Body Configuration was calculated at different angles of attack and compared with experimental results.

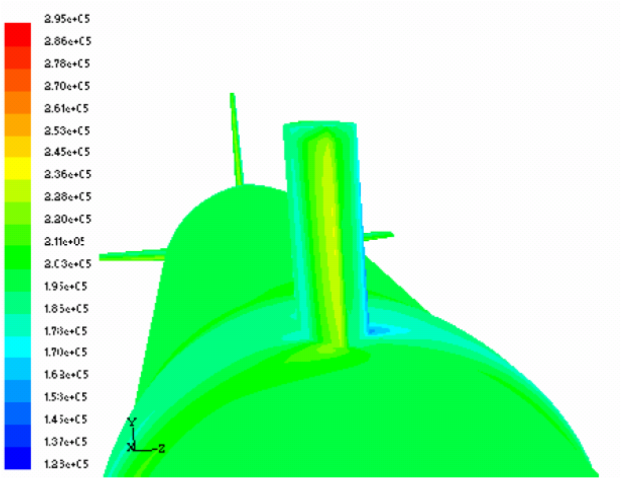

Fig. 12. Pressure contours over the submarine wall at angle of Drift=4 Degree

Fig. 13 shows a good agreement with the experimental results, especially at low angles of attack. The simulation results deviated slightly at high angles of attack and the deviation was within 15%. At high angle of attack, the submarine had a streamlined structure delay flow separation; thereby, reducing the resistance. The viscosity flow caused by the differential pressure force played a leading role. Fig. 14 shows that by increasing the length of the Submarine, increases the Normal force and decreases by decreasing length of the body. Pitching Moment for Full Body Configurations was calculated at different angles of attack and compared with the experimental results.

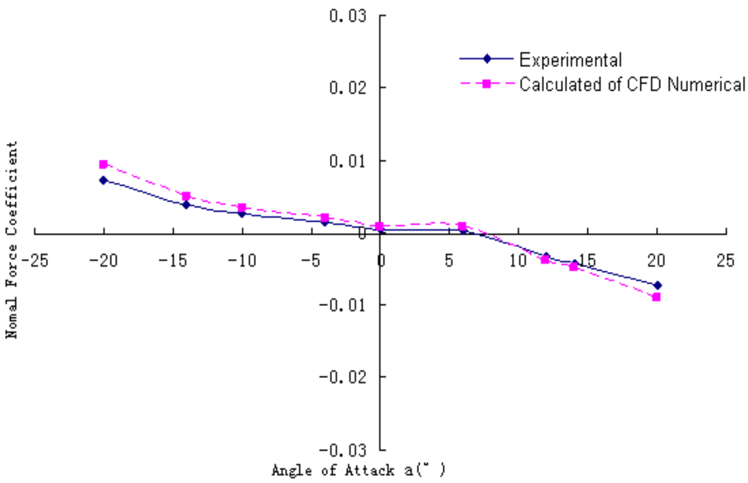

Fig. 13. Comparison of Normal Force from SUBOFF for Length 4.36 m

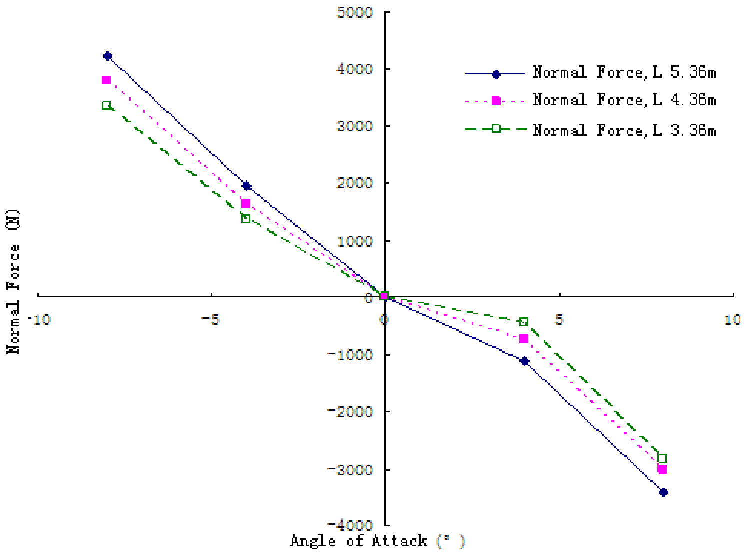

Fig. 14. Comparison of Normal Force for varying Middle Body length

Fig. 15 shows that the Pitching Moment coefficient was consistent with the experimental results. There was a deviation from the experiments at high angles of attack but this deviation was within 18% when compared with the experimental data [2].

Fig. 16 shows that by increasing the length of the submarine, Pitching Moment increased and decreased by decreasing the length of the body. Figure 17 shows that the value of Yawing moment coefficients increased by increasing the Angle of Drift and decreased by decreasing the angle. Figure 18 displays that by increasing the length of the submarine, Drag Coefficients increased and decreased by decreasing the length of the body.

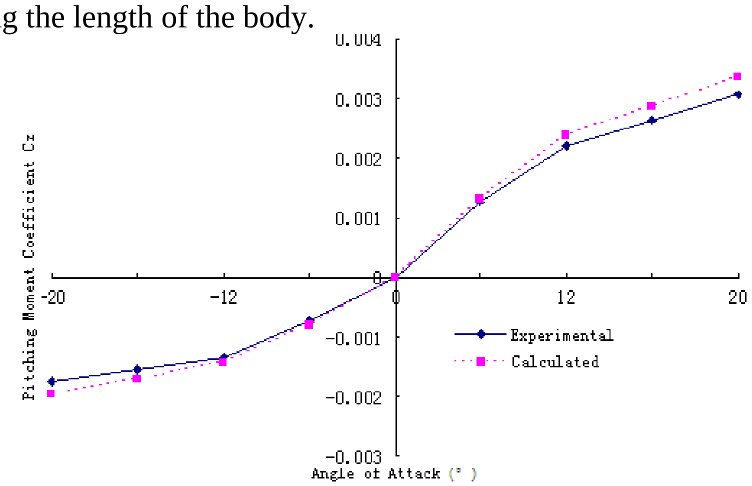

Fig. 15. Comparison of Pitching Moment coefficient,Body length

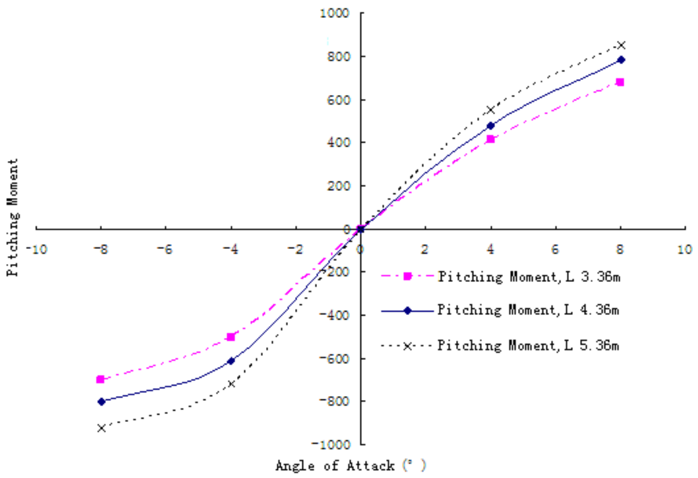

Fig. 16. Comparison of Pitching Moments for different Middle Body length L

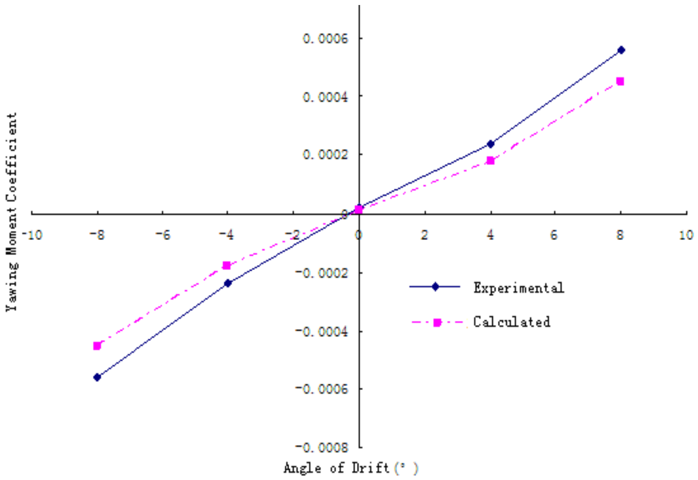

Fig. 17. Comparison of Yawing Moment coefficient Middle Body length

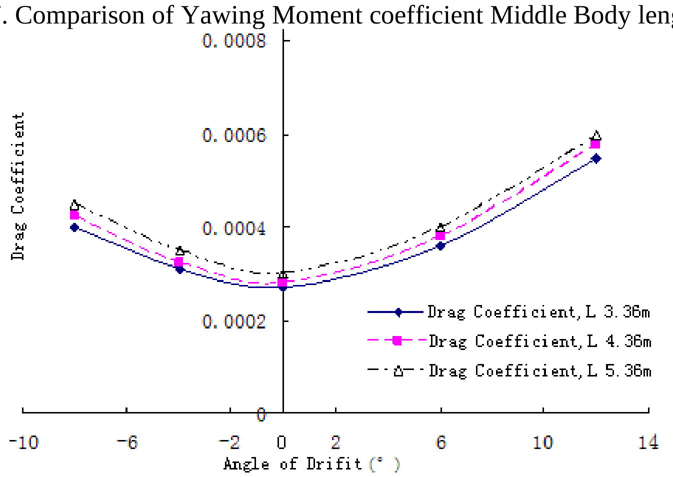

Fig. 18. Comparison of Drag Coefficients for Varying Length of Submarine SUBOFF

Table 1

Comparison of calculation data of SUBOFF hydrodynamic

model	hydrodynamic derivative	experiment value	calculated value	difference value
SUBOFF 1 (Length 3.36m)	Z'_w	--	–0.0110	--
	M'_w	--	0.0114	--
	$Z'_{w\|w\|}$ a=-8°~+8°	--	–0.0453	--
	$M'_{w\|w\|}$ a =-8°~+8°	--	–0.0149	--
SUBOFF 2 (Length 4.36m)	Z'_w	–0.0132	–0.0126	–4.01
	M'_w	0.0124	0.0119	–3.96
	$Z'_{w\|w\|}$ a=-8°~+8°	–0.0469	–0.0483	5.10
	$M'_{w\|w\|}$ a =-8°~+8°	–0.0161	–0.0170	5.02
SUBOFF 3 (Length 5.36m)	Z'_w	--	–0.0144	--
	M'_w	--	0.0152	--
	$Z'_{w\|w\|}$ a=-8°~+8°	--	–0.0498	--
	$M'_{w\|w\|}$ a =-8°~+8°	--	–0.0196	--

Table 1 shows the results of hydrodynamic calculations of a fully attached submarine. The deviation between the numerical simulation results and the experimental values is less than 5%.

5. Conclusions

Herein, it is shown that Reynolds averaged equations can be reliably used for the analysis of hydrodynamic performance of submarine. The primary conclusions are written as follows:

The model which has 1.8 million cell mesh number and CO-type grid can ensure the calculation accuracy. At this point, the values of vertical force and moment were relatively stable and did not change significantly.

The simulated flow details and computed hydrodynamic forces and moments were in good agreement with the experimental data.

Comparison of Normal force, pitching moment, and Yawing Moment of a complete submarine having middle body length 4.36 m shows an extremely reasonable agreement with the experimental results of SUBOFF at low Angle of attack. The results deviated slightly at high angles of attack. This is because at high Angle of attack, submarine had a streamlined structure delay flow separation, leading to a reduction in the resistance. Viscosity flow caused by differential pressure force played a leading role.

Pitching moment and Normal Force were increased by increasing the length of the submarine and decreased by decreasing the length of the submarine. Also, the Drag on Submarine body was increased by increasing the Length.

Acknowledgements

The authors would like to acknowledge Funded project (No.10572094) supported by the National Natural Science Foundation of China and Innovation platform open fund Project (No.2018C01044) and (No.2018A03025) Supported by Scientific Research Fund of Ministry of Education.

R E F E R E N C E S

[1]. R. *N. Joubert*, "Some Aspects of Submarine Design. Defense Science and Technoloy Organization", Australian, 2006.

[2]. *C. W. Cindy*, "Steady and Unsteady Force and Moment Data on a DARPA2 Submarine. Master of Science in Aerospace Engineering", Blacksburg, Virginia, **vol. 5**, no. 2, August 1999, pp. 102-119.

[3]. *Groves N. C., Huang T. T., Chang M. S.* "Geometric Characteristics of DARPA SUBOFF models", David Taylor Research Center, Ship Hydrodynamics Department, 1989.

[4]. *Yang Q.F., Wang Y.S., Zhang Z.H*. "RANS simulation of viscous flow over full appended submarine and field variables walidation and vorticity analysis", Chinese Journal of Computation Mechanics, **vol. 29**, no. 4, August. 2012, pp. 567-573.

[5]. *Y.C. Pan.* "Numerical prediction of submarine hydrodynamic coefficients using CFD simulation", Journal of Hydrodynamics, **vol. 24**, no. 6, Ser. B, 2012, pp. 840-847.

[6]. *Pan Z.Y., Wu B.S., Shen H.C.* "Research of CFD application in engineering estimation of submarine maneuverability hydrodynamic forces", Journal of Ship Mechanics, **vol. 8**, no. 5, 2004, pp. 42-51.

[7]. *Huang Z.Y., Zhou L.D*. "Numerical simulation of flows over underwater axis symmetric bodies with full appendages", Shipbuilding of China, no. 1, 2001, pp. 4-13.

[8]. *Qiu L.Y., Shi Z.K., Hou G.X., Wei F.F. "*Validation of Numerical Simulation of the Flow over Submarine Geometries with Full Appendages", Journal of Ship Mechanics, **vol. 11**, no. 3, 2007, pp. 341-350.

[9]. *Liu S.* "Numerical Study of hydrodynamic forces on a maneuvering submarine", Shanghai Jiaotong University, 2011

[10]. *Alin N., Fureby C.* "3D Unsteady Computations for Submarine-like Bodies", AIAA Aerospace Sciences Meeting and Exhibit. Reno, 2005.

[11]. *Coutier D. O., Reboud J. L., Delannoy Y.* "Numerical simulation of the unsteady behaviour of cavitating flows", Int J Numer Meth Fl, **vol. 8**, no. 4, 2003, pp. 115-120.

[12]. *Alexander B. Phillips, Stephen R. Turnock, Maaten F.* "Influence of turbulence closure models on the vortical flow field around a submarine body undergoing steady drift", Journal of Marine Science and Technology, **vol. 15**, no. 3, 2010, pp. 201-217.

[13]. *Pasinato H., Wang Y. Q., et al*. "Numerical investigation of flow past a prolate spheri-od", Journal of Fluids Engineering, **vol. 124**, 2002, pp. 904-910.

[14]. *Kobayashi T.* "Large eddy simulation for engineering applications", Fluid Dynamics Research, **vol. 38**, 2006, pp. 84-107.

[15]. *Sheng C., Taylor L., Whitfied D., "*Mltiblock multigrid solution of three-dimensional incompressible turbulent flows about appended submarine configurations", 33rd Aerospace Sciences Meeting and Exhibit. Reno, 1995. (AIAA-95-0203).