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Research Article

THE INVESTIGATION INTO RESISTANCE AND FLOW CHARACTERISTICS AROUND UNDERWATER BODIES OPERATING NEAR FREE SURFACE

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ABSTRACT:
The coastlines of Thai territories are approximately over 1,500 miles which are required the routine and special patrol operations to protect the national oceanic resources and treasuries. The collaboration of surface, air and underwater operations is the main responsibility for Royal Thai Navy and associated affiliations. Usually, underwater operation requires the submarine with different capabilities. As the main roles of the submarine are different depending on the user requirements and design. The small submarine or Midget Submarine normally has different capabilities and mission envelopes which are normally close to the coastline and shallow water compared with the bigger submarines. Analysis of the submarine hydrodynamic characteristics with the effects of the free surface as the near surface operation is one of the aspects that need to be investigated. Resistance and wave elevation are the main aspects that are more concerned to ensure that the submarine can operate with the desire speed and avoid the wave effects. To demonstrate those characteristics, four different underwater platforms including spherical model, teardrop, torpedo and submarine are investigated. As the advancement of the computer, Computational Fluid Dynamic (CFD) code, STAR CCM+, with the Reynolds-Averaged Navier-Stokes equations (RANS) is used as a tool to assess the underwater platform performance. The resistance coefficients are performed on the speeds of 0.325, 0.651, 1.301, 1.952 and 2.440 m/s which are corresponding to operating speed of 2, 4, 8, 12 and 15 knots respectively for the 30-meter Midget Submarine. Wave elevation is measured to calculate wave resistance to demonstrate the critical speed that generates wave and cause the increase of resistance.

Keywords: *Computational Fluid Dynamics (CFD), Free surface effects, Midget Submarine, Wave resistance*

1. INTRODUCTION

The Computational Fluid Dynamics (CFD) application to the ship science has now been growing rapidly for the past few decades and mature enough to evaluate the hydrodynamics performance for the marine vessels. As the advantage of the increasing speed of computer processing capability, the computational time for the CFD application has also been reduced. The investigations into the marine vessel using the CFD application are now the main stream research routine. The CFD code with the Reynolds-Averaged Navier-Stokes (RANS) equations and turbulent models are

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widely used. There are various research works that use the CFD code with RANS equations and turbulent models as seen in [1, 2] and [3] for example.

To investigate the submarine resistance near free surface, it is important to understand how to setup the suitable flow physic to represent the real flow characteristics. Unlike the fully submerged submarine, when the submarine operates near free surface, it will be affected by free surface. Hence, in this case, the flow phenomena around submarine operating near free surface must be treated the same manner with surface ship.

The investigations that focus on resistance and free surface flow of the surface ship are found in [4, 5] and [6] while the works involving submarine are seen in [7, 8] and [9] for instance. These researches initially concern the grid generation to capture free surface wave and the total numbers of cell to provide the acceptable results. Turbulent models are another aspect that can deter the results as of the nature of different turbulent models. The use of turbulent models including $k - \varepsilon$ and $k - \omega$ [10] in the submarine studies which are found in [11, 12] and [13] respectively.

As discussed earlier and found in [7] – [13] and more, most of the investigation into submarine performances and hydrodynamic characteristics are made mainly for fully submerged operation regime. Due to the limitation to the periscope depth or near free surface operation investigation for the submarine, this study tries to fulfil those aspects by focusing on estimating resistance and flow characteristics around underwater bodied and comparing the differences between various hull geometries to further understanding of submarine hull performance.

2. Submarine Resistance

The resistance components are mainly expressed in non-dimensional form according to the types of force acting on the hull surface. These components are total resistance, frictional resistance and residuary resistance which are derived by Froude. In another way, Hughes introduced the broken down of resistance by considering total resistance equals the sum of viscous resistance and wave resistance. Normally, submarine resistance is broken down into small components as the surface ship when operating on surface. However, when the submarine is fully submerged the sum of the forces is treated slightly different as shown in Fig. 1. In the submerged case, wave resistance is neglected where only viscous and frictional resistance are existed.

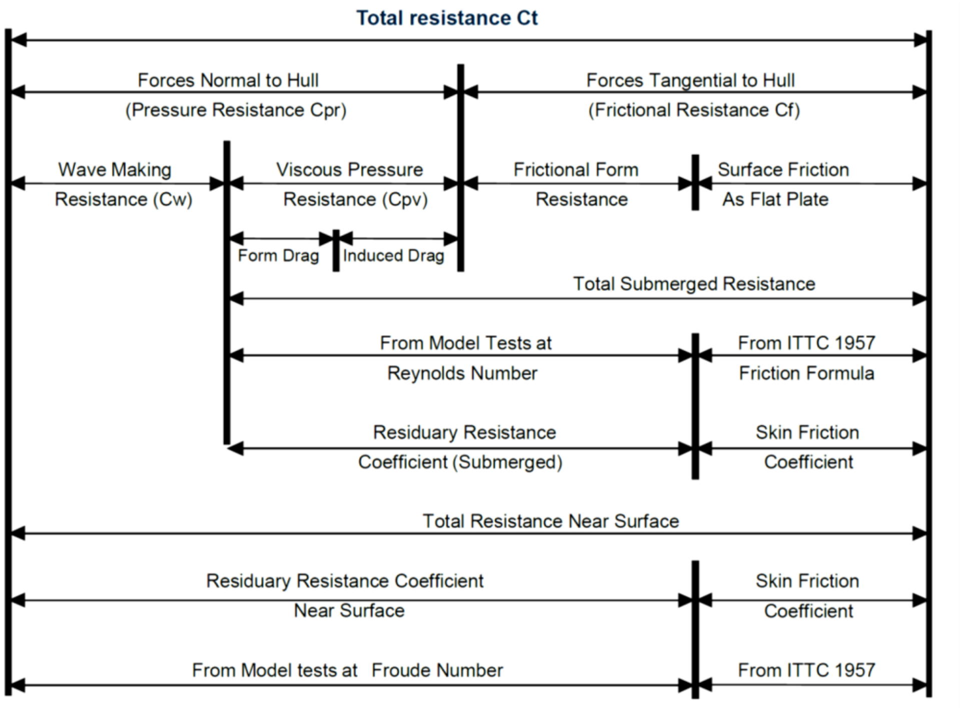


Fig. 1. The broken down of ship resistance [14]

The non-dimensional form or resistance coefficient are calculated as follow:

$$C_x = \frac{R_x}{\frac{1}{2} \times \rho \times U^2 \times S} \tag{1}$$

Where, ρ is water density (kg/m^3).
U is ship velocity (m/s).
S is the wetted surface area (m^2).

The ITTC skin friction resistance coefficient is calculated as:

$$C_F = \frac{0.075}{(logRe - 2)^2} \tag{2}$$

Where Re is Reynolds' number.

Resistance of submerged submarine can be expressed as:

$$C_T = C_V = C_F + C_{R\_Submerged} \tag{3}$$

When submarine is operated near surface the effect of wave making resistance can induce the increase of total resistance as shown in Fig. 1. Hence, the total resistance for the submarine operating near free surface is expressed as:

$$C_T = C_V + C_W = C_F + C_R \tag{4}$$

To calculate these resistance components, Computation Fluid Dynamics (CFD) application is used. The total resistance is derived from the sum of sheer (tangential) and pressure (normal) forces which are directly measured from the CFD application.

3. THEORETICAL FORMULA, HULL GEOMETRIES, AND GRID GENERATION

3.1 Theoretical Formula

The theoretical formula of the CFD principle are summarized in the work of [15]. The governing equations for unsteady, three-dimensional, compressible viscous flow can be written as:

- Continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho U) = 0 \tag{5}$$

- Momentum Equations:

$$\frac{\partial(\rho u)}{\partial t} + \nabla \cdot (\rho u U) = -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} + \rho f_x \tag{6}$$

$$\frac{\partial(\rho v)}{\partial t} + \nabla \cdot (\rho v U) = -\frac{\partial p}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} + \rho f_y \tag{7}$$

$$\frac{\partial(\rho w)}{\partial t} + \nabla \cdot (\rho w U) = -\frac{\partial p}{\partial w} + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} + \rho f_z \tag{8}$$

Where: ρ is fluid density
$U = (u, v, w)$ is the fluid velocity
p is pressure
$f = (f_x, f_y, f_z)$ is a body force e.g. weight due to gravity and magnetic force.
τ_{nn} is viscous stress

These equations are known as the Navier-Stokes equations. The continuity equation is rewritten as:

$$\nabla \cdot U = 0 \tag{9}$$

The momentum equations are as follow:

$$\rho \frac{Du}{\partial t} = -\frac{\partial p}{\partial x} + \mu \nabla^2 u + \rho f_x \tag{10}$$

$$\rho \frac{Dv}{\partial t} = -\frac{\partial p}{\partial y} + \mu \nabla^2 v + \rho f_y \tag{11}$$

$$\rho \frac{Dw}{\partial t} = -\frac{\partial p}{\partial z} + \mu \nabla^2 w + \rho f_z \tag{12}$$

Where D/Dt is the substantial derivative given by:

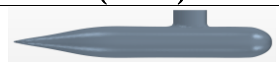
$$\frac{D}{Dt} = \frac{\partial}{\partial t} + u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y} + w\frac{\partial}{\partial z} \tag{13}$$

Hence, that continuity and momentum equations are decoupled from the energy equation and enough to solve the velocity and pressure fields in incompressible flows.

3.2 Hull Geometries

Four hull geometries including sphere, teardrop, torpedo and midget submarine are evaluated to demonstrate the effects of free surface to the increase of total resistance using CFD code. The model particulars are shown in Table 1. These hulls are created to demonstrate the flow around the submerged platform operated near free surface starting from the simple to complex hulls. Hull geometries are created in CAD software and then imported into the CFD code, STAR CCM+.

Table 1: Hull geometries

Models	**Sphere**	**Teardrop**	**Torpedo**	**Midget Submarine (MSub)**
				
Length, m	0.386	0.84	3.19	3.0
Breadth, m	0.386	0.386	0.386	0.386
Depth, m	0.386	0.386	0.386	0.576
Wetted surface area (WS), m^2	0.044	0.0818	2.48	2.18
Volume, m^3	0.0276	0.0608	0.3111	0.2682

3.3 Grid Generation

Numerical domain is set to be similar for all models. The inlet boundary is 3L (of the midget submarine) from the fore end of hull geometry. The outlet boundary is 7L from the after part of the hull geometry. The side boundary is 3L from the hull geometry centerline. The top and bottom boundaries are set to be 2L and 3L from the hull centerline respectively. The representation of numerical domain is shown in Fig. 2.

To evaluate the hydrodynamics properties and flow characteristics of the underwater platform operating near free surface, the periscope depth of the midget submarine which is normally equaled the length of the periscope mast which is approximately the height of bridge fin or sail. Hence, the depth of the underwater platform investigated in this paper is considered as 1.5D measured from the geometry centerline.

Grid generation of the numerical domain is shown in Fig. 3. To capture wave elevation on free surface, the refinement blocks are added into the free surface area. In the same way, the area around the geometry needs more cells to capture the complex flow. According to these refinement techniques, the final numbers of cell are around 2M cell. As this study involves the turbulent flow, the k – ε model is used to assess the resistance components and flow field for the underwater platforms.

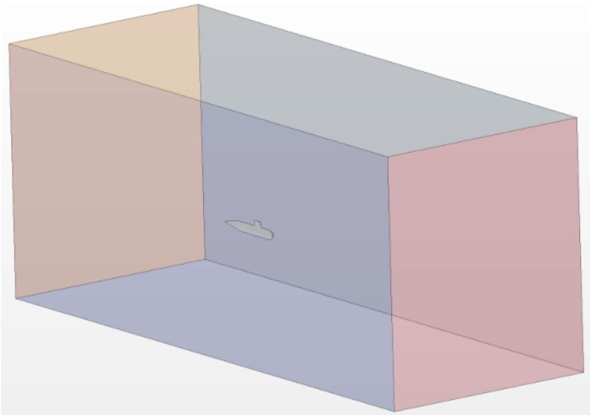


Fig. 2. Numerical domain

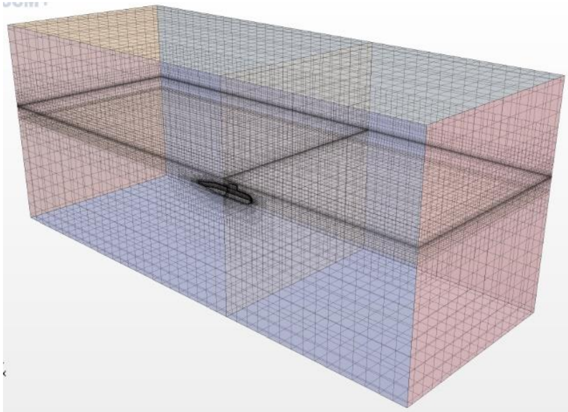


Fig. 3. Grid generation

4. Results And Discussions

4.1 Resistance

To evaluate and compare resistance of the underwater bodies with different model geometries, it is important to define the reference parameters. As the aim and objectives of this study are mainly to investigate resistance and the flow around the midget submarine by demonstrating the flow characteristics around underwater platforms with different geometries, to overcome this, the 30-meter long midget submarine is the reference geometry to determine speed and depth as the baseline for the investigation. The 30-meter long midget submarine operated at speeds of 2, 4, 8, 12 and 15 knots which are equal Froude number of 0.06, 0.12, 0.24, 0.36 and 0.45 respectively, is scaled down to 3 m and evaluated in the CFD code. To run the 3-meter long midget submarine at the same set of Froude numbers, final speeds are 0.325, 0.651, 1.301, 1.952, and 2.44 m/s respectively. Hence, all hull geometries investigated in this study are evaluated using these set of speeds which represent *Froude numbers of the 3-meter midget submarine* and not iso-Froude numbers for all models.

Figure 4 shows the simulation results for the spherical hull geometry. The skin friction resistance coefficient (C_F) is measured and validated against the International Towing Tank Conference (ITTC) skin friction correlation line (C_{F_ITTC}) and shows a good agreement with a slightly under prediction. Total resistance coefficient (C_T) shows the sharp increase for the lower speed (from 0.325 to 1.301 m/s) and then reduce after U = 1.301 m/s. Residuary resistance coefficient (C_R) is calculated by deducting C_T by C_F. From the results shown here, it seems to be convinced that the rise of total resistance occurs at the speed of 0.651 m/s.

The results for the teardrop hull geometry are presented in Fig. 5. The CFD C_F agree very well with the C_{F_ITTC} with small amount of under prediction. With a slight longer hull geometry compared with the spherical body, the increase of total resistance seems to shift from the 0.651 m/s to 1.301 m/s with the maximum value of 0.054.

Figure 6 shows the resistance results for the torpedo-like hull geometry. CFD C_F shows a good agreement with C_{F_ITTC}. Total resistance coefficient, C_T, decreases in the range of speed U = 0.325 to 0.651 m/s and then slightly increases for U = 1.301 m/s. The obvious increase of CFD C_T is found at the speed of 2.44 m/s with the value of 0.0165. This means that wave resistance clearly occurs at a very high-speed regime for torpedo geometry. The 3-meter midget submarine shows similar trend with the torpedo which the effects of wave resistance is clearly seen in the high speed (see Fig. 7). For the torpedo and midget submarine, at the speed lower than 2.44 m/s, CFD C_R is lower than both CFD and ITTC C_F which can be said that wave resistance is a small proportion to the total resistance.

Wave resistance component can be analytically evaluated by Michell's Integral [16]. Many researchers, i.e. Doctors [17] have implemented his work in order to develop and improve this such classic methodology. Nevertheless, this evaluation method is obviously complicated, and it is not practically used for the early stage wave resistance evaluation. In order to quantify the actual wave resistance, I_W parameter is introduced to replace the complicate Michell's Integral. It consists of evaluation of the area enclosed by the wave cut along the center plane with respect to the still water level. The results are show in Fig. 8. It can be seen that I_W for the spherical geometry is highest compared with other models and seems to increase at a very lower Froude number. Another model that shows a high I_W is teardrop which the increase shifts to Fr = 0.12. I_W for torpedo and midget submarine shows the same trend with a slight increase. The increase of I_W for torpedo and midget marine shows the highest value at the highest speed which is clearly seen compared with the lower Froude number. This confirms the resistance results shown in Fig. 6 and 7 which wave resistance dominates other resistance components.

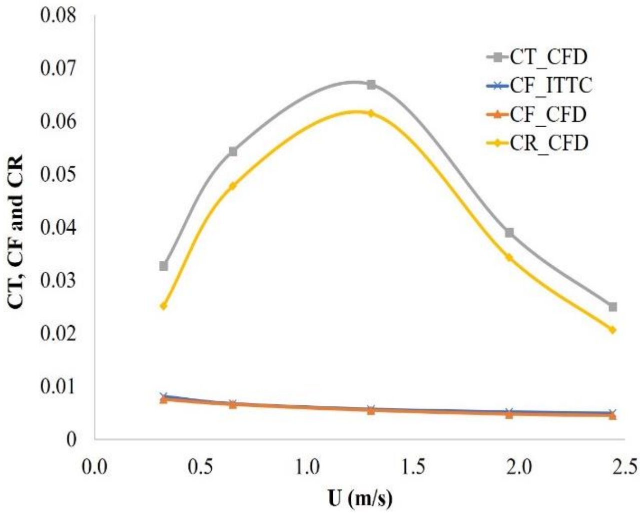


Fig. 4. Resistance for Sphere

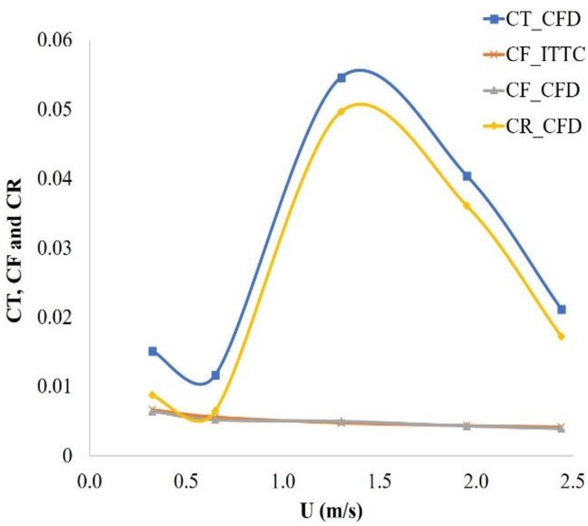


Fig. 5. Resistance for Teardrop

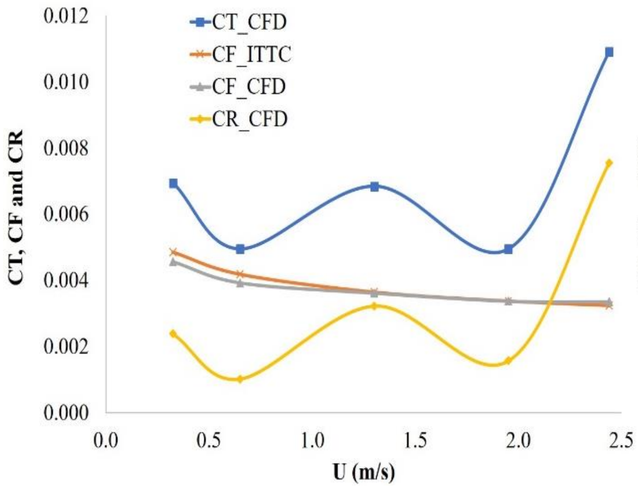


Fig. 6. Resistance for Torpedo

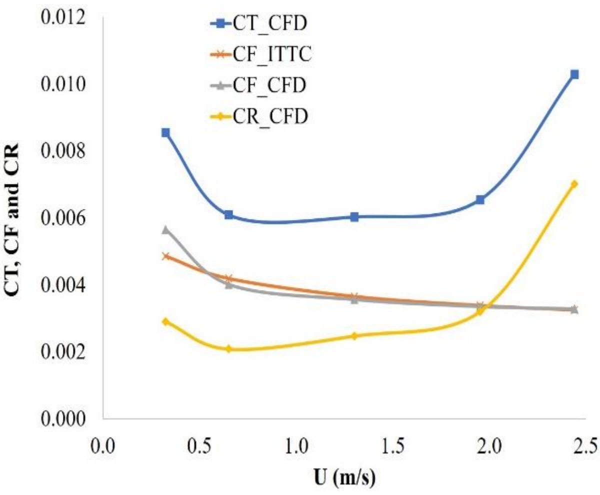


Fig. 7. Resistance for Midget Submarine

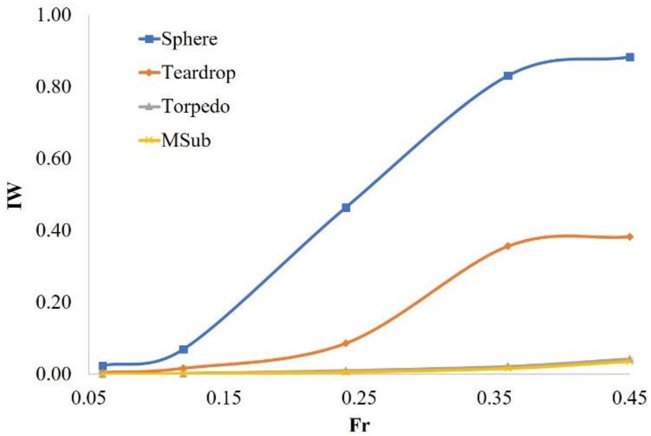


Fig. 8. I_W for different models

4.2 Wave Elevation and wave contour

Figure 9 to 12 show wave elevation at the centerline of sphere, teardrop, torpedo and midget submarine respectively. It can be seen that for lower Froude numbers i.e. Fr = 0.06 and 0.12 (or 2 and 4 knots for 30-meter midget submarine), wave elevation for all hull geometries is very small compared with the hull diameter. Wave elevation is clearly seen for high-speed regime for Fr > 0.12 for all hull geometries.

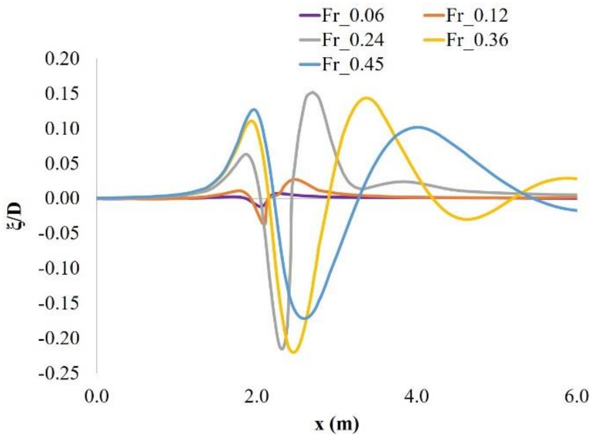


Fig. 9. Wave elevation for Sphere

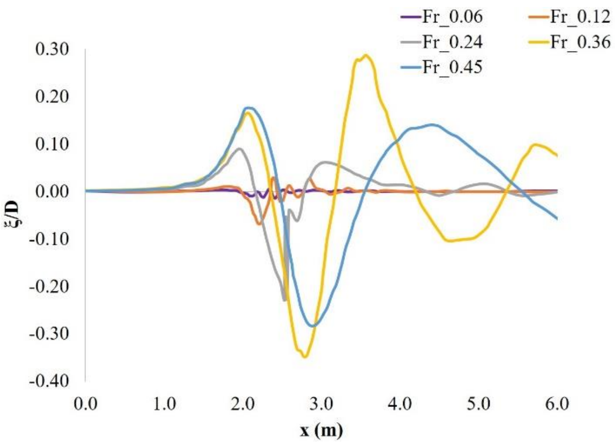


Fig. 10. Wave elevation for Teardrop

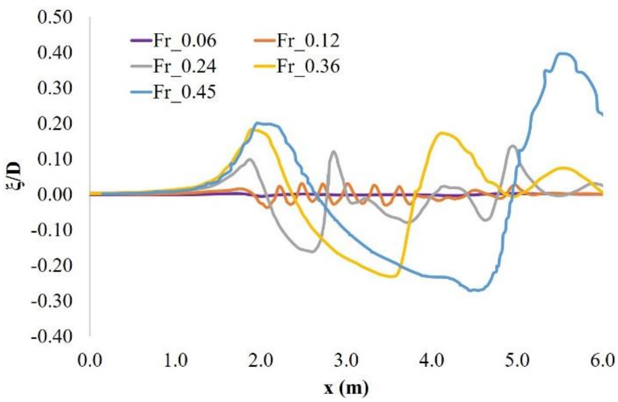


Fig. 11. Wave elevation for Torpedo

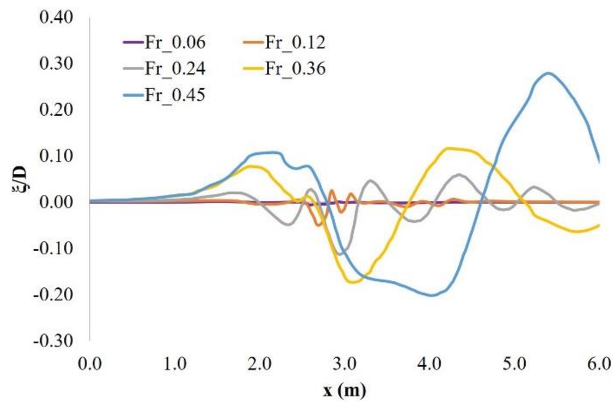


Fig. 12. Wave elevation for Midget Submarine

The comparison of wave elevation at the same Froude number for different models are shown in Fig. 13 (a) – (e) for Fr = 0.06 – 0.45 respectively. At the very low Froude number, wave elevation for sphere seems to be highest, however, the wave amplitude for other models is lower than 0.5% of the hull diameter. Wave elevation for Fr = 0.12 (or 4 knots for 30-meter midget submarine) is lower than 4% of the hull diameter. For Fr = 0.24, the percentage of wave elevation is about 15 which is still small. For the higher Froude numbers (Fr = 0.36 and 0.45) the highest wave amplitude compared with hull diameter is almost the same of approximately 25 – 30%. Free surface wave contours are shown in Fig. 14 – 17 for sphere, teardrop, torpedo and midget submarine respectively. The graphical results show that for lower Froude numbers i.e. Fr = 0.06 and 0.12, surface waves nearly invisible as seen in (a) and (b) for Fig. 14 – 17. Wave system starts to develop for Fr = 0.24 or higher which can be seen in (c), (d) and (e) in Fig. 14 – 17.

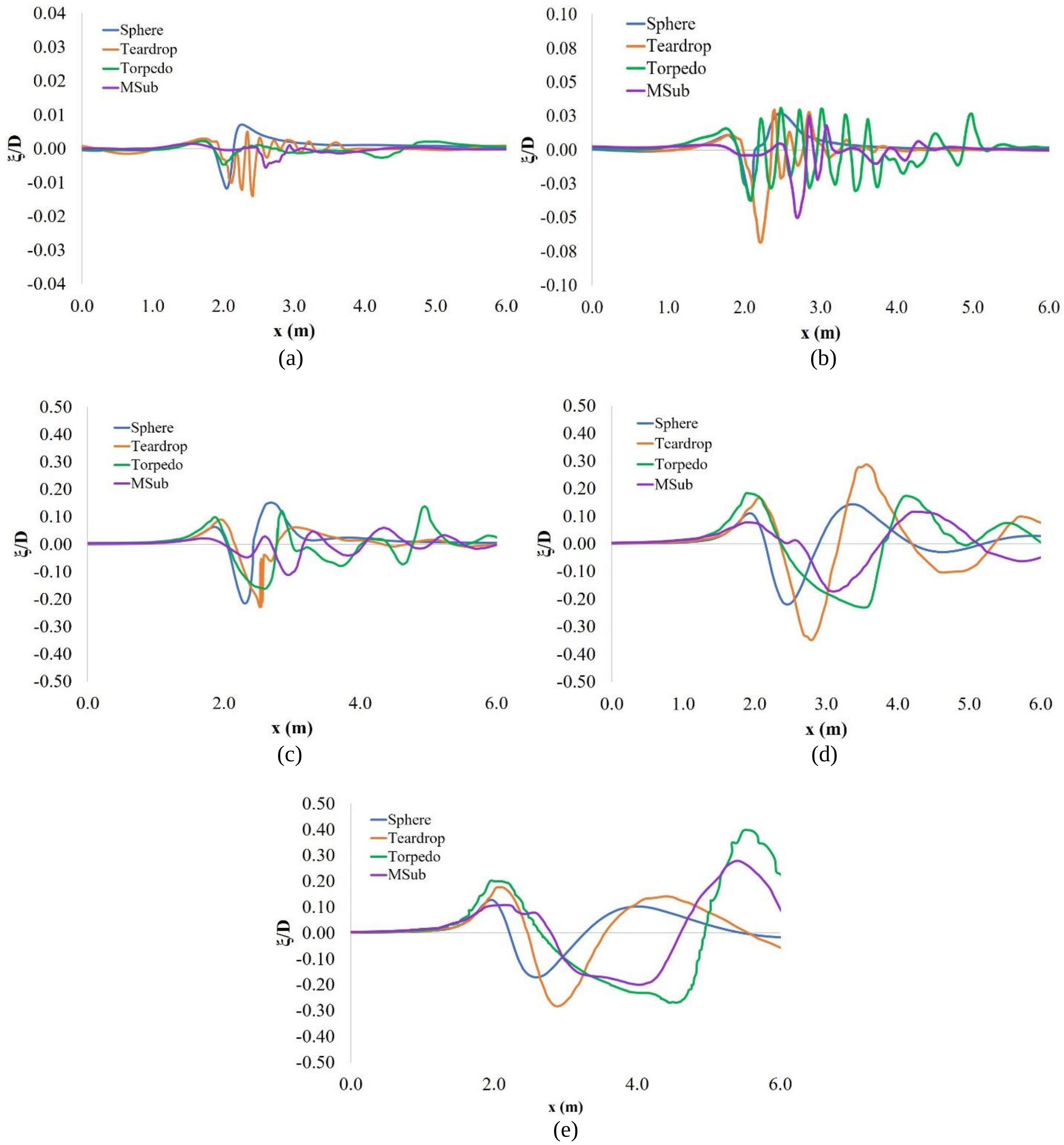


Fig. 13. The comparison of wave elevation at the centerline for different models at (a) Fr = 0.06, (b) Fr = 0.12, (c) Fr = 0.24, (d) Fr = 0.36 and (e) Fr = 0.45

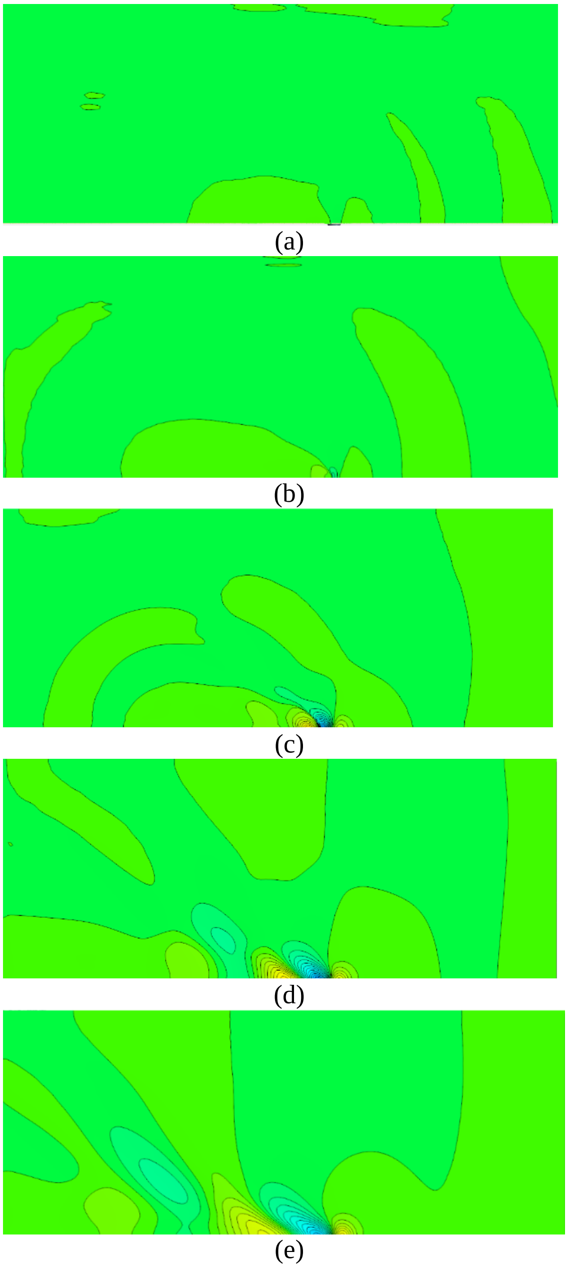


Fig. 14. Wave contour for Sphere at (a) Fr = 0.06, (b) Fr = 0.12, (c) Fr = 0.24, (d) Fr = 0.36 and (e) Fr = 0.45

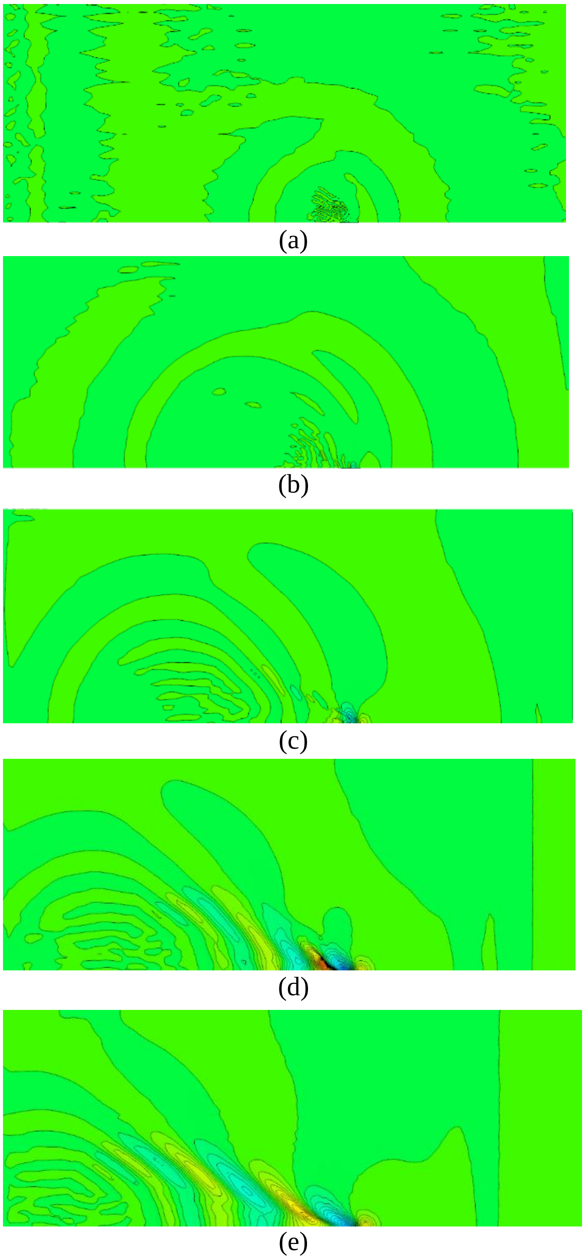


Fig. 15. Wave contour for Teardrop at (a) Fr = 0.06, (b) Fr = 0.12, (c) Fr = 0.24, (d) Fr = 0.36 and (e) Fr = 0.45

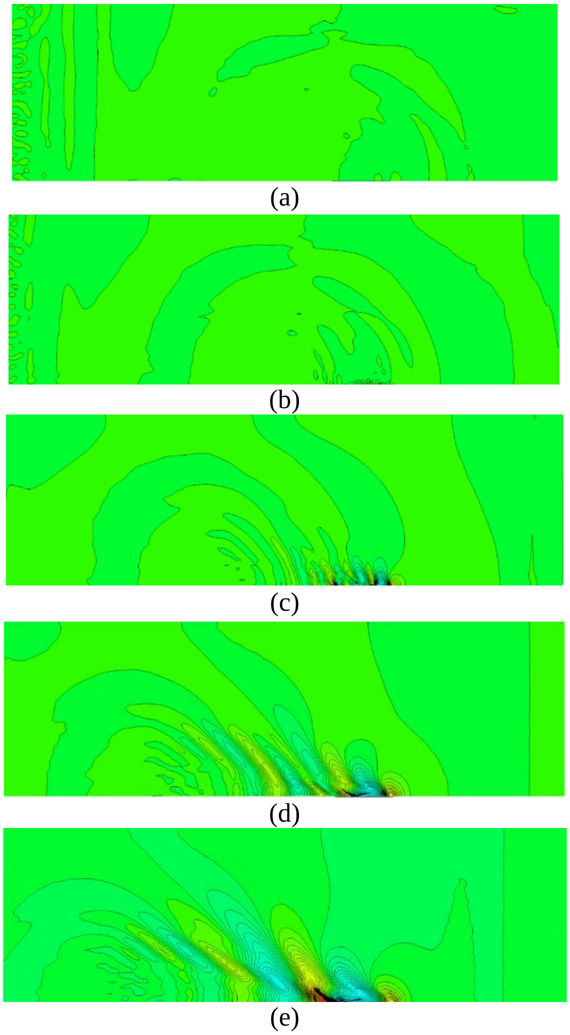


Fig. 16. Wave contour for Torpedo at (a) Fr = 0.06, (b) Fr = 0.12, (c) Fr = 0.24, (d) Fr = 0.36 and (e) Fr = 0.45

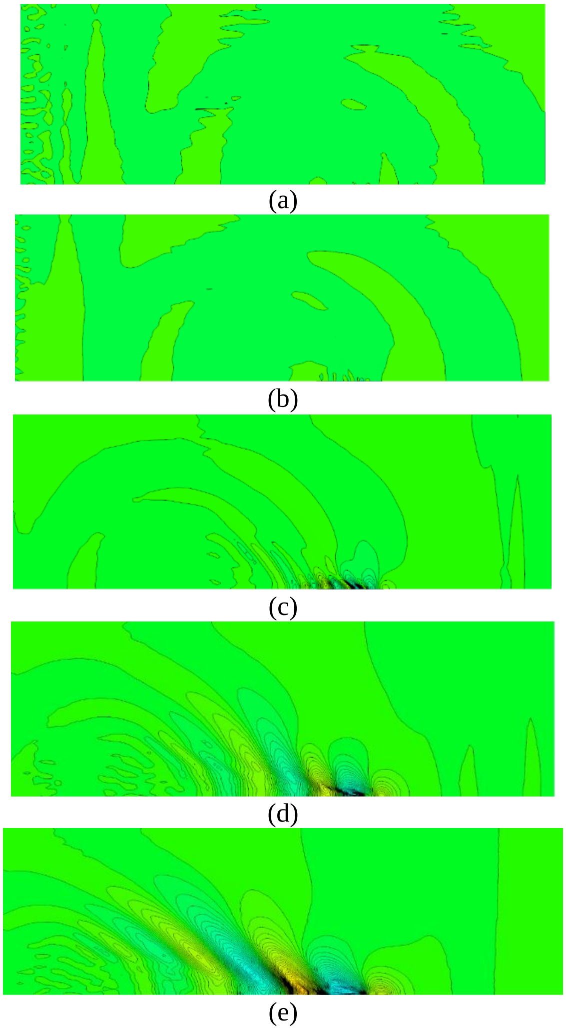


Fig. 17. Wave contour for Midget Submarine at (a) Fr = 0.06, (b) Fr = 0.12, (c) Fr = 0.24, (d) Fr = 0.36 and (e) Fr = 0.45

5. Conclusion

The numerical computation of resistance near free surface for four different hull geometries including spherical, teardrop, torpedo and midget submarine is performed in this investigation using CFD code with RANS equations and $k-\varepsilon$ turbulent model. The results show that the CFD C_F agree with ITTC C_F quite well, the total resistance coefficient (C_T) increases at very low speed (0.325 m/s) for spherical model, at 1.301 m/s for teardrop and at highest speed for torpedo and submarine. The I_W is introduced to quantify and represent wave resistance and shows that the shorter models, i.e. sphere and teardrop, have higher I_W at the same speed which results in the increase of total resistance (hence, C_R or wave resistance) at low Froude numbers. For the longer models, torpedo and midget submarine, the I_W is clearly seen in the highest Froude numbers which is corresponding to sharp increase of total resistance. Wave elevation and contour plots show that for lower Froude numbers, wave amplitude at the centerline through the numerical domain is very small which is lower than 4% of the hull diameter. On the other hand, for higher Froude numbers, wave systems start to occur and can be seen, however, the wave amplitude is lower than 25% of hull diameter for sphere, torpedo and midget and lower than 30% of hull diameter for teardrop.

NOMENCLATURE

B	Hull breadth *(m)*
C_F	Frictional resistance coefficient *(-)*
C_R	Residuary resistance coefficient *(-)*
C_T	Total resistance coefficient *(-)*
C_V	Viscous resistance coefficient *(-)*
C_W	Wave resistance coefficient *(-)*
D	Hull Depth *(m)*
Fr	Froude number *(-)*
L	Hull length *(m)*
Re	Reynolds' number *(-)*
U	Hull velocity *(m/s)*
ξ	Wave Elevation (*m*)

REFERENCES

[1] Wackers, J., Koren, B., Raven, H.C., Van der Ploeg, A., Starke, A., Deng, G. and Ohashi, K. Free-surface viscous flow solution methods for ship hydrodynamics, Archives of Computational Methods in Engineering, Vol. 18(1), 2011, pp. 1-41.

[2] Voxakis, P. Ship hull resistance calculations using CFD methods, 2012, Department of Mechanical Engineering, Massachusetts Institute of Technology, Massachusetts.

[3] Zha, R., Ye, H., Shen, Z. and Wan, D. Numerical computations of resistance of high-speed catamaran in calm water, Journal of Hydrodynamics Ser. B, Vol. 26(6), 2015, pp. 930-938.

[4] Wood, C. Compartment Flooding and Motions of Damaged Ship, PhD Thesis, 2013, University of Southampton, Southampton.

[5] Windén, B., Turnock, S.R. and Hudson, D.A. Validating force calculations using OpenFOAM on a fixed Wigley hull in waves, paper presented in 15th Numerical Towing Tank Symposium, 2012, Cortona, Italy.

[6] Srinakaew, S., Taunton, D.J. and Hudson, D.A. A Study of Resistance of High-Speed Catamarans and Scale Effects on Form Factor, paper presented in proceeding of the 19th Numerical Towing Tank Symposium (NUTTS'16), 2016, St Pierre d'Oleron, France.

[7] Phillips, A.B., Turnock, S.R. and Furlong, M. 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(3), 2010, pp. 201-217.

[8] Cao, L.S., Zhu, J. and Wan, W.B. Numerical investigation of submarine hydrodynamics and flow field in steady turn, Journal of China Engineering, Vol. 30, 2015, pp. 57-68

[9] Marshallsay, P.G. and Eriksson, A.M. Use of Computational fluid dynamics as a tool to assess the hydrodynamic performance of a submarine, paper presented in 18th Australasian Fluid Mechanics Conference, 2012, Launceston, Australia.

[10] Wilcox, D.C. Turbulence Modeling for CFD, 2nd edition, 1998, DCW Industries, Canada.

[11] Sarkar, T., Sayer P.G. and Fraser S.M. A Study of Autonomous Underwater Vehicle Hull Forms Using Computational Fluid Dynamics, International Journal for Numerical Methods in Fluids, Vol. 25, 1997, pp. 1301-1313.

[12] Lam, C.K.G. and Bremhorst, K. A Modified Form of the k-e Model for Predicting Wall Turbulence, ASME Journal of Fluid Engineering, Vo.103, 1981, p. 456.

[13] Baker, C. Estimating Drag Forces on Submarine Hulls, Report DRDC Atlantic CR 2004-125, Defence R&D Canada-Atlantic, 2004.

[14] Crossland, P. Submarine Resistance and Propulsion, UCL Submarine Design Course, November 2018, University College London, London.

[15] Srinakaew, S. A Numerical Study of Resistance Components of High-Speed Catamarans and Scale Effects on Form Factor, PhD Thesis, 2018, University of Southampton, Southampton.

[16] Michell, J.H. The Wave Resistance of a Ship, Philosophical Magazine, Vol. 45, 1898, pp. 106-123.

[17] Doctors, L.J. Modifications to the Michell's Integral. Improvement predictions of ship resistance, paper presented in proceeding of the Twenty Seventh Israel Conf. on Mech. Eng., 1998, Technion City, Israel.