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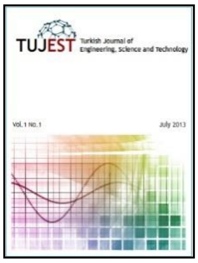

Minimum immersion depth for eliminating free surface effect on submerged submarine resistance

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Abstract

This paper offers the minimum depth of submergence of a submarine which the free surface effect on resistance, could be eliminated. For ships in calm water, the free surface of water, causes wave resistance but for a submarine at the deep depth of water (fully submerged depth), there is not wave resistance because there is not a free surface. In every depth between surface mode and fully submerged mode, the movement of a submarine or torpedo, causes turbulence on the surface of water. This paper tries to define minimum depth as fully submerged depth which in this depth, free surface effect and wave resistance could be ignorable. This depth is depended on the dimensions of a submarine. In this paper, only bare hull without appendages is considered. This analysis is performed by Flow Vision (V.2.3) software based on CFD method and solving the RANS equations. Two models of torpedo shape with different ratios of L/D, are simulated in several depths but in a constant speed.

1. Introduction

Submarines have two modes of navigation: surfaced mode and submerged mode. Conventional naval submarines are periodically obliged to transit near the surface of water for surveillance and recovery affairs such as: intake fresh air, charge the high pressure air capsules and start the diesel-generators for recharging the batteries. The process of charging the battery is the most time-consuming task at near surface depth or snorkel depth for usually 6~10 hours that depends on the specifications of electric power system and battery storage. Submarines have usually 220~440 battery cell that should be charged in the period of snorkeling. Minimizing the resistance of a submarine, transiting close to the ocean surface, is very important, because a submarine must save the energy for earlier charging the batteries and lesser need to stay at snorkel depth. If the submarine, waste a lot of energy for propulsion, it needs to stay more and more in snorkel depth. It is a very dangerous situation for a submarine because of the increase in the probability of detection.

Some torpedoes are obliged to approach the free surface too. It depends on the operational demands and the type of torpedo, for example, cruising just beneath the sea surface for receiving the target information by radio electronic devices or satellite. In this condition, the submergence depth of torpedo should be less than 2-3 meters equal to maximum permeability depth of electro-magnetic wave into the water. For every submersible, the more resistance is equal to the

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more power requirement and thus, lesser range and lesser duration of operation or endurance. In contrast to a surface vessel, a deeply submerged submarine, doesn't encounter the penalty of wave making resistance. Wave making resistance, in critical Froude numbers, can make up more than 50% of total resistance.

When a submarine ascents from the deep depth to the near the surface of water, the free surface effects, causes a steep increase in the resistance because of appearance of wave making resistance. Hydrodynamic aspect in submarine design is discussed by P.N.Joubert [1,2], R.Burcher and L.J.Rydill [3], Y.N.Kormilitsin and O.A.Khalizev[4], U.Gabler[5], L.Greiner[6] and in Ref.[7] by a group of authorities. In surfaced mode of navigation, such as ships, the body interferes with free surface of water. In surface mode in calm water, the wave making resistance is a main part of resistance that depends on the Froude number. For a submarine at the deep depth of the water, there is not wave resistance because there is not a free surface. This depth is named "fully submerged depth".

In every depth between surface mode and fully submerged mode, the movement of a submarine or torpedo, causes turbulence on the surface of water. This effect decreases by increasing the depth of submergence but there is a certain depth, which free surface effect and wave resistance is very little and ignorable. In all depths more than this depth, there is fully submerged condition. This paper tries to define this "fully submerged depth". This depth is depended on the dimensions of a submarine. The fully submerged depth, in Refs.[8,9], is defined as a multiple of the outer diameter of submarine hull (D) but in Ref.[10], is defined as a multiple of the length of the submarine hull (L). Fully submerged condition in reference [10] is defined as half of submarine length (h=L/2) and in reference [8] is defined as 3D (h=3D) and in reference [9], this depth is suggested 5D (h=5D). In Refs.[11,12], M.Moonesun *et al* showed that, according to experimental tests in towing tank for short values of L/D for submarines, the depth, h=5D can be a good suggestion but this depth can be lesser.

Now, this paper has concentrated the studies, to find out this depth for high values of L/D and short values of L/D, by CFD method. There are few published scientific articles about the hydrodynamic effects on a submerged body near a free surface, such as dynamics and maneuvering effects by K.Rhee, J.Choi, S.Lee [13], C.Polish, D.Ranmuthugala, J.Duffy, M.Renilson [14] and D.Neulist [15]. Resistance and wave making effects near the free surface are studied by E.Dawson, B.Anderson, S.V.Steel, M.Renilson, D.Ranmuthugala [16], S.Wilson-Haffenden [17] and S.V.Steel [18] which all of them conducted by Australian Maritime Collage. For investigating the wave making resistance of a submarine below the free surface, before this paper, Refs.[17,18] have been the main published articles which both are based on the DARPA SUBOFF submarine model in low Froude numbers. For these analyses, the base method is Experimental Fluid Dynamics (EFD) but to some extent, is reviewed by Computational Fluid Dynamics (CFD). This article wants to extend the studies about resistance of submersibles which travel near the free surface of calm water in low and high Froude numbers.

2. Wave making resistance in submarines

Total hull resistance is split up into friction, form and wave resistance components. The friction resistance is due to viscosity and wave making resistance is due to pressure variations of fluid surrounding the body. The friction drag coefficient is given as:

$$\mathbf{C_F} = \frac{\mathbf{0.075}}{(\mathbf{log_{10}Re-2})^2} \tag{1}$$

Where C_F is the non dimensional frictional resistance coefficient, and Re is the Reynolds number based on the body length scale. For the total resistance coefficient it can be write:

$$\mathbf{C_T} = \frac{\mathbf{R_T}}{\mathbf{0.5\rho V^2 S}} \tag{2}$$

Where S is the wetted surface in motionless water, v is the model speed and ρ is the density of the water of towing tank. The residual drag is a significant parameter that typically used in hydrodynamic studies. The residual drag is defined as total resistance except for skin friction drag. Residual drag coefficient is considered as: $C_R=C_T-C_F$. Decomposition and classification of resistance in marine applications are shown in Fig.1 which presents the different levels of resistance [9,10]. A well known classification in marine engineering for total resistance is a summation of wave resistance, viscous pressure resistance and friction resistance. It means $C_R = C_{vp} + C_w$.

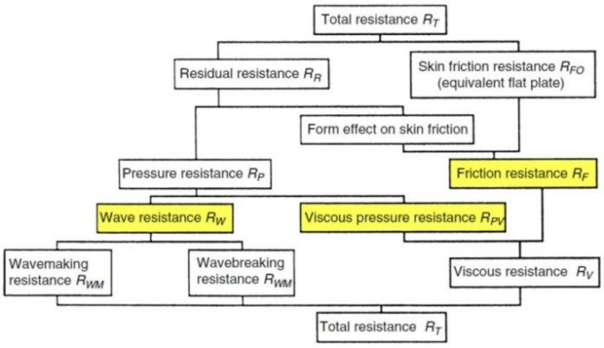


Figure 1. Decomposition and classification of resistance in marine applications [10]

Wave resistance is the biggest component (up to 50%) of total resistance at high Froude numbers. The wave length of the submarine is expressed as:

$$\lambda=\frac{2\pi V^2}{g} \tag{3}$$

Where V is vehicle velocity, and g is gravity. If a period of wave length extends to total length of the submarine, it is possible to consider L instead of λ. It means for an absolute period of the wave, one may write:

$$\frac{V^2}{L}=\frac{g}{2\pi} \tag{4}$$

Where for a semi period; Nπ is considered instead of 2π and the equation changed to:

$$\frac{V^2}{L}=\frac{g}{N\pi} \tag{5}$$

Here, the main challenge is determination of L. In marine vehicles and ships, there are several definitions for "length" such as: LOA, LWL and LBP but here some other definitions may be considered such as length between the pressure centre of bow and stern (LCP). Some differences about critical Froude number in scientific sources are because of that. In Ref.[10], for ships, L has been defined as L=0.9 LBP (LBP is the length between perpendiculars) and N is the semi period number that is shown in Fig.2:

$$\mathbf{N}=\frac{\mathbf{0.9Lg}}{\mathbf{V^2\pi}} \tag{6}$$

$$\frac{\mathbf{V}}{\sqrt{\mathbf{Lg}}}=\sqrt{\frac{\mathbf{0.9}}{\mathbf{N.\pi}}}=\mathbf{F_n} \tag{7}$$

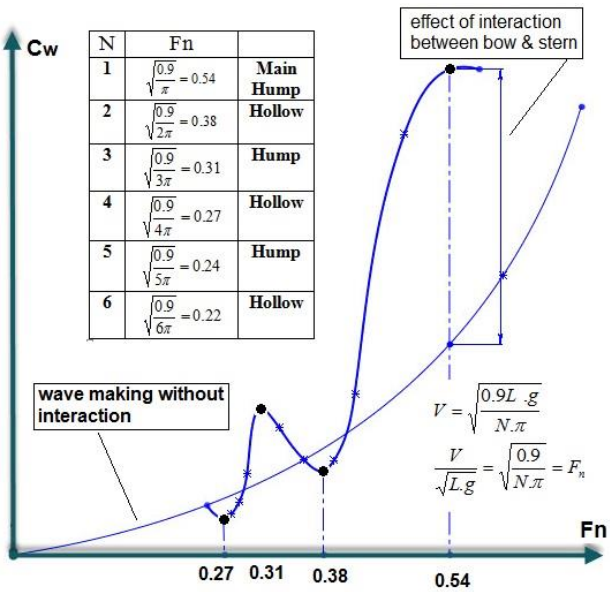


Figure 2: Variations of wave resistance coefficient versus Froude number (based on the L definition in Ref.[10])

approximate formula for estimating the wave resistance is as below:

$$\mathrm{Cw} = 3561.3\mathrm{Fn}^6 - 8812.6\mathrm{Fn}^5 + 8148.4\mathrm{Fn}^4 - 3454.3\mathrm{Fn}^3 + 654.09\mathrm{Fn}^2 - 40.235\mathrm{Fn} \quad (8)$$

Figure 3 shows the resistance coefficient (C_D) which decreases by increasing submergence depth because by increasing the depth, the wave making resistance, decreases.

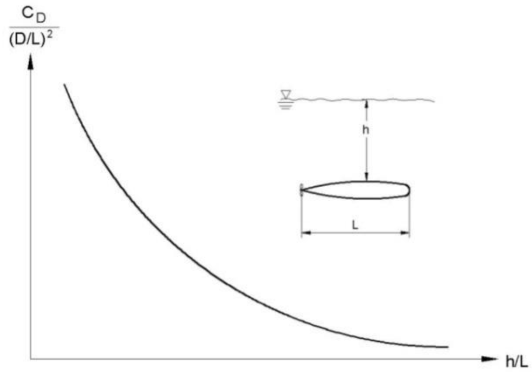


Figure 3. General variations of total Resistance coefficient versus submergence depth

The general variation of wave making resistance coefficient versus Froude number is represented in Fig.2. A brief study about wave making in [10], shows that, there are several peaks and trough (hump and hollow) in wave making resistance coefficient diagram. Hump points indicate the unfavorable interaction between the bow wave and stern wave because of unsuitable Froude numbers around Fn=0.31 and 0.54. Hollow points indicate the favorable interaction between the bow wave and stern wave because of suitable Froude numbers around Fn=0.38. As mentioned before, the exact critical values of Froude number, depends on the "L" or the distance between the centre of pressure of the bow and stern. It is obvious in Fig.4, that Cw, decreases by increasing the depth.

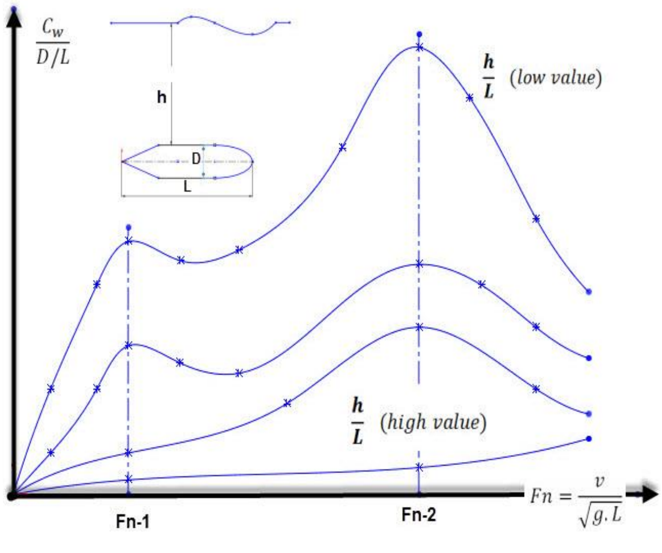


Figure 4. General variations of wave making resistance coefficient versus Froude number and depth of submergence

3. Assumptions for the Models

The base models that considered here, is an axis-symmetric body similar to torpedo, without any appendages because in this study, only bare hull, wants to be studied. It helps to quarterly CFD modeling of the body and saving the time. These are two models, with different values of L/D: 1)Model A: with normal value in submarines with L/D=8.33, L=5m and D=0.6m. 2)Model B: as a long vehicle with L/D=20, L=4m and D=0.2m. The specifications of two models are presented in Tab.1 and Fig.5.

Table 1: Main assumptions of models

Model	v (m/s)	Fn	L (m)	D (m)	L/D	S (m2)

A	5	0.71	5	0.6	8	7.87
B	5	0.8	4	0.2	20	2.17

The speeds of models are constant and equal to 5 m/s but are so selected that the values of Froude number be more than the range of hump and hollow, i.e. more than 0.7.

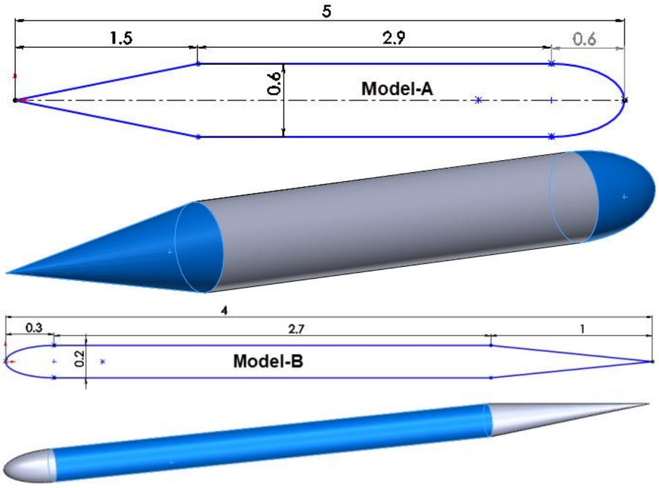


Figure 5. General configuration of the models

4. CFD Method of Study

This analysis is performed by Flow Vision (V.2.3) software based on CFD method and solving the RANS equations. Generally, the validity of the results of this software has been done by several experimental test cases, and nowadays this software is accepted as a practicable and reliable software in CFD activities. For modeling these cases in this paper, Finite Volume Method (FVM) is used. A structured mesh with cubic cell has been used to map the space around the submarine. For modeling the boundary layer near the solid surfaces, the selected cell near the object is tiny and very small compared to the other parts of domain. For selecting the proper quantity of the cells, for model-A, v=5m/s and H*=1.5D, six different amount of meshes were selected and the results were compared insofar as the results remained almost constant after 1.1 millions meshes, and it shows that the results are independent of meshing (Fig.6). In all modeling the mesh numbers are considered more than two millions.

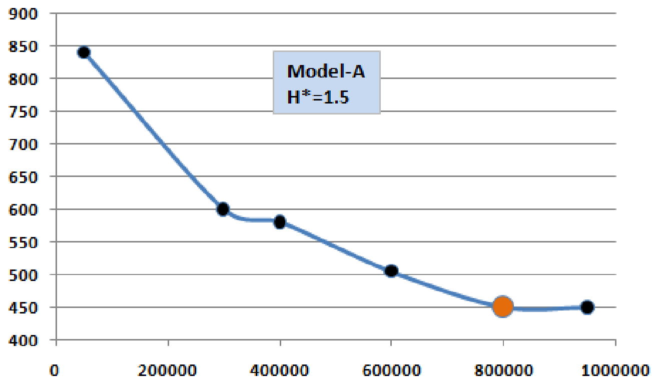


Figure 6. Mesh independency evaluations

For the selection of suitable iteration, it was continued until the results were almost constant with variations less than one percent, which shows the convergence of the solution. All iterations are continued to more than one millions. Each Model is evaluated in several depths as Table 2. H* is defined as:

$$H^* = \frac{submergence\ depth\ (h)}{D} \qquad (9)$$

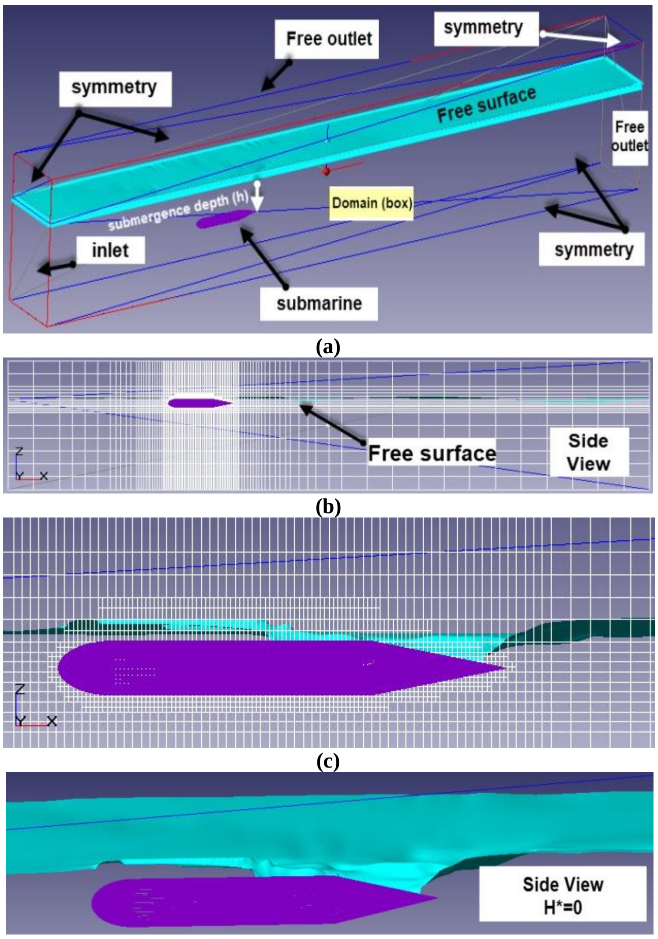
The parameter "h", is the depth from the free surface to the top of the hull, as showed in Fig.4.

Table 2. Simulation depth of Models

Model-A	Model-B
h	h

0	0	**0**	0
0.5D	0.3	**0.25D**	0.05
D	0.6	**0.6D**	0.12
1.5D	0.9	**1D**	0.2
2.8D	1.7	**1.5D**	0.3
3.5D	2.1	**2.5D**	0.5
4.5D	2.7	**3.5D**	0.7
6.5D	3.9	**4.5D**	0.9
infinite	Without free surface	**6.5D**	1.3
		20D=L	4
		infinite	Without free surface
		infinite	Without free surface

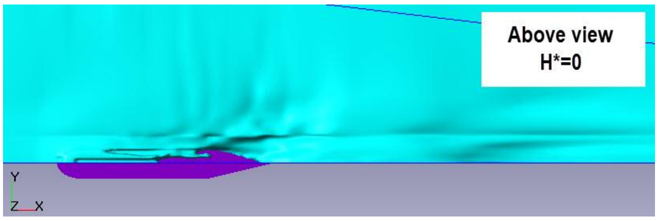
The domain as shown in Fig.7, has inlet (with uniform flow), Free outlet, Symmetry (in the four faces of the box) and Wall (for the body of submarine). Dimensions of cubic domain are constant for Model-A and B with 50m length (that frontal distance of the model is 12.5 m), 6m beam and 10m height (7m for water depth and 3m for air). Pay attention to that only half of the body is modeled because of axis-symmetric shape, and the domain is for that. Meanwhile, the study has shown that the beam and height more than 10D in this study can be acceptable. The base model of analysis is "Free surface" with the method of "Volume of Fluid" and turbulence model is K-Epsilon and minimum y^+ is considered equal to 30. The considered fluid is fresh water in 20 degrees of centigrade and constant velocity of 5 m/s. Free surface modeling is shown in Fig.7.



(a)

(b)

(c)



(d)

Figure 7: (a) Domain and structured grid (b) tiny cell around free surface (c)Very tiny cells near the wall for boundary layer modeling and keeping y+ about 30 (d) Half modeling because of axis-symmetry and free surface variations

5. CFD Results and Analysis

The modeling of these two models is represented:

Model-A) The geometrical specification of this model is presented in Tab.1. Total resistance in each depth is shown. Viscous resistance is constant at all depths because it is depended on the viscosity, velocity, form and wetted area which all of them are constant at all depths. By increasing the depth, total resistance, decreases until the fully submerged depth, that the free surface effect eliminates and total resistance, remains constant. To ensure that fully submerged condition is provided, a modeling without free surface is performed in Flow Vision, which can simulate the infinite depth modeling. Last row in Tab.3 shows the deeply submerged resistance that contains only viscous resistance. This value is constant at all depths, and only wave resistance, varies in every depth.

As mentioned in Fig.1: **Wave resistance= Total resistance - Viscous resistance.**

Table 3: Resistance of Model-A in several depths

Depth	Rt (N)	Rv (N)	Rw (N)	Rr/Rt (%)
0	906	410	496	54.7
0.5D	864	410	454	52.5
D	500	410	90	18.0
1.5D	450	410	40	8.9
2.8D	434	410	24	5.5
3.5D	426	410	16	3.8
4.5D	410	410	0	0.0
6.5D	410	410	0	0.0
infinite	410	410	0	0.0

Diagrams of Fig.8, shows the values of the total, viscous and wave resistance in all depths. It is obvious that total resistance and wave resistance in H*=0, are the largest values. By increasing the depth, wave resistance decreases and because of that, total resistance decreases. After a certain depth, wave resistance, eliminates completely and after this depth, total resistance remains constant. It is "fully submerged depth".

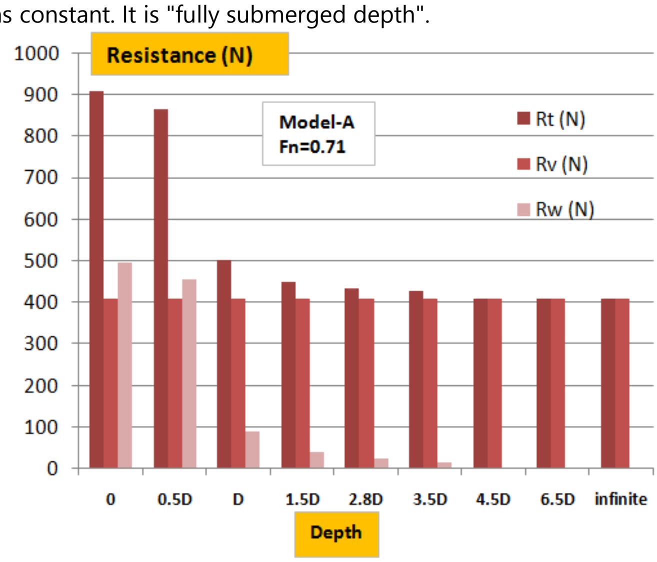


Figure 8. Diagrams of each part of resistance for Model-A

The variations of total resistance versus depth for Model-A, in Fig.9, shows that fully submerged depth is happened in H*=4.5 or h=4.5D. A sharp decline in resistance is happened from just near surface (H*=0) to the H*=1 which wave resistance decreases by 80%. It is "Milestone depth". Milestone depth in Model-A is at H*=1 or h=D or h=0.12L.

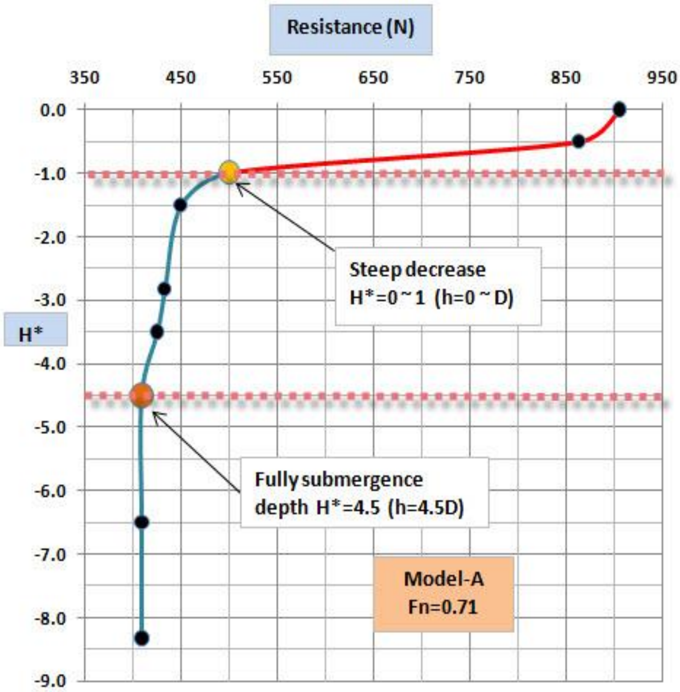


Figure 9. Variations of total resistance versus depth in Model-A

Model-B) This model is a long model with high values of L/D. The geometrical specification of this model is presented in Tab.1. By increasing the depth, total resistance, decreases until the fully submerged depth. To ensure that fully submerged condition is provided, a modeling without free surface is performed in Flow Vision and is shown in the last row in Tab.4.

Table 4: Resistance of Model-B in several depths

Depth	Rt (N)	Rv (N)	Rw (N)	Rr/Rt (%)
0	240	102	138	57.5
0.25D	218	102	116	53.2
0.6D	210	102	108	51.4
1D	182	102	80	44.0
1.5D	134	102	32	23.9
2.5D	110	102	8	7.3
3.5D	106	102	4	3.8
4.5D	102	102	0	0
6.5D	102	102	0	0
20D=L	102	102	0	0
infinite	102	102	0	0

As mentioned before, diagrams of Fig.10, shows the values of the total, viscous and wave resistance in all depths. Total resistance and wave resistance in H*=0, are the largest values. By increasing the depth, wave resistance decreases.

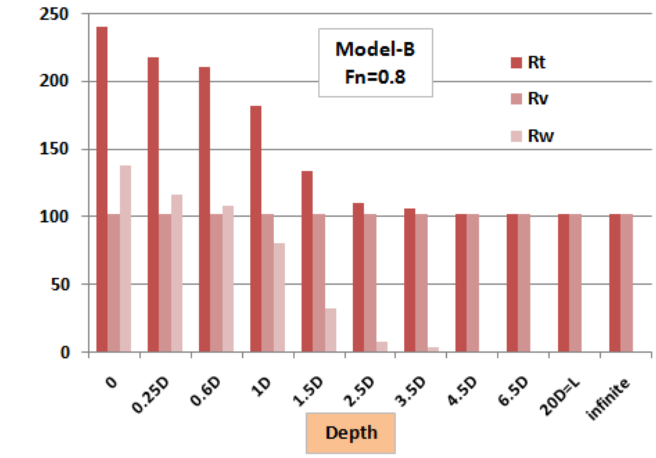


Figure 10. Diagrams of each part of resistance for Model-B

The variations of total resistance versus depth for Model-B, in Fig.11, shows that fully submerged depth is happened in H*=4.5 or h=4.5D. A sharp decline in resistance (Milestone depth) is happened at H*=2.5 which wave resistance decreases by 95%. Milestone depth in Model-B is at H*=2.5 or h=2.5D or h=0.125L.

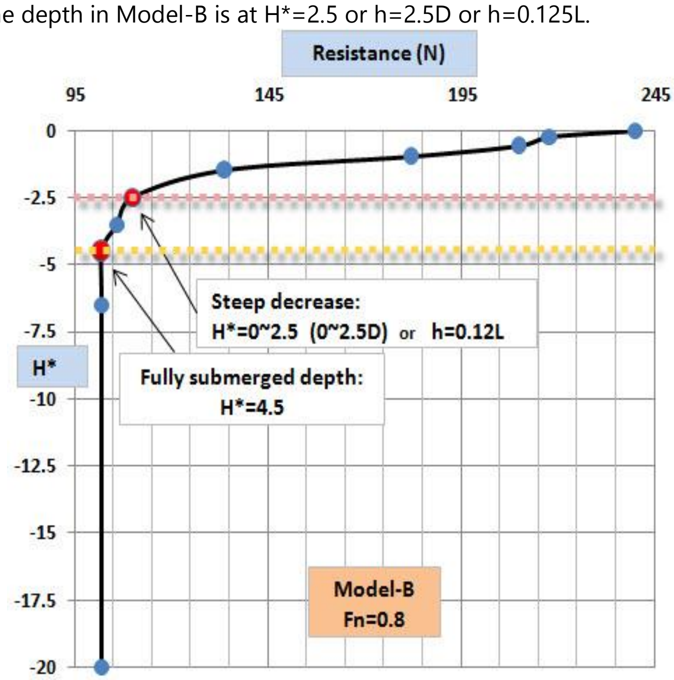


Figure 11. Variations of total resistance versus depth in Model-B

In comparison with the results of Model- A and B these can be derived that: 1) Model-A has a normal value of L/D but Model-B is a long vehicle with large values of L/D. 2) Froude numbers of Models A and B are 0.71 and 0.8 respectively that show high Froude number condition of modeling. Froude numbers in Refs.[16-18] is in the range of 0.13~0.66 that means low Froude numbers in the range of the hump and hollow of the wave resistance diagram. 3)Fully submerged depth for both models are equal to 4.5D for high Froude numbers. It is independent of the L/D value of the model. This value in Refs.[16-18] for low Froude number is earned equal to 2.8D (or 3.3D from the free surface to the centre line of the body). 4)Milestone depth for both models is obtained equal to 0.125L. It seems that "Milestone depth" can't be stated as a function of "D", but as a function of "L" because this value is dependent on the L/D ratio. For long vehicles, it happens later. For model-A equal to 1D and for model-B equal to 2.5D but the criterion of 0.125L can be used for all values of L/D.

6. Conclusion

General results of this paper is graphically shown in Fig.12 and for high Froude numbers (more than 0.7) such as torpedoes and high speed submarines, these can be stated as:

1) Flow Vision software can be used for free surface modeling.

2) In submergence depth, there are two important depths: "Milestone depth" that wave resistance decreases more than 80% and "Fully submerged depth" that wave resistance is eliminated completely.
3) First advise for submarines and torpedoes is moving in the depth more than fully submerged depth, or at least, in the depth between milestone depth and fully submerged depth. Generally, the more depth is equal to less resistance.
4) The ratio of L/D is important in the statement of Milestone depth but is not an essential parameter.
5) Froude number is an important parameter in the evaluation of submergence depth. The characteristics are different for ordinary values (Fn<0.5) and high values (Fn>0.7).
6) Fully submerged depth for high Froude numbers is equal to 4.5D.
7) Milestone depth for high Froude numbers is equal to 0.125L.

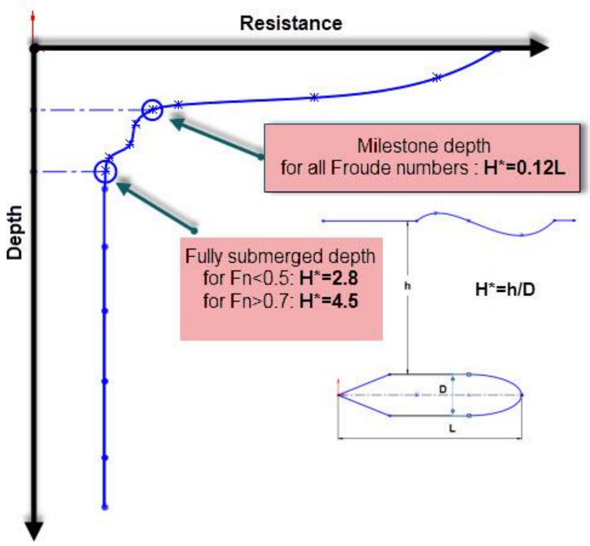


Figure 12. Milestone and Fully submergence depth in high and low Froude numbers

Nomenclature

C_f	Friction resistance coefficient
Cw	Wave making resistance coefficient
C_R	Residual resistance
C_t	Total resistance coefficient
CFD	Computational Fluid Dynamics
D	maximum diameter of the outer hull (m)
EFD	Experimental Fluid Dynamics
Fn	Froude number- $Fn = v/\sqrt{g.L}$
h	Submergence depth (m)
H*	non-dimensional depth
IHSS	Iranian Hydrodynamic Series of Submarines
L	overall length of hull (m)
N	Semi period number
R	maximum radius of the outer hull (m)
Rt	Total resistance (N)
Rv	Viscous resistance (N)
Rw	Wave resistance (N)
S	Wetted surface area (m^2)
v	Speed of submarine (m/s)
ρ	Water density (kg/m^3)
λ	Wave length (m)

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