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CFD analysis of the bow shapes of submarines

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Abstract This paper discusses about an optimum hydrodynamic shape of the bow of submarine in minimum resistance point of view. Submarines have two major categories for hydrodynamic shape: tear drop shape and cylindrical middle body shape. Here, submarines with parallel (cylindrical) middle body are studied because, the most of naval submarines and ROVs have cylindrical middle body shape. Every hull shape, have three parts: bow, cylinder and stern. There is not conning tower (sail) or any other appendages in this analysis. This paper wants to propose an optimum bow shape by CFD method and Flow Vision software. Major parameters in hydrodynamic design of the bow of naval submarines are the noise field (flow noise around the sonar and acoustic sensors) and the resistance. The focus of this paper is on the resistance at fully submerge mode without free surface effects. Firstly, important parameters of arrangement inside the bow of naval submarines, which affect the bow form, are discussed. Secondly, for understanding the concepts of bow design, all available shapes for the bow shapes of submarines are represented in the samples of applications in the really naval or historic submarines. Thirdly, for all shapes, CFD analysis has been done. In all models, these parameters are constant and only the bow shape varies: the velocity, dimensions of domain, dimensions of submarine; diameter, stern shape and the total length (bow, middle and stern length).

Keywords CFD, naval, submarine, hydrodynamic, resistance, optimum, shape, bow.

Introduction

There are some rules and concepts about submarines, and submersibles shape design. There is an urgent need for understanding the basis and concepts of shape design. Submarine shape design is strictly depended on the hydrodynamics such as other marine vehicles and ships. Submarines are encountered to limited energy in submerged navigation and because of that, the minimum resistance is vital in submarine hydrodynamic design. In addition, the shape design is depended on the internal architecture and general arrangements of submarine. Convergence between hydrodynamic needs and architecture needs is vital for determination of overall shape design of submarine. The hull structure of submarine has two main categories: pressure hull and light hull. Pressure hull, provides a dry space in atmospheric pressure for human life, electric and other devices that are sensitive to the humidity and high pressures. Light hull, provides a wetted space for the devices which can sustain the pressure of the depth of the ocean. Submarines have two modes of navigation: surfaced mode and submerged mode. In surfaced mode of navigation, the energy source limitation is lesser than the submerged mode. Therefore, in really naval submarines, the base of determination of the hull form, is the submerged mode. Submarines have two major categories for hydrodynamic shape: tear drop shape and cylindrical middle body shape. In this paper, submarines with parallel (cylindrical) middle body are studied because, the most of naval submarines and ROVs have cylindrical middle body shape. Naval submarine shape design with regarding the hydrodynamic aspects has been designed [1,2]. There is the basis of submarine shape selection with all aspects such as general arrangement, hydrodynamic, dynamic stability, flow noise and sonar efficiency [3-4]. Earlier reported literature [5] contains a lot of scientific materials about naval submarine hull form and appendage design with hydrodynamic considerations. Some studies about submarine hull form design with minimum resistance by CFD method are also performed by Moonesun M *et al* [6-11]. Special discussions about naval submarine shape design are presented in Iranian Hydrodynamic Series of Submarines (IHSS) [7, 12]. Some case study discussions about the hydrodynamic effects of the bow shape and overall length of the submarine by CFD method are presented [13-14]. Defense R&D Canada, has suggested a hull form equation for bare hull, sailing and appendages [15-16] as the name of "DREA standard model". An equation has been presented for teardrop hull form with the limitations of their coefficients [17-19], but the main source of their equation is presented in [20] and the simulation of the hull form with different coefficients is also described [21].

Other equations for torpedo hull shape are reported [22]. Formula "Myring" as a famous formula for axisymmetric shapes has been described [23]. Extensive experimental results about hydrodynamic optimization of teardrop or similar shapes are presented [24] as a main reference book in the field of the selection of aerodynamic and hydrodynamic shapes based on experimental tests. A collective experimental study on the shape design of the bow and stern of the underwater vehicles are presented and based on the underwater missiles but the most parts of this book [25], is practicable in naval submarine shape design. Another experimental study of the several teardrop shapes of submarines are presented [26-28], all equations of hull form, sailing and appendages are presented with experimental and CFD result for SUBOFF project. Bow of submarine, plays some roles in submarine hydrodynamic design, specially stagnation point (location and pressure) that forms the boundary layer on the overall of the body. The focus of this paper is on the resistance at fully submerge mode without free surface effects. In addition to the hydrodynamic, the shape of the bow, depends on the internal architecture and arrangements inside the bow part.

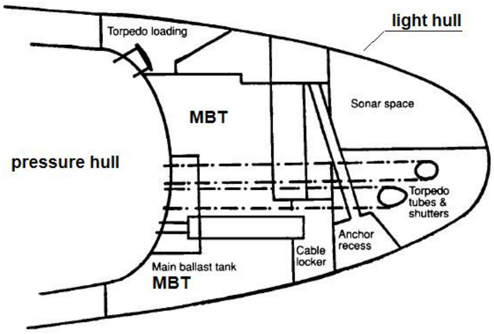
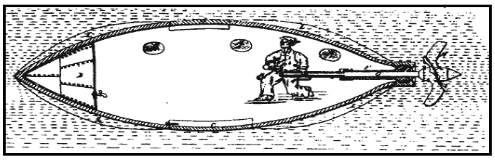


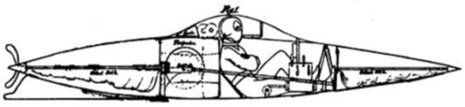
Figure 1: Typical bow arrangement [3]

Figure 1 shows a usual internal arrangement inside the bow part of submarine that limits and forms the shape of the bow. Related materials about general arrangement in naval submarines are presented [3-4]. According to figure 1, the bow part, is composed of pressure hull (fore compartment) and light hull. The light hull, is a steel hull with a small thickness (compare to the pressure hull) that can be formed easily. The curvature of the bow shape should be acceptable for arranging all equipment with reasonable clearance for accessibility and repairing. The most part of the bow is occupied by main ballast tank (MBT) which needs a huge volume inside the bow but doesn't affect the bow shape because only the absolute volume is important.

Passive sonar occupies a big volume that is vital for submarine navigation, therefore, can strongly affect the bow shape. Several torpedo tubes, are the next important parts for arranging inside the bow. The resultant shape, should have the minimum resistance. The focus of this paper is on the curvature of the bow for minimizing the resistance. Figure 2 shows some bow shape of submarines.



Ogive shape bow- Philips submarine (1852)

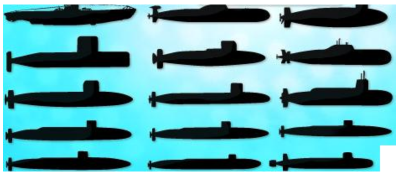


Conic shape bow- J.Holland (1874)

Ship shape bow- German submarine (U-Boat) (1941)

Conic-elliptic bow- Astute Class Nuclear Submarine (1977)

Elliptic bow shape- Le Terrible class submarine (2010)



Today modern submarines

Figure 2: Some bow shape of submarines

Some important factors in bow form design

For a well judgment and the best selection of bow form, the most important factors in the bare hull form design are counting as: 1) minimum flow noise specially around sonar and acoustic sensors. 2) minimum submerged resistance 3) general arrangement demands specially for Main Ballast Tanks (MBT) and torpedo tube arrangement. The focus of this paper is on the curvature and the shape of the bow for minimizing the resistance.

Bow form equations

As mentioned in "Introduction", there are several sources about equations of bow form, which will be presented here. Extensive hull form equations of submarine are presented [31].

A) The equations are presented as "DREA Model" that is shown in Fig.3 and includes the specification of bare hull and appendages. The DREA model is specified in three sections; bow, midbody and tail [15-16]. The fineness is L/D=8.75 so that bow length is equal to 1.75D and midbody length is 4D and stern length is 3D. Axisymmetric profile of the bow is:

$$\frac{r}{D} = 0.8685\sqrt{\frac{x_F}{D}} - 0.3978\frac{x_F}{D} + 0.006511\left(\frac{x_F}{D}\right)^2 + 0.005086\left(\frac{x_F}{D}\right)^3 \qquad (1)$$

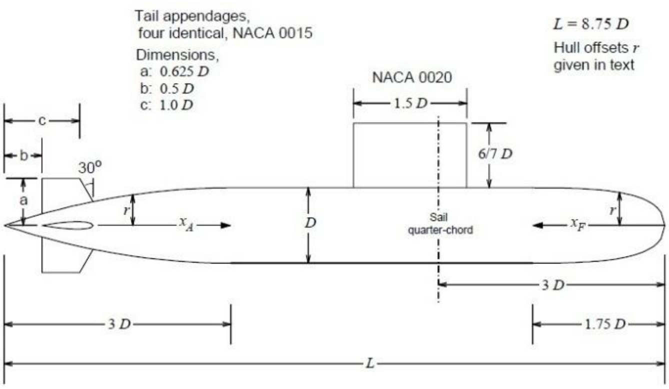


Figure 3: Parameters of DREA submarine hull [15]

B) The equations are presented as "Hull Envelope Equation". The envelope is first developed as a pure tear drop shape with the fore body comprising 40 percent of the length and after body comprising the remaining 60 percent [17-21]. The forward body is formed by revolving an ellipse about its major axis and is described by the following equation:

$$Y_f = R\left[1-\left(\frac{X_f}{L_f}\right)^{n_f}\right]^{1/n_f} \qquad (2)$$

The quantity Y_f is the local radius of the respective body of revolution with X_f describing the local position of the radius along the body (figure 4). For n_f=2; the bow shape profile is an elliptic form, and for n_f=1; the bow profile is a conical form. If a parallel middle body is added to the envelope, then cylindrical section with a radius equal to the maximum radius of the fore and after the body is inserted in between them.

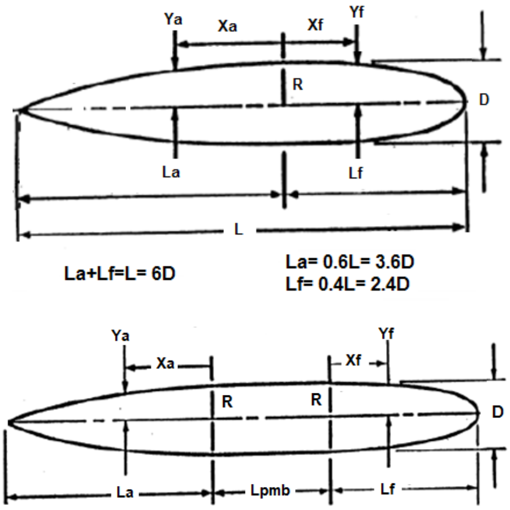


Figure 4: Coordinates and parameters in submarine hull

This equation is rewritten to another face [18, 30-31] for another coordinate origin (figure 5), and the shape optimization is done for snorkeling in snorkel depth.

$$r_f = R\left(1-\left(\frac{(x-L_a-L_c)}{L_f}\right)^{n_f}\right)^{1/n_f} \qquad (3)$$

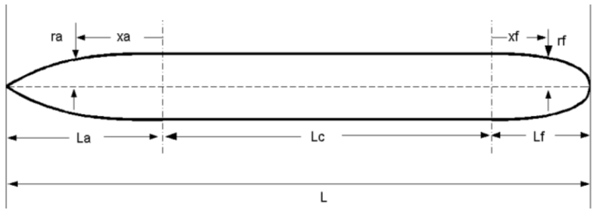


Figure 5: Coordinates and parameters in submarine hull

The simulation of the hull form with different coefficients is presented in figure 6.

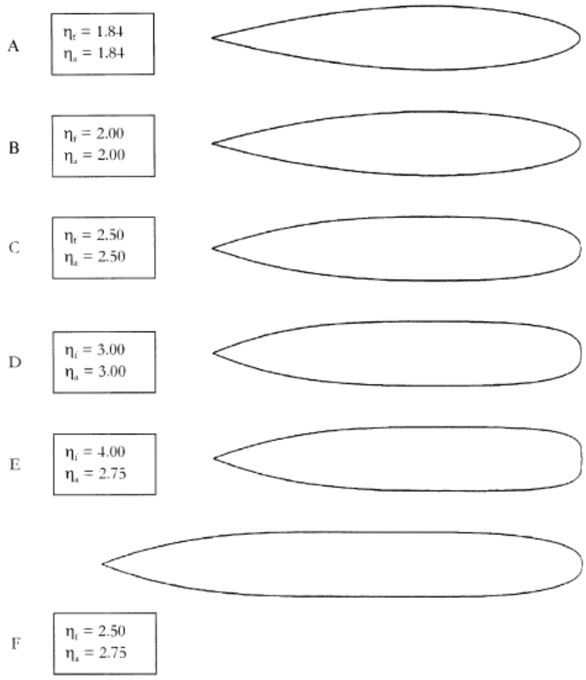


Figure 6: Hull form with coefficients of na, nf [21]

C) The equations are presented as "Myring Equations" for earning minimum resistance, and many submarines, AUVs and UUVs are designed according to these equations such as REMUS [22] which describes a body contour with a minimal drag coefficients for a given fineness ratio (maximum length to the maximum diameter). The parameters "a,b,c,d,θ" are shown in figure 7. Parameter "n" is an exponential parameter which can be varied to give different body shapes [22-23]. These equations assume an origin at the nose of the vehicle. Nose shape is given by the modified semi-elliptical radius distribution.

$$r(\Xi) = \frac{1}{2} d \left[1 - \left(\frac{\Xi + a_{\text{offset}} - a}{a} \right)^2 \right]^{\frac{1}{n}} \tag{4}$$

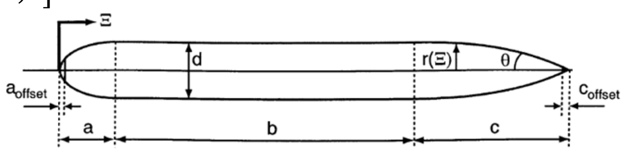


Figure 7: Myring profile

D) The equations are presented as "SUBOFF Model" from Defence Advanced Research Project Agency (DARPA) that is shown in figure 8 with coordinate location. Two geometrically identical models are designed to a linear scale ratio of 24 with detailed equations and shape specifications for computer programming and modeling in CFD and experimental model test [26-27]. Extensive hydrodynamic results are presented [28].

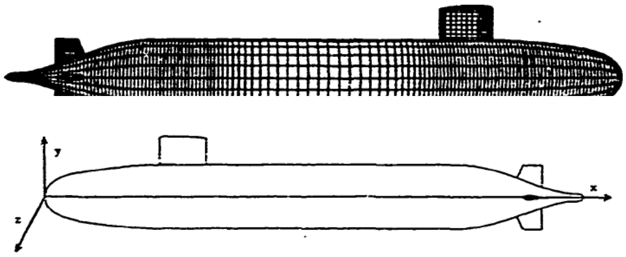


Figure 8: SUBOFF hull and coordinate [27]

Bow equation in 0<x<3.333 (ft) is:

$$r = R\{1.126395101x(0.3x-1)^4 + 0.442874707x^2(0.3x-1)^3 + 1 - (0.3x-1)^4(1.2x+1)\}^{1/2.1} \quad (5)$$

Specifications of the models

The base model that considered here; is an axis-symmetric body similar to torpedo, without any appendages because in this study, only bow effect on resistance, is wanted to be studied. It helps to quarterly CFD modeling of the body and saving the time. The stern is conical and middle part is a cylinder, but bow part is different in each model. In this paper, 19 models are studied. The 3D models and its properties are modeled in Solid Works. There are three main assumptions:

Assumptions 1: For evaluating the hydrodynamic effects of the bow, the length of the bow is unusually supposed large. It helps that the effects of bow be more visible.

Assumptions 2: The shapes of the stern and middle part are constant in all models. Stern shape is a conical shape, and middle shape is a cylindrical shape.

Assumptions 3: For providing more equal hydrodynamic conditions, the total length, bow, middle and stern lengths are constant. The diameter is constant too. Thus, L/D is constant in all models. These constant parameters, provide equal form resistance with except the bow shape which varies in each model. Then, the effects of bow shape, can be studied. Therefore, every model has different volume and wetted surface area.

Dimensions and speed of all models are mentioned in table 1.

Table 1: Main assumptions of models

V (m/s)	L (m)	L_f (m)	L_m (m)	L_a (m)	D (m)	L/D	bow shape
10	6	3	1	2	1	6	Different for each model

Table 2: Models of stage A

	bow shape profile	Aw	A0	volume
A1	ogive	12.77	0.785	2.58
A2	ogive- capped with circle	13.19	0.785	2.67
A3	conic	11.16	0.785	2.09
A4	conic caped with elliptic	14.41	0.785	3.03
A5	ship shape	13.85	0.785	2.49
A6	hemisphere	15.8	0.785	3.53
A7	elliptical	13.87	0.785	2.88
A8	DREA form (according to Eq.1)	15.19	0.785	3.33

The analysis is performed in two stages: Stage A) General shapes of bow for understanding the basis and principles of submarine bow design. Stage B) Bow shape based on the Eq.2 for different values of nf. This equation is a well-known and well practice equation that covers a wide range of bow forms. The specifications of all models are represented in table 2 and 3. In table 2, there is modeling of stage A, and table 3 included modeling of stage B. In addition, for CFD modeling in all models, velocity is constant and equal to 10 m/s that results Reynold's number of more than 60 millions. This Reynolds is suitable for turbulence modeling because

M.Moonesun proved that total resistance coefficient after Reynolds of five millions can be supposed constant [11].
The forms of these models are shown in figure 9. In the model A1, bow is an ogive shape, consist of an ogive section of a circle so that be tangent to the cylinder. Model A2 is an ogive shape that is capped by a circle. This shape is usual in small wet submarines. Model A3 has a conic bow that is not usual in submarines but for understanding that, why this bow is not applicable in today submarines, are represented. Model A4, has a conical bow that is capped by an elliptic so that, the elliptic and conic are tangent together. Model A5, has a ship shape bow with a vertical sharp edge. This shape of the bow is unusual in today submarines because this bow shape is efficient for ships and free surface of water. This bow has minimum resistance in surfaced navigation but has a large amount of resistance in submerged navigation. It was usual in old submarines because those had a little battery storage and then, the most time of navigation had performed on the surface, and only for attacking had gone to submerged mode of navigation for a restricted time. Models A6 and A7 have a hemispherical and elliptical bow. Hemispherical bow is not a common practice bow but elliptical bow, is the most usual form of the bow. Most of the equations that mentioned above, are similar to elliptical bow, for example, in Eq.2, for nf=2, the bow shape profile is an elliptic form. Model A8 is designed according to Equation.1 for DREA submarine. The configurations of these models are presented in Fig.3.

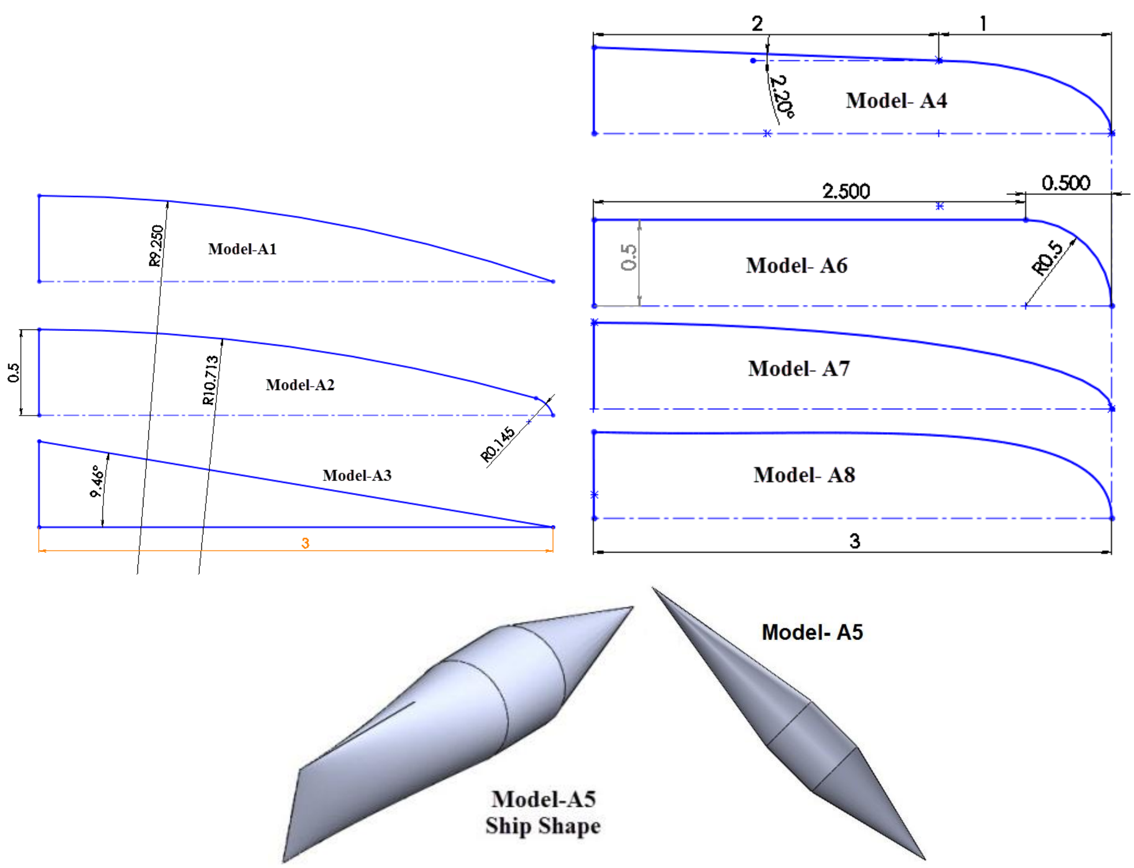


Figure 9: Configuration of models (stage A)

In table 3, some profiles of the bow are presented, based on Equation (2). As showed in Fig.10, the values of nf, can be varied between 1.8~4 but for better understanding the effect of nf, the range of 1~5 are considered. For nf=2, the bow shape profile is an elliptic form, and for nf=1, the bow profile is a conical form. Increasing in nf is equivalent to increase in wetted surface area and enveloped volume. The configurations of these models are presented in figure 10.

Table 3: Models of stage B according to Eq.2

	nf	Aw	A0	volume
B1	**1**	11.16	0.785	2.09
B2	**1.15**	11.79	0.785	2.26
B3	**1.35**	12.48	0.785	2.45
B4	**1.5**	12.9	0.785	2.58
B5	**1.65**	13.25	0.785	2.68
B6	**1.75**	13.45	0.785	2.75
B7	**1.85**	13.63	0.785	2.8
B8	**2**	13.87	0.785	2.88
B9	**2.5**	14.48	0.785	3.08
B10	**3**	14.87	0.785	3.21
B11	**4**	15.36	0.785	3.37
B12	**5**	15.64	0.785	3.46

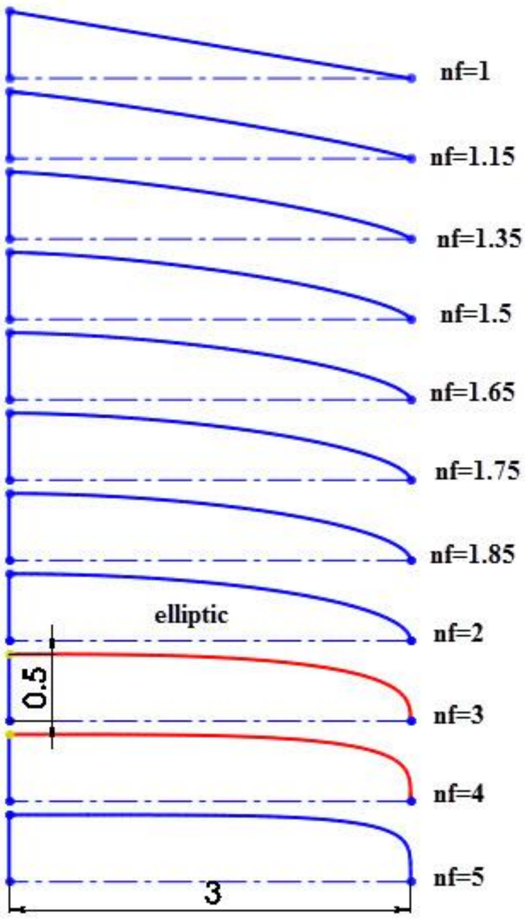


Figure 10: Configuration of models (stage B)

Preparations of CFD analysis

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 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. The mesh dimensions near the object, should be so tiny that can cover the boundary layer variation. Transition of laminar layer to the turbulent layer in boundary layer, and flow separation is a very important factor in resistance calculations. Two significant parameters in CFD, for modeling the boundary layer, are Y^+ and mesh numbers, which should be selected correctly. For selecting the proper quantity of the cells, for one certain model (Model.A7) and v=10m/s, eight different amount of meshes were selected and the results remained almost constant after 1.2 millions meshes, and it shows that the results are independent of meshing (Fig.11). In all modeling the mesh numbers are considered more than 1.7 millions.

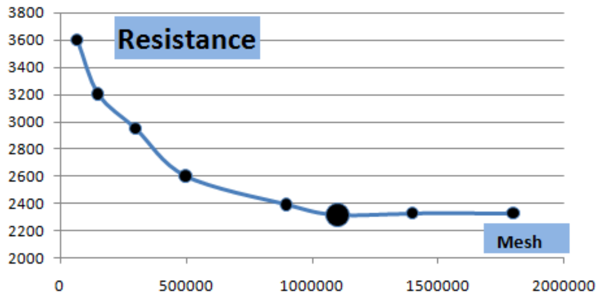
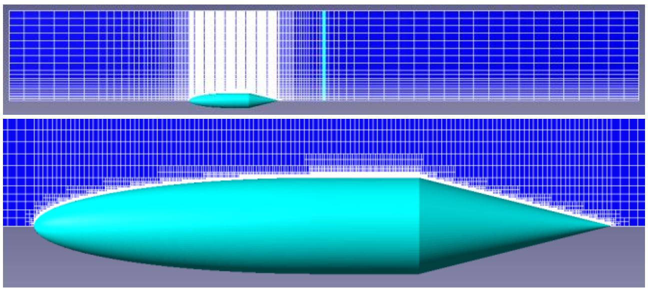
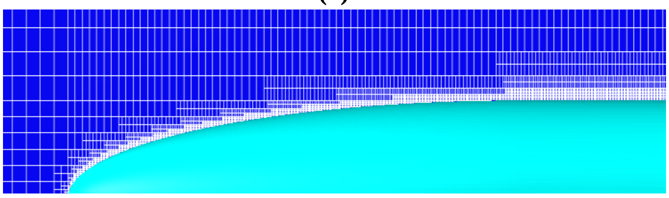


Figure 11: Mesh independency evaluations

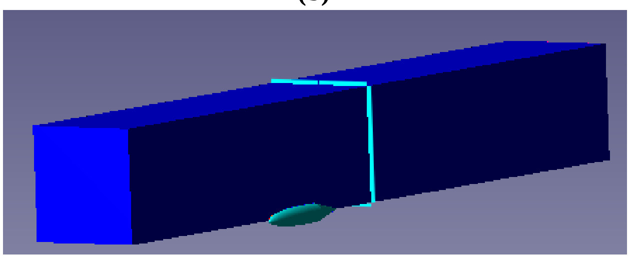
For the selection of suitable iteration, it was continued until the results were almost constant with variations less than one percent, which shows the convergence of the solution. All iterations are continued to more than one millions. In this domain, there is inlet (with uniform flow), Free outlet, Symmetry (in the four faces of the box) and Wall (for the body of submarine). Dimensions of cubic domain are 42m length (equal to 7L), 6m beam and 6m height (equal to L or 6D). Only quarter 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 equal to 6D in this study can be acceptable. Here, there are little meshes in far from the object. The forward distance of the model is equal to 2L and after distance is 4L and the total length of 7L (Fig.12). The turbulence model is K-Epsilon and y^+ is considered equal to 30. The considered flow is incompressible fluid (fresh water) in 20 degrees centigrade and constant velocity of 10 m/s.

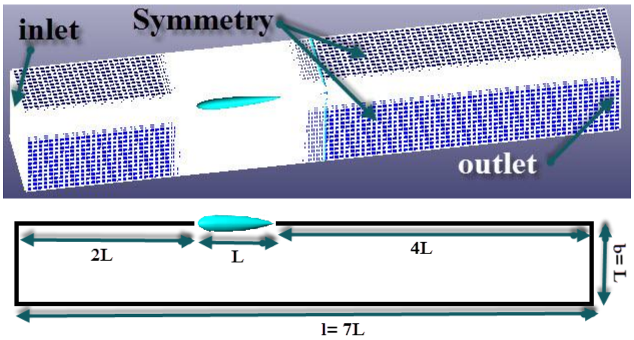


(a)



(b)





(c)

Figure 12: (a) Domain and structured grid (b) Very tiny cells near the wall for boundary layer modeling and keeping y+ about 30 (c) Quarterly modeling because of axis-symmetry

CFD Analysis

In this paper, the main goal is estimation of the resistance. The total resistance of a fully submerged submarine is composed of frictional resistance and viscous pressure resistance, but there is not wave resistance. The frictional resistance depends on the wetted area, and viscous pressure resistance depends on the form of the object. Here, for optimization of the bow shape, both of these resistances are needed because in a given length, by changing the bow shape, the wetted area and the form will be changed. These values are presented in table 4 and 5.

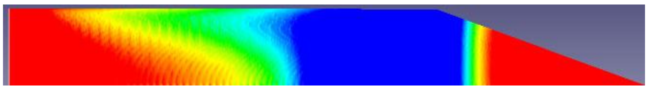
Table 4: Resistance components of Models in stage (A)

bow shape	R	Rvp	Rf	Rvp/R
ogive	1948	292	1656	15.0
ogive-circle	2036	348	1688	17.1
conic	1944	452	1492	23.3
conic-elliptic	2416	608	1808	25.2
ship shape	2488	660	1828	26.5
hemisphere	3280	1360	1920	41.5
elliptical	2336	620	1716	26.5
canadian form	2624	800	1824	30.5

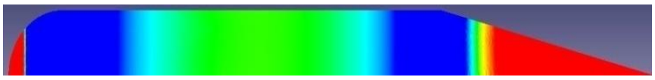
Table 5: Resistance components of Models in stage (B)

nf	Rt	Rvp	Rf	Rvp/Rt (%)
1	1944	452	1492	23.3
1.15	1820	276	1544	15.2
1.35	1876	284	1592	15.1
1.5	1952	316	1636	16.2
1.65	2060	344	1716	16.7
1.75	2200	452	1748	20.5
1.85	2264	500	1764	22.1
2	2196	424	1772	19.3
2.5	2388	556	1832	23.3
3	2724	872	1852	32.0
4	3052	1204	1848	39.4
5	3368	1512	1856	44.9

Pressure resistance depends on the pressure distribution over the body, and pressure distribution depends on the form. The more uniform pressure distribution meant lesser resistance. The pressure distribution for several shapes is presented in figure 13. Ships shape bow, is not a good design for fully submerged condition (without free surface), thus, it can be seen in figure 13-a, that high pressure area encompassed the most parts of the bow. It causes the high value of resistance. Hemispherical bow is a blunt and thick bow. Therefore, there is a very intense high pressure area on the tip of the bow, as shown in figure 13-b. It causes a very high value of resistance. The elliptical bow, as shown in figure 13-c, has almost uniform distribution of pressure, which can result in lesser value of resistance. The pressure on the hull will be imposed on the volume of fluid about it, as shown in figure 13-c.

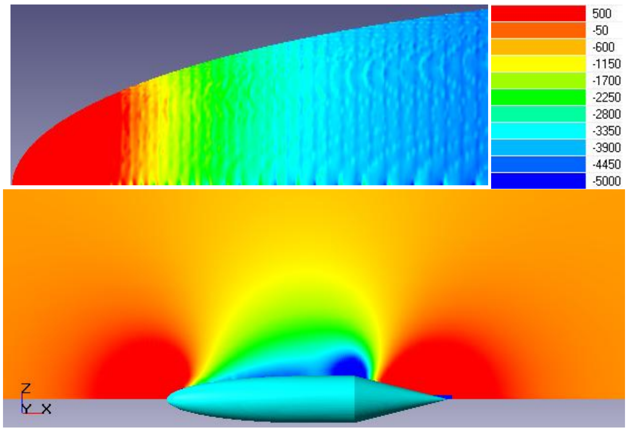


(a) Model A-5: ship shape bow



(b) Model A-6: hemisphere bow

(c) Model A-7: elliptical bow



(d) Contours of pressure and related values

Figure 13: Pressure distribution over the body

The results of CFD analysis in stage "A" is presented in table 5 and diagrams of figure 14.

In table 5, C_d, is resistance coefficient based on wetted area (Aw) but Cv, is resistance coefficient based on $(\text{volume})^{2/3}$ that can describe the effect of earned volume in every shape.

The formula is:

$$Cv = \frac{R}{0.5.\rho.v^2.V^{\frac{2}{3}}} \quad (6)$$

As mentioned before, there are several parameters, which affect the bow shape design such as resistance and volume. Another coefficient that can describe both parameters is "Semnan" so as:

$$Semnan\ coefficient\ (Ksn) = \frac{(Volume\ )^{\frac{1}{3}}}{Resistance\ \ Coefficient} \quad (7)$$

This coefficient can be named "Hydro-Volume" efficiency, because it counts both resistance and volume. For this coefficient, the bigger values meant the better design. In some cases, a shape has minimum resistance but has a little volume in a given constant length. Thus it can't be a good selection (such as Model A3 and A5). These diagrams are presented in figure 14.

According to this figure 14 a & b, conic bow shape has the least values of wetted area and volume but hemispherical bow shape, has the most values of them. In figure 14-c, resistance diagram, it is obvious that in a given length, hemispherical bow has the most values, and conic bow has the least

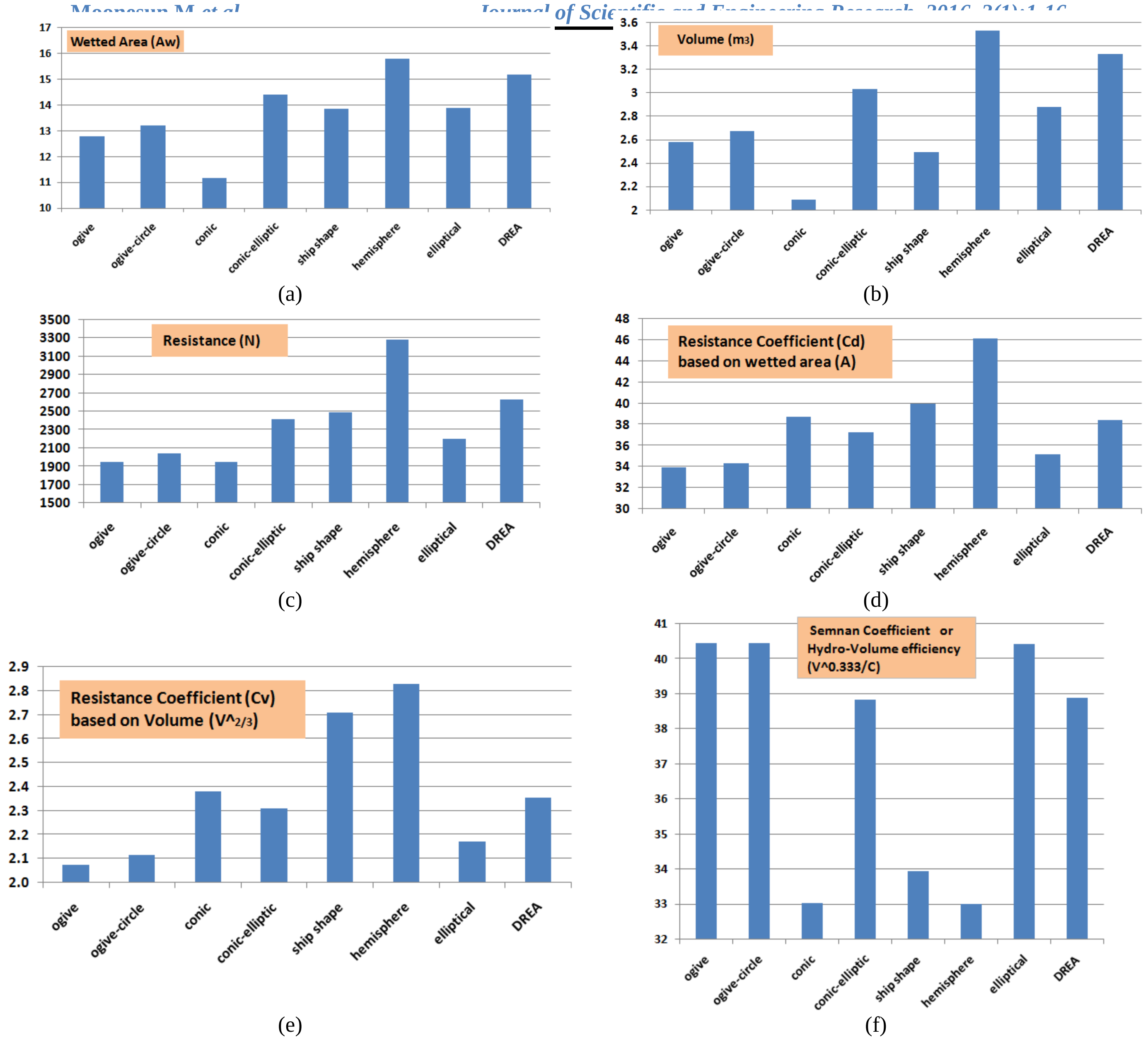
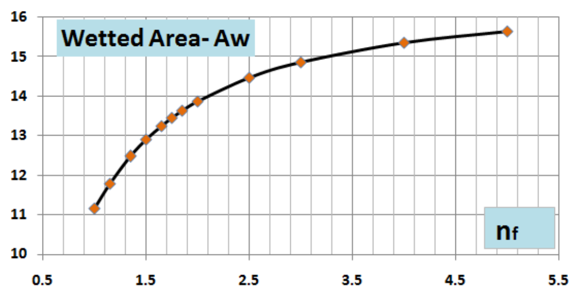


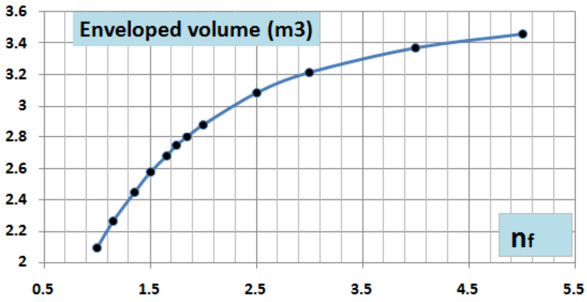
Figure 14: Results of CFD analysis on different bow shape (stage A)

values. Resistance coefficient based on wetted area is shown in Fig.14-d, which shows, hemisphere bow and ship shape bows have the most (worst) values. ogive bow has the least (best) value and elliptical and conic elliptical bows, have the middle values of the resistance coefficients. Resistance coefficient based on volume (Figure 14-e) shows that, the hemisphere and ship shape bows have the most (worst) values, and ogive bow has the least (best) value. Finally, the figure 14-f, represents the best criterion for judging between the bow shapes. This figure shows that ogive shape has the most efficiency and conic, hemisphere and ship shape bow, have the least (worst) values. Now we can select a good bow shape. As shown in figure14, the bow shapes of conic, hemisphere and ship shape, are the worse selection in resistance and volume point of view. Hemisphere bow has the most values of resistance coefficient and resistance, while provides a good space for architecture but figure14-f, showed that hemisphere bow can't be a good selection. Conic shape results the minimum values of resistance and middle values of resistance coefficients but has the minimum volume in a given length; then conic bow can't be a good selection, as it was shown in figure 14-f with minimum efficiency. Ship shape bow has high values of resistance coefficient and resistance with low value of volume. Therefore it has a very low efficiency in figure14-f, and is rejected for selection. Ogive and ogive capped with the hemisphere, have the minimum values of resistance coefficients and low values of resistance. Ogive bow seems to has a good condition in resistance aspect of view but isn't a good selection because it has low values of volume. This bow has steep frontal curvature that isn't a good configuration for arranging the sonar and torpedo tubes in the front of really naval submarines. Thus ogive bow is rejected despite the maximum values of efficiency in figure 14-f and minimum values of the resistance coefficients. Finally, three remained bows can be discussed as a good selection: elliptical, conic elliptical and DREA form. These three bows have almost similar results. DREA form has more resistance and resistance coefficient compare to other two bows, but has better efficiency in figure14-f, thus can be a good selection. Generally elliptically bows are recommended.

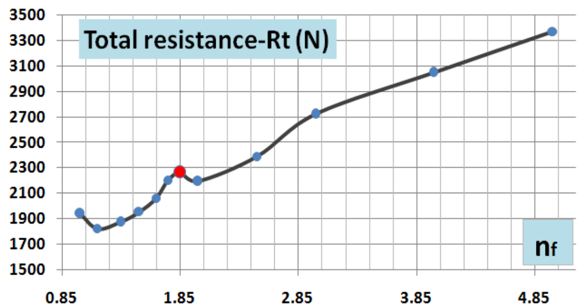
The result of CFD analysis in stage "B" is presented in table 6 and diagrams of figure15.



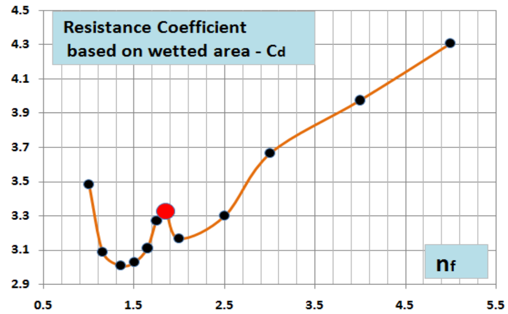
(a)



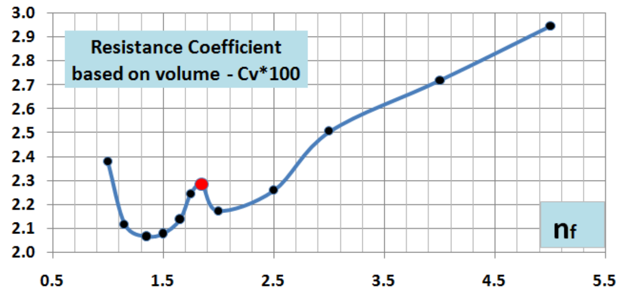
(b)



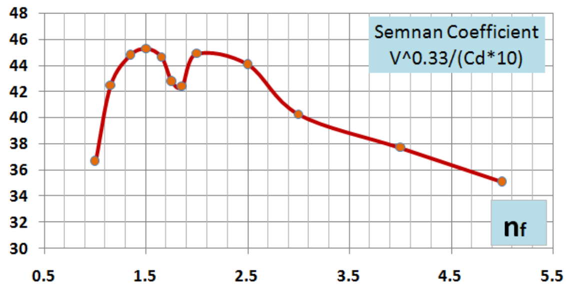
(c)



(d)



(e)



(f)

The focus on this stage, is on the Equation 2 by variation in the values of nf. This equation, covers a wide variety of bow profiles, thus the focus of this paper in stage B, is concerned to it. As showed in figure 15, the values of nf, can be varied between 1.8~4 but for better understanding the effect of nf, the range of 1~5 are considered. For nf=2, the bow shape profile is an elliptic form, and for nf=1, the bow profile is a conical form. Increasing in nf is equivalent to increase in wetted surface area and enveloped volume. In this paper, the range of nf=1.35~2 is studied more because this range has some extremum points. The variations after nf=2, is approximately linear, and the values less than n=1.35 aren't common practice in naval submarines. An overview on the results shows that, in this range, nf=1.85 has maximum resistance and resistance coefficient, and minimum efficiency coefficient that means the worst results. The total resistance diagram shows that n=1.15 has minimum value and nf=1.85 has the most value. Bow shape according to nf=1.15, is a sharp bow that is not suitable in architecture point of view. Diagrams in Fig.15-d and 15-e, that are resistance coefficients, which show that nf=1.35 has the minimum (best) values, and nf=1.85 has the maximum (worst) values. Diagram "f" in figure 15 is the most important parameter for judging between them. This diagram shows that around nf=1.65 and 2.5, there are local maximum points, which meant good selections for design, especially in nf=2.5 that has maximum hydro-volume efficiency (Semnan coefficient). Values around nf=1.75~1.85, show the local minimum points which must be avoided in design.

Table 6: Specification of Models in stage (B)

nf	Rt	Aw	Cd*1000	V/(Cd*10)	Cv*100
1	1944	11.16	3.484	59.99	2.38
1.15	1820	11.79	3.087	73.20	2.11
1.35	1876	12.48	3.006	81.49	2.07
1.5	1952	12.9	3.026	85.25	2.08
1.65	2060	13.25	3.109	86.19	2.14
1.75	2200	13.45	3.271	84.06	2.24
1.85	2264	13.63	3.322	84.28	2.29
2	2196	13.87	3.167	90.95	2.17
2.5	2388	14.48	3.298	93.38	2.26
3	2724	14.87	3.664	87.62	2.51
4	3052	15.36	3.974	84.80	2.72
5	3368	15.64	4.307	80.34	2.95

According to these diagrams, some formulas can be fitted to them. The formula of relation between resistance coefficient (Cd) and nf is:

For 1.15<nf<2:

$$C_d = (-11.85.n_f^4 + 70.31.n_f^3 - 153.73.n_f^2 + 146.62.n_f - 48.48) * 10^{-3} \qquad (8)$$

Conclusion

In this paper, a study of the equations of bow form of submarines and CFD analysis on them, has been performed. These are the most famous equations in submarine form design. For a well judgment and the best selection of the bow form, the most important factors in bow form design must be counted such as: minimum flow noise specially around sonar and acoustic sensors, minimum submerged resistance and general arrangement and volume demands. The focus of this paper is on the CFD analysis of submerged resistance by Flow Vision software. This study has shown that:

1) "Semnan Coefficient" can be presented as a important parameter in submarine shape design that counts both parameters: resistance coefficient and volume. It can be named "hydro-volume efficiency".

2) Conic bow and ship shape bow aren't a good design because of high values of resistance coefficients and very low values of hydro-volume efficiency.

3) Simple hemispherical bow isn't a good selection in design because of high values of resistance coefficients and the least value of hydro-volume efficiency. This form is not recommended at all.

4) Ogive bow shape has a good result in resistance coefficient and hydro-volume efficiency, but this shape isn't a common practice in really naval submarines because of many difficulties in internal arrangements of the bow.

5) Elliptical bow and other shapes similar to that, have the best acceptable results in resistance coefficients and hydro-volume efficiency. This shape of the bow, is highly recommended.

6) The coefficients around nf=1.75~1.85 may have the worse results, but the coefficients around nf=1.65 and 2.5 are good selections for design, especially in nf=2.5 that has maximum hydro-volume efficiency.

Nomenclature

A0	Cross section area (m^2)
Aw	Wetted surface area (m^2)
Cd	Resistance coefficient based on wetted area
Cv	Resistance coefficient based on volume
D	Maximum hull diameter (m)
K_{sn}	Semnan coefficient
L	Maximum hull length (m)
La	Length of stern (m)
Lf	Length of bow (m)
Lm	Length of middle part (cylindrical) (m)
n_f	Bow coefficient in Eq.2
n_a	Stern coefficient

R Hull radius (m)
Rt Total resistance in (N)
r (Y) Radial coordinate of hull (m)
x Longitudinal coordinate of hull (m)
V Volume of body in (m3)
v velocity in (m/s)

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