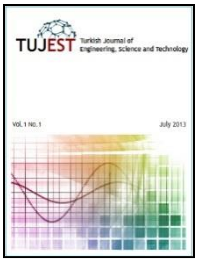
Turkish Journal of Engineering, Science and Technology 01 (2015) 11-19

Turkish Journal of Engineering, Science and Technology

journal homepage: www.tujest.com



Power Series Optimization for Submarine bare hull Form

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Article Info

Article history:
Received Sep 29, 2014
Accepted Dec 27, 2014
Available online Mar 02, 2015

Keywords:
Submarine,
hull,
form,
shape,
hydrodynamic,
power series,
resistance.

Abstract

This paper presents the best form of submarine bare hull according to power series equations for minimizing the resistance. There are several types of hydrodynamic form of submarines which the most famous equations are "power series" equations. In these formulas, there are two coefficients which affect the submarine bow and stern form. This paper, has studied the several forms by changing these coefficients, and CFD analysis are performed on these shapes for achieving the minimum resistance. In this paper, only bare hull form are studied without appendages. Bare hull has three main parts: bow, cylinder and stern. This analysis is performed by Flow Vision (V.2.3) software based on CFD method and solving the RANS equations.

1. Introduction

There are some rules and concepts about submarines and submersibles shape design. There is 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 are vital for determination of overall shape design of submarine.
Submarine have two modes of navigation: surfaced mode and submerged mode. In surfaced mode of navigation, the energy source limitation is lesser than submerged mode. Therefore, in real naval submarines, the base of determination of the hull form, is submerged mode. The several parts of submarine are bare hull and sailing. The parts of bare hull are the bow, middle part and stern. In some forms, there is not middle body part, thus bare hull is direct connection of bow to the stern. The focus of this paper is on this type of bare hull.

Refs [1,2] are the main references that describe the notes of naval submarine shape design with regarding the hydrodynamic aspects. In Refs [3], there are the basis of submarine shape selection with all aspects such as general arrangement, hydrodynamic, dynamic stability, flow noise and sonar efficiency. Ref.[4] contains a lot of scientific materials about naval submarine hull form and appendages design with hydrodynamic considerations. Some studies about

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submarine hull form design with minimum resistance by CFD method is done in Ref [5-10] by M.Moonesun and colleagues. Special discussions about naval submarine shape design are presented in Iranian Hydrodynamic Series of Submarines (IHSS)[6,11]. In Ref[12,13] some case study discussions about the hydrodynamic effects of the bow shape and overall length of the submarine by CFD method are presented. Defence R&D Canada, suggested a hull form equation for bare hull, sailing and appendages [14,15] as the name of "DREA standard model". Refs.[16-18] presents an equation for teardrop hull form with the limitations of their coefficients but the main source of their equation is presented in Ref.[19], and the simulation of the hull form with different coefficients is presented in Ref.[20]. Other equation for torpedo hull shape is presented in Ref[21]. Formula "Myring" as a famous formula for axisymmetric shapes is presented in Ref.[22]. Extensive experimental results about hydrodynamic optimization of teardrop or similar shapes are presented in Ref.[23] as a main reference book in the field of the selection of aerodynamic and hydrodynamic shapes based on experimental tests. A collective experimental study about the shape design of bow and stern of the underwater vehicles are presented in Ref [24] that are based on the underwater missiles but the most parts of this book, is practicable in naval submarine shape design. Another experimental studies on the several teardrop shapes of submarines are presented in Ref.[25]. In Refs[26,27], all equations of hull form, sailing and appendages are presented with experimental and CFD result for SUBOFF project.

2. Some important factors in bare hull form design

Bare hull, is an outer hydrodynamic shape that envelopes the pressure hull. For a well judgment and the best selection of bare hull form, the most important factors in bare hull form design are counting as: 1) minimum submerged resistance: the ratio L/D and bow shape are the important factors. Demand for minimum resistance in submerged navigation is versus surfaced navigation but in submarine resistance calculation, the main criterion is submerged mode. Optimization of submarine shape, based on minimum resistance is represented in Refs.[28,29] with a logical algorithm. Optimization of shape based on minimum resistance in snorkel depth is shown in Ref.[30]. Optimization of shape in surface condition (such as ships) is not regarded because in new modern submarines with using high storage batteries or nuclear storage or fuel cells, there isn't any need to surfacing, and air suction is done by snorkel mast in snorkel depth. 2) general arrangement demands specially for D. 3) enough volume for providing enough buoyancy according to given weight. 4) minimum flow noise specially around sonar and acoustic sensors. 5) minimum cavitation around propeller. 6) suitable for single hull or twin hull: in single hull submarine, there is almost cylindrical pressure hull, and hydrodynamic envelope there is only in the bow and stern parts. In twin hull submarine, hydrodynamic envelope (light hull), envelopes the pressure hull, totally. The shape demands of these two kinds of hull are different.

There are two main parameters which affect the submarine shape design: resistance and volume. The coefficient that can describe both parameters is "Semnan" coefficient:

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

This coefficient can be named "Hydro-Volume efficiency", because it counts both resistance and volume. For this coefficient, the more values mean 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.

3. Bare hull form of power series equations

According to Refs.[16-20], the equations are presented as "Hull Envelope Equation". The envelope is first developed as a pure tear drop shape with the forward body comprising 40 percent of the length and the after body comprising the remaining 60 percent [18]. The forward body is formed by revolving an ellipse about its major axis and is described by the following equation:

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

The after body is formed by revolving a line around axis and is described by:

$$\mathrm{Y_a} = \mathrm{R}\left[1-\left(\frac{\mathrm{X_a}}{\mathrm{L_a}}\right)^{\mathrm{n_a}}\right] \qquad (3)$$

The quantities Y_a and Y_f are the local radius of the respective body of revolution with Xa and Xf describing the local position of the radius along the body (Fig.1). If parallel middle body is added to the envelope, then cylindrical section with a radius equal to the maximum radius of the fore and after body is inserted in between them. The local radii represent the offsets for drawing the submarine hull and also determine the prismatic coefficient for the hull section. The prismatic coefficient (Cp) is a hull form parameter for fullness and is the ratio of volume of the body of revolution divided by the volume of a right cylinder with the same maximum radius. For an optimum shape, the fore and after bodies will have different values for Cp. Cp is used to determine the total hull volume by the following relation:

$$\text{Volume} = \frac{\pi D^2}{4}\left[3.6DC_{pa} + \left(\frac{L}{D} - 6\right)D + 2.4DC_{pf}\right] \qquad (4)$$

Where the added term (L/D-6)D accounts for the volume of the parallel middle body where Cp=1. The surface area for the body can be described by the following relation:

$$\text{Wetted Surface} = \pi D^2\left[3.6DC_{sa} + \left(\frac{L}{D} - 6\right)D + 2.4DC_{sf}\right] \qquad (5)$$

Surface coefficient (CS), describes the ratio of the surface area of the body to the surface area of a cylinder with the same maximum radius. The factors n_f and n_a in equations, describe the "fullness" of the body by affecting the curvature of the parabolas. The range of these parameters, regarded for sample, represented in Fig.2. These equations are rewrited to another face in Refs.[17,29,30] for another coordinate origin (Fig.3).

$$r_a = R\left(1 - \left(\frac{(L_a - x)}{L_a}\right)^{n_a}\right) \qquad (6)$$

$$r_f = R\left(1 - \left(\frac{(x - L_a - L_c)}{L_f}\right)^{n_f}\right)^{1/n_f} \qquad (7)$$

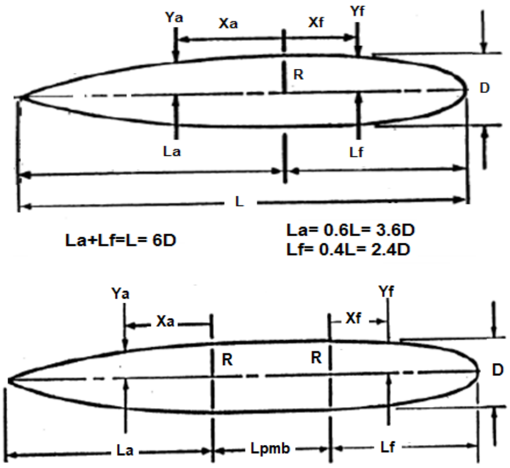
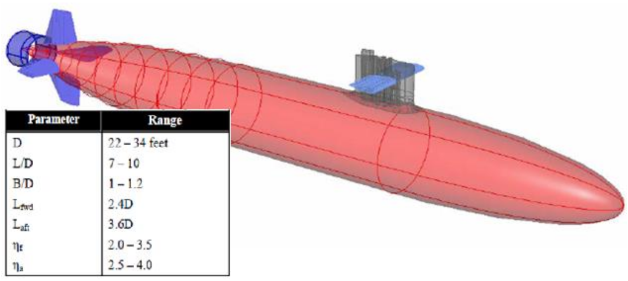


Fig. 1: Coordinates and parameters in submarine hull



Parameter	Range
D	22 – 34 feet
L/D	7 – 10
B/D	1 – 1.2
L_{fwd}	2.4D
L_{aft}	3.6D
η_f	2.0 – 3.5
η_a	2.5 – 4.0

Fig. 2. A sample of hull form according to power series form with values of n_a, n_f [20]

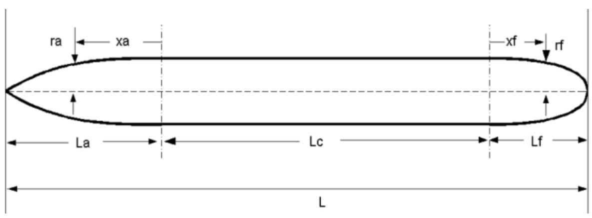


Fig 3. Coordinates and parameters in submarine hull

4. 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 bare hull effect on resistance, wants to be studied. It helps to quarterly CFD modeling of the body and saving the time. The bow and stern form in each model, change with the nf and na. Middle part is a cylinder. In this paper, 19 models are studied. The 3D models and its properties are modeled in Solid Works (Fig.4). For evaluating the hydrodynamic effects of bare hull, the length of stern, middle, bow and total length are constant. The L/D ratio is constant too, because the maximum diameter is constant. Therefore, every model has different volume and wetted surface area. The Tab.1 contains these assumptions. The specifications of all 11 models are presented in Tab.2.

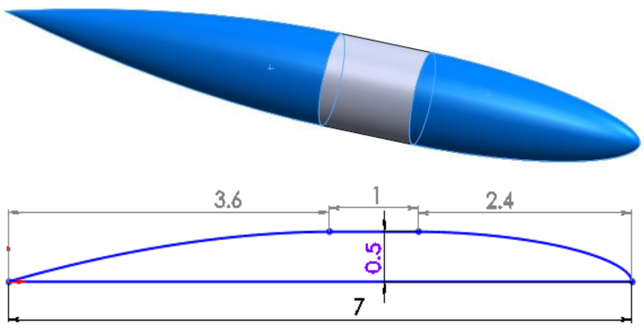


Figure 4: General configuration of the models

Table 1: Main assumptions of models

v (m/s)	L_t (m)	L_f (m)	L_m (m)	L_a (m)	D (m)	L_t/D	A_0 (m2)
10	7	2.4	1	3.6	1	7	3.14

Table 2: Specifications of 11 Models

Model	specification of Model	Aw	V
1	nf=1.35, na=1.35	14.6	2.89
2	nf=1.35 , na=1.85	15.45	3.15
3	nf=1.35 , na=4	17.18	3.71
4	nf=1.5 , na=1.5	15.22	3.07
5	nf=1.85 , na=1.85	16.37	3.43
6	nf=2 , na=2	16.57	3.49
7	nf=2.5 , na=2.75	18.03	3.96
8	nf=3 , na=3	18.55	4.13
9	nf=3.5 , na=3.5	19.1	4.31
10	nf=4 , na=2.75	18.76	4.19
11	nf=4 , na=4	19.53	4.44

Wetted surface area (Aw) is used for the resistance coefficient and the total volume is used for "Semnan" coefficient. Total volume is different and is represented in fourth column. In addition, for CFD modeling in all models, velocity is constant and equal to 10 m/s. This velocity is selected so that the Reynolds number be more than five millions because in ref.[19] it was proved that total resistance coefficient after Reynolds of five millions can be remained constant. Configurations of all models are represented in Fig.5. In every model, the coefficients, nf and na change. The coefficient nf, varies the bow form, and na, varies the stern form.

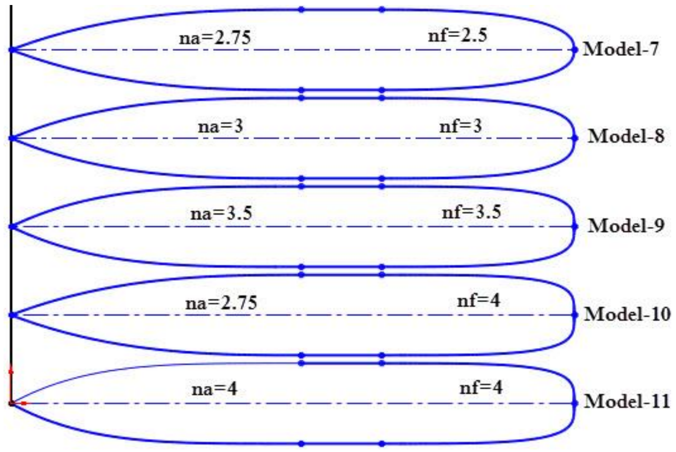


Figure 5: Configurations of Models

5. 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 one certain model (nf=1.35, na=1.35) and v=10m/s, seven 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 1.2 millions.

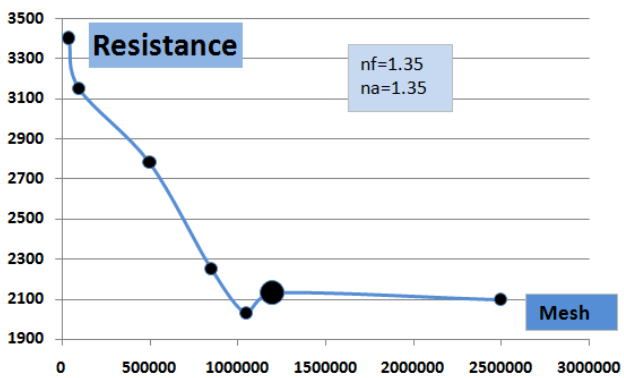


Figure 6: Mesh independency evaluations

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. 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 49m length (equal to 7L), 7m beam and 7m height (equal to L or 7D). Pay attention to that 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 7D 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 in the total length of 7L (Fig.7). 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.

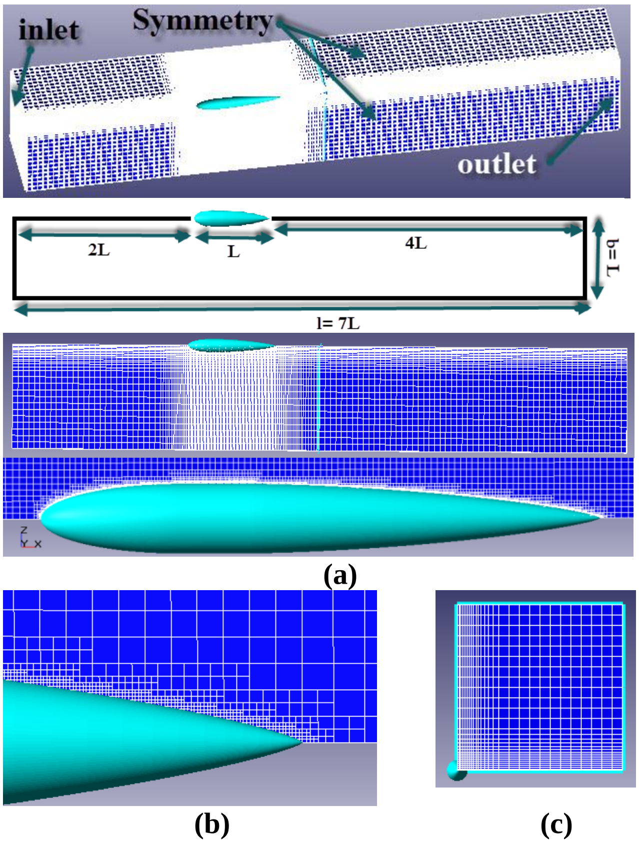


Figure 7: (a) Domain and structured grid (b) Very tiny cells near the wall for boundary layer modeling and keeping y+ about 30 (c) Quarterly modeling because of axis-symmetry

6. CFD Results Analysis

The results of analysis are represented in Tab.3 and Fig.8. According to these results, total resistance increases with increase in fullness of body and coefficients of nf and na.

Table 3: Resistance, resistance coefficients and Semnan coefficients of models

Model	R	Ct*10000	Semnan Coef./10
1	2128	29.15	48.85
2	2220	28.74	50.99
3	2456	28.59	54.12
4	2236	29.38	49.45
5	2512	30.69	49.12
6	2584	31.19	48.61
7	3012	33.41	47.33
8	3388	36.53	43.90
9	3696	38.70	42.03
10	3812	40.64	39.65
11	3944	40.39	40.67

Resistance coefficient (based on wetted area surface), similar to resistance diagram, has an upward trend with numbers of models, but there is an local minimum value for Model 3 (nf=1.35, na=4). It means that, for constant wetted surface area, the bare hull form of nf=1.35 and na=4, has the best results and minimum resistance. For selecting a good shape form of submarine, enough volume should be provided, thus Semnan coefficient is very important.

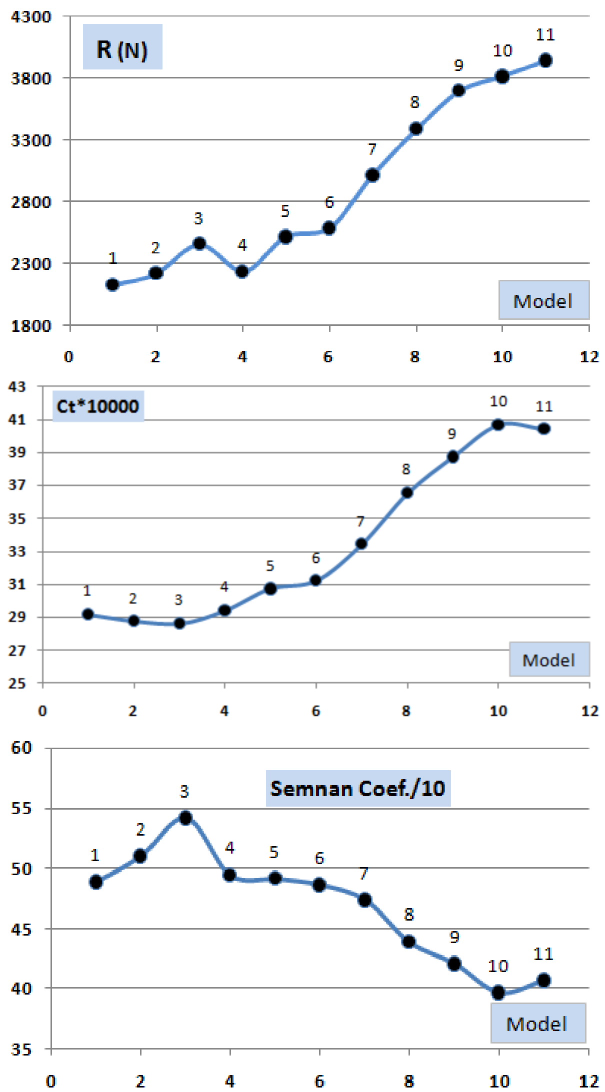


Figure 8: Resistance, resistance coefficients and Semnan coefficients of models

According to last diagram of Fig.8, Semnan coefficient diagram, has downward trend but there is a local maximum point in Model 3, that shows a good form of this model. It seems that Model 3 (nf=1.35, na=4), be a good selection, because it has a maximum value in Semnan coefficient and a minimum value in resistance coefficient that shows the best condition and ideal form. But in real naval submarines, the form of Model 3, cannot be a good selection because of sharpness of bow shape and internal arrangements problems. For better arrangement in the bow and stern, the blunt, thick and bulky form is ideal. For hydrodynamic form, more the thin form is ideal, thus in hydrodynamic point of view, Model 3 has the best form.

7. Conclusion

Submarine bare hull form selection is a very important stage in submarine design. There are several parameters which take part in the form design such as: minimum resistance (hydrodynamic notes), general arrangement, enough volume for providing enough buoyancy, minimum flow noise, minimum cavitation around propeller, suitable for single hull or twin hull. Hydrodynamic and minimizing resistance has a unique and important role in naval submarine form design, because it causes to more speed, more duration at the depth of the water and thus, more range of navigation. According to the studies of this paper, the Model 3 by nf=1.35 and na=4, has the best results. These diagrams show that, the more blunt and thick form (more value of nf and na), causes steep increase in resistance coefficient values. The exact needed values of nf and na, depend on the other parameters of design, which mentioned above.

NOMENCLATURE

Cs	Surface coefficient
Cp	Prismatic coefficient
D	maximum diameter of the outer hull
IHSS	Iranian Hydrodynamic Series of Submarines
L	overall length of hull
La	Length of aft (stern)
Lf	Length of forward part (bow)
nf	Coefficient of fore (bow) part of bare hull
na	Coefficient of aft (stern) part of bare hull
R	maximum radius of the outer hull
xa	X from stern
xf	X from bow
Ya	Y from axis in bow
Yf	Y from axis in stern

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