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Concepts in submarine shape design

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This paper uses CFD method for analysis of six different models of submarines. The resistance coefficients of each shape are presented and compared so that could understand the reason of submarine shape selection with tapered stern and curved bow. Focus of this paper is on the cylindrical middle body submarine such as the most of naval submarines and ROVs. Determination of diameter and length of submarine is related to the L/D ratio that is somewhat discussed here by CFD modeling. The tools of CFD modeling is Flow Vision (v.2.3) software that is known as a skilled software in CFD modeling.

[Key world: *Submarine, Hydrodynamic, CFD, Resistance, Shape, Form***]**

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. Technical discussions about submarine hydrodynamic design were done in Ref. books [1,2,3,4,5,6,7&8] and Ref. papers [9,10,11,12,13,14,15&16]. In addition, the shape design is depended on the internal architecture and general arrangements of submarine. Related materials about general arrangement in naval submarines are presented in[1,2,3,4&17] and discussions about general shape of submarines there are in[18,19,20,21]. Convergence between hydrodynamic needs and architecture needs are vital for determination of overall shape design of submarine.

Submarines have two major categories for hydrodynamic shape: tear drop shape and cylindrical middle body shape. Tear drop shape has a lot difficulties in construction and cost but has unique advantages in hydrodynamics. Most real naval submarines and ROVs have cylindrical middle body shape, for example, the basic shape in IHSS series is based on the cylindrical middle body submarines[22,23]. 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 required power of propulsion engines is submerged mode. The focus of this paper is on resistance at fully submerge mode without free surface effects.

Materials and Methods

Specification of models

There are six models with torpedo shape without any appendages. For all models, according to Fig.1 there is a constant length equal to 10 meters, constant diameter equal to 2 meters and constant L/D equal to 5 but different volume. In all models, bow length is 2 meters, and stern length is 3 meters. Middle part is a cylinder with 5 meters length. Model 1 is a simple cylinder without a tapered bow and stern that shows the most resistance coefficient and the worst selection. Model 2 is a cylinder but with a conical stern. Model 3 is a cylinder but with an elliptical bow. Model 4 has a conical bow and stern. Model 5 has an elliptical bow and conical stern such as today submarines. Model 6 is similar to Model 5 but with a curved stern instead of conical stern. This curvature is provided by sector of a circle with radius of 5 meters. This sector is tangent to the cylinder without any discontinuity.

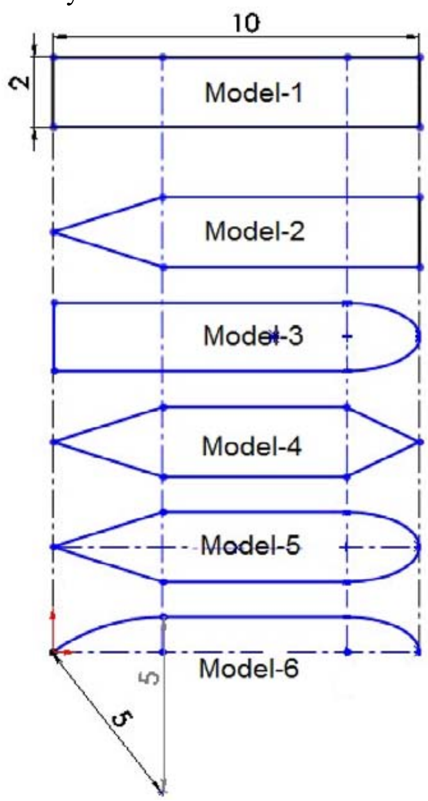

Fig. 1 — Shapes of six models

Provisions of Analysis

This analysis is done 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. The turbulence model is K-Epsilon and y^+ is considered equal to 50. The considered flow is incompressible fluid (fresh water) in 20 degrees centigrade.

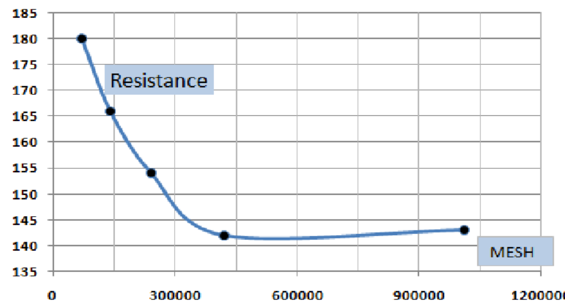

Fig. 2 — Mesh independency evaluations

For selecting the proper quantity of the cells, for one certain shape (Model 6 with v=1 m/s), five different amount of meshes were selected and the results were compared insofar as the results remained almost constant after 0.4 millions meshes, and it shows that the results are independent of meshing (Fig.2). In all modeling the mesh numbers are considered more than 0.6 millions. 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 that are depended on the amount of meshes. In this domain, there are inlet (with uniform flow), Free outlet, Symmetry (in the four faces of the box) and Wall (for the body of submarine). Dimensions of cubic half domain are 50m length (equal to 5L), 4m beam (half beam equal to 4R) and 8m height (equal to 8R). Pay attention that because of Axi-symmetric shape, the only half or quarter of body can be modeled. Meanwhile, the study has shown that the half beam equal to 4R can be acceptable. Here, there are little meshes in far from the object. The forward distance of the model is equal to L and after distance is 3L in the total length of 5L (Fig.3). For validation of the results, there aren't any experimental results but according to Ref.[24], the resistance coefficient for simple cylinder is 0.89 and according to CFD results, it is earned 0.81. It shows 8.9% difference and error, which can be acceptable in numerical methods. The range of velocity for modeling is selected on the base of Reynolds number. Ref.[25] showed that resistance coefficients after Reynolds 5 millions remain almost constant. Because of that, the velocities are so selected that 3 points before 5 millions, one point on the 5 millions and others, after that can be shown on the diagrams. The velocities in m/s are: 0.02, 0.05, 0.1, 0.5, 0.7, 1, 2 and 3.

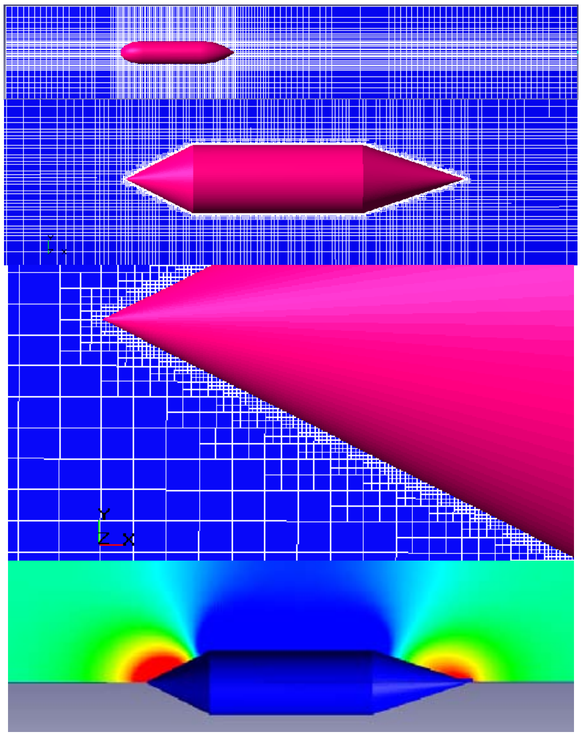
Fig. 3 — Modeling of domain, structured meshes and models of submarines

Results

The total resistance is equal to summation of frictional and pressure resistance. In Flow Vision software, the total resistance and pressure resistance is presented. Frictional resistance is equal to total resistance minus pressure resistance. Similar to this subject relies on coefficients. In Fig.4, the diagrams of total resistance versus Reynolds number are presented for all six models. All resistance coefficients are based on cross section area equal to 3.14 square meters. Logically, the first model has most resistance coefficient, and sixth model has a minimum coefficient but amount of differences between models are important and considerable. Attention on these differences can show the logic of submarine shape design. Now questions in these fields can be answered for example: Why we cannot use sharp shape for submarines? Why the stern should be conical? Why the bow should be curved? Why the curved stern is better than simple conical stern? and so on.

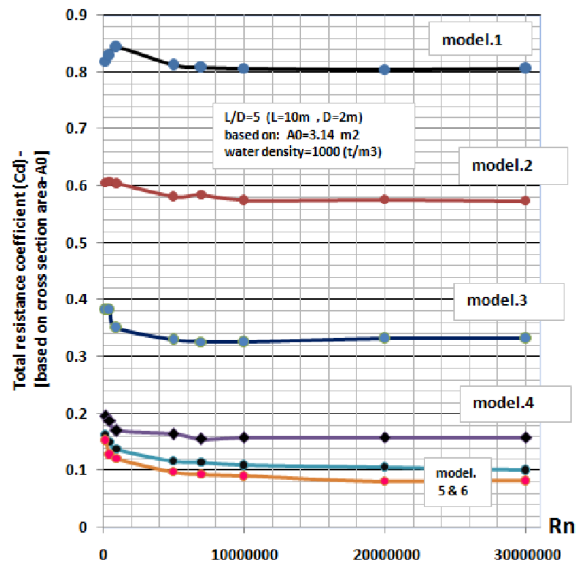

Fig. 4—Total resistance coefficients for six models

Diagrams of pressure resistance coefficient versus Reynolds numbers are presented in Fig.5. Pressure resistance is a function of the shape of the object (submarine) so that it names "form resistance". Here, assumption is inviscid fluid. Viscosity effect is regarded in friction resistance. As mentioned before, all coefficients after Reynolds 5 millions are almost constant.

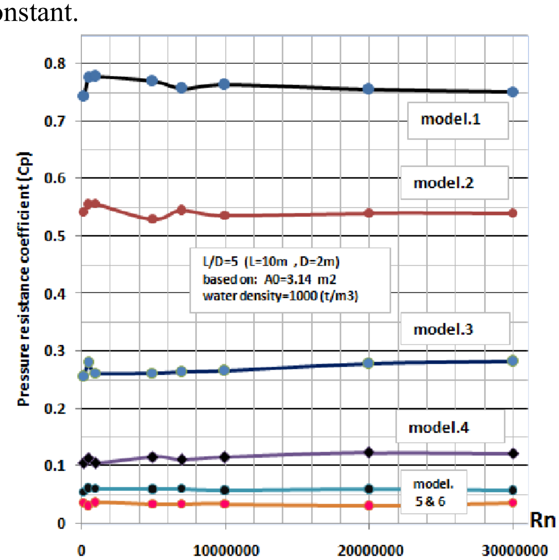

Fig. 5— Pressure resistance coefficients for six models

For better comparison between the coefficients, all total and pressure resistance coefficients are presented in Tab.1 &2.

Discussion

There are many huge different between the coefficients in model 1 and model 6. Ordinary shape of today submarines are similar to model 6, and this model is selected as a base model. With comparing these results, it can be understood the concepts of shape design of submarines. Table 3 shows the total resistance coefficients for all six models. Remember that L, D and then L/D for all models are constant. It shows that coefficient of model 1 is 10 times of model 6. By adding a conical stern in model 2, the resistance coefficient becomes 7.19 times of model 6 that means 28% lesser resistance from model 1. According to model 4, by adding a conical bow to model 2, the resistance becomes 80% lesser than model 2. It shows the important role of bow shape. By adding the elliptical bow to the simple cylinder, according to model 3, the resistance becomes 59% lesser than model 1. It shows that curved bow has a significant role in reducing the resistance. If the model has an elliptical bow with conical stern as model 5, the resistance coefficient becomes 70% lesser than model 3 and 88% lesser than model 1. Finally, the model 6, has the least resistance coefficient that shows the best design for the hull shape. Table 4 shows the comparison between pressure resistance coefficients. The intensities of variations of pressure resistance coefficients are more than viscose and total resistance.

Table 1 — Total resistance coefficients

V (m/s)	Rn	Model-1	Model-2	Model-3	Model-4	Model-5	Model-6
0.02	200000	0.819	0.605	0.382	0.195	0.162	0.153
0.05	500000	0.829	0.606	0.382	0.188	0.150	0.127
0.1	1000000	0.843	0.604	0.350	0.169	0.138	0.120
0.5	5000000	0.812	0.581	0.329	0.164	0.117	0.097
0.7	7000000	0.808	0.584	0.326	0.155	0.114	0.093
1	10000000	0.807	0.575	0.326	0.158	0.109	0.090
2	20000000	0.805	0.576	0.331	0.158	0.105	0.081
3	30000000	0.806	0.574	0.332	0.159	0.101	0.082

Table 2 — Pressure resistance coefficients

V (m/s)	Rn	Model-1	Model-2	Model-3	Model-4	Model-5	Model-6
0.02	200000	0.742	0.541	0.255	0.105	0.054	0.035
0.05	500000	0.776	0.555	0.280	0.114	0.061	0.031
0.1	1000000	0.778	0.557	0.262	0.106	0.060	0.036
0.5	5000000	0.770	0.530	0.262	0.116	0.059	0.034
0.7	7000000	0.757	0.545	0.264	0.111	0.060	0.034
1	10000000	0.764	0.535	0.266	0.116	0.058	0.034
2	20000000	0.756	0.540	0.278	0.123	0.059	0.031
3	30000000	0.752	0.540	0.283	0.123	0.057	0.036

Table 3—Comparison between total resistance coefficients

model	Ct	Times
Model-1	0.8	10
Model-2	0.575	7.19
Model-3	0.33	4.125
Model-4	0.16	2
Model-5	0.1	1.25
Model-6	**0.08**	**1**

Table 4—Comparison between pressure resistance coefficients

model	Cp	Times
Model-1	0.76	25.33
Model-2	0.54	18
Model-3	0.27	9
Model-4	0.12	4
Model-5	0.06	2
Model-6	**0.03**	**1**

Conclusion

Bow and stern of submarine should be tapered gradually (by comparison between models 1 and other models). Sharp narrow bow isn't a good selection, but a blunt shape such as an elliptical bow is recommended (by comparison between models 4 and 5). Curved stern is better than conical stern (by comparison between models 5 and 6). Effects of the bow on the resistance is strongly more than the effect of stern (by comparison between models 2 and 4). Curved bow (such as elliptical) and curved stern (such as a sector of circle or parabolic) with cylindrical middle part can be good recommendation for submarines and submersibles (by comparison between models 6 and other models).

Nomenclature

L	overall length of hull
D	maximum diameter of the outer hull
R	maximum radius of the outer hull
V	speed of water in m/s
A0	Cross section area of model= 3.14 m^2
Rn	Reynolds number
Ct	Total resistance coefficient
Cp	Pressure resistance coefficient
Cf	Frictional resistance coefficient
IHSS	Iranian Hydrodynamic Series of Submarines
CFD	Computational Fluid Dynamics

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