A “satisficing”[1] approach to submarine hull design

Gokhan Budak

Serdar Beji

Budak and Beji describe a heuristic approach to advanced submarine hull design.

Who should read this paper?

This paper will be of interest to naval architects and ocean engineers who are involved in the design of underwater vehicles.

Why is it important?

In 1989, the Submarine Technology Program Office of the US Defense Advanced Research Projects Agency (DARPA) funded a coordinated computational fluid dynamics program to assist in the development of advanced submarines for the future. The resulting so-called DARPA-SUBOFF models allow for the evaluation, in a competitive environment, of flow field predictions against a standard axisymmetric hull with and without appendages.

It is generally understood that fully submerged submarines experience a combination of viscous frictional resistance and asymmetrical or adverse pressure resistance originating from turbulence. The more poorly streamlined hull form, the more pronounced the turbulence even at lower speeds. Therefore, given a submarine with a defined surface area and corresponding frictional drag, overall streamlining of the hull form is crucial to lower the resistance.

The work reported in this paper describes a heuristic (trial and error) approach to improving the resistance characteristics of submarine hull forms. Variants on a standard design are intuitively generated and their resistance values are then calculated using computational fluid dynamics software. By comparing the simulated non-dimensional resistance values of different hull forms the lowest resistance form may be identified. This intermediate step in the design process allows for time and cost effective preliminary evaluation of a set of possibilities before moving to the final, more time consuming and expensive step of testing a model in a tow tank.

About the authors

Gokhan Budak holds B.Sc. and M.Sc. degrees in Ocean Engineering from Istanbul Technical University. His master’s thesis developed a heuristic approach of improving resistance characteristics of vessels with the aid of CFD computations. He is currently pursuing his PhD studies on the subject of ship manoeuvres. Serdar Beji holds a PhD in Ocean Engineering from the University of Rhode Island and is currently a Professor in the Faculty of Naval Architecture and Ocean Engineering, Istanbul Technical University. His research areas include physical oceanography, nonlinear water wave modelling and ship hydrodynamics.

[1] *Term coined by Nobel laureate Herbert A. Simon to denote a situation where the solution to a problem is “good enough.”*

COMPUTATIONAL RESISTANCE ANALYSES OF A GENERIC SUBMARINE HULL FORM AND ITS GEOMETRIC VARIANTS

Gokhan Budak and Serdar Beji
Faculty of Naval Architecture and Ocean Engineering, Istanbul Technical University, Istanbul, Turkey

ABSTRACT

This study investigates resistance characteristics of a DARPA-SUBOFF submarine bare hull form and its geometric variants using a commercial code ANSYS-FLUENT. First, benchmark tests were carried out by comparing the available experimental data with RANS computations performed by selecting shear stress transport (SST) k-ω turbulence model for computations. These tests provided the means of setting optimum computational parameters for the turbulence model. Then, using the generic DARPA-SUBOFF bare hull as the basis, three slightly different bow and three stern forms were generated. These new bow and stern patterns were combined with each other so that a total of nine new submarine forms were created. Finally, keeping the tuned parameters the same, numerical resistance calculations of the newly created submarine forms were carried out. The results show that one of the form variants has the lowest resistance among others and that it is possible to use the proposed approach to obtain a hull form with minimum resistance by generating a family of forms from a generic model.

KEYWORDS

CFD; RANS; SST k-ω turbulence model; DARPA-SUBOFF; Submarine resistance

INTRODUCTION

Towing tank experiments are quite important to obtain accurate information about resistance of ships and submarines. On the other hand, particularly in preliminary design stage, high costs and long set-up durations stand as the main disadvantages of experiments. For these reasons, researchers and designers resort to numerical means more and more to obtain the quantities necessary for assessing the performance of their work models.

Resistance is defined as the force acting in the opposite direction of the movement of a vessel advancing in any kind of fluid. Components of resistance are different for surface and submerged vessels. Greater part of the total resistance of a surface ship results from wave-making. The effects of wave-making and wind resistance may be completely ignored for a submarine sufficiently below the free surface. Thus, unlike surface going ships, submarines advancing fully submerged experience only viscous frictional resistance and asymmetrical or adverse pressure resistance originating from turbulence. For a poorly streamlined vessel form, turbulence is more pronounced and triggered at lower speeds. Therefore, given a submarine with a definite surface area hence corresponding frictional drag, overall streamlining of the form is crucial to lower the resistance. The present study attempts to reduce the resistance of an underwater vessel through development of a better streamlined version of a generic submarine.

Experimental measurements of DARPA-SUBOFF submarine model of Han-Lieh and Thomas [1998] have been used in various contexts, in particular for tests involving the performance of numerical simulations. Gross et al. [2011] calculated the resistance of DARPA-SUBOFF submarine model with different angle of attack values using computational fluid dynamics (CFD) method and compared these results with the towing tank test results. Likewise, Chase [2012] and later Moonesun et al. [2013] used numerical methods to compute various available characteristics of DARPA-SUBOFF submarine model and then compared their findings with relevant experimental measurements.

In the first stage of the present work, the commercial software ANSYS-FLUENT with the k-ω turbulence model option was employed to compute the resistance values of DARPA-SUBOFF model for velocities 5.14 m/s, 6.10 m/s, and 7.16 m/s, in accord with the experimental measurements. Several trial runs were done to set the computational parameters for the best possible overall agreement with the corresponding measurements. The setting of parameters was done for an average agreement of around 8%-9%. In the second stage, nine new forms were created as variants of the generic DARPA-SUBOFF bare hull. Keeping the optimum computational parameters the same, the resistance values of these new forms were then computed for three different velocities. Finally, the dimensionless resistance values were plotted so that in terms of resistance the best possible form could be identified.

GEOMETRY AND SOLUTION DOMAIN

DARPA-SUBOFF model has L=4.356 m length and B=0.508 m maximum breadth. Taking advantage of its axial symmetry of the form, only a quarter of the bare hull was used

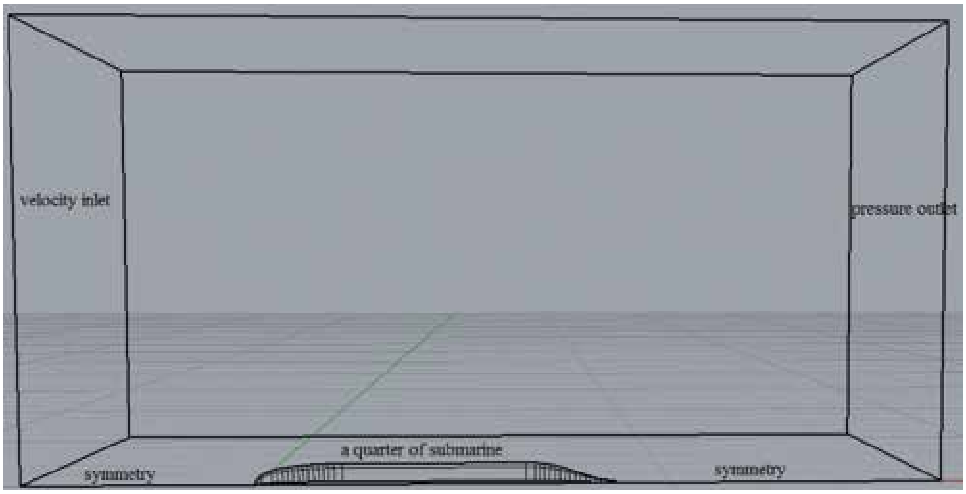


Figure 1: Numerical solution domain.

in the computations. Numerical solution domain was constructed as shown in Figure 1, by allowing a large enough distance of $5L$ from the free surface to avoid wave effects. To establish a uniform enough flow, a distance of $2.5L$ from the incoming boundary to the submarine bow was deemed sufficient and finally to avoid any undesirable disturbances at the pressure outlet, quite a large distance of $6.5L$ from back of the submarine model was used. Boundary conditions were defined as "velocity inlet" where the flow enters solution domain and as "pressure outlet" where the flow leaves solution domain. The "wall condition" was used over a quarter of the bare hull form of submarine and the "symmetry condition" along the line in front of and behind the submarine.

BENCHMARK TESTS

Resistance calculations of the generic bare hull form were carried out to compare the results with the measurements and accordingly establish the mesh construction details and set the computational parameters for ensuring satisfactory and reliable computational results. ANSYS-Workbench was used for generating mesh in the numerical solution domain. A typical grid construction for the entire domain is shown in Figure 2 while a close-up detail in the vicinity of the hull is given in Figure 3. Flow simulations were performed with RANS (Reynolds Average Navier-Stokes) equations solver ANSYS-FLUENT, a commercial CFD software. The control volumes with generated mesh systems were imported to the ANSYS-FLUENT software. Shear stress transport (SST) with the k-ω turbulence model option was selected for modelling the turbulence in the flow. SST with the k-ω turbulence model, named as the two-equation-turbulent-model, solves transport equations for turbulent kinetic energy k and specific dissipation rate. Specific dissipation rate is defined as the dissipation rate per unit turbulent kinetic energy [Menter, 1994]. The two-equation-turbulence-model is based on the k-ε and k-ω turbulence models. That is to say the turbulence model acts as the k-ε model far from the walls and as the k-ω model near wall regions [Menter et al., 2003; Karim et al., 2011].

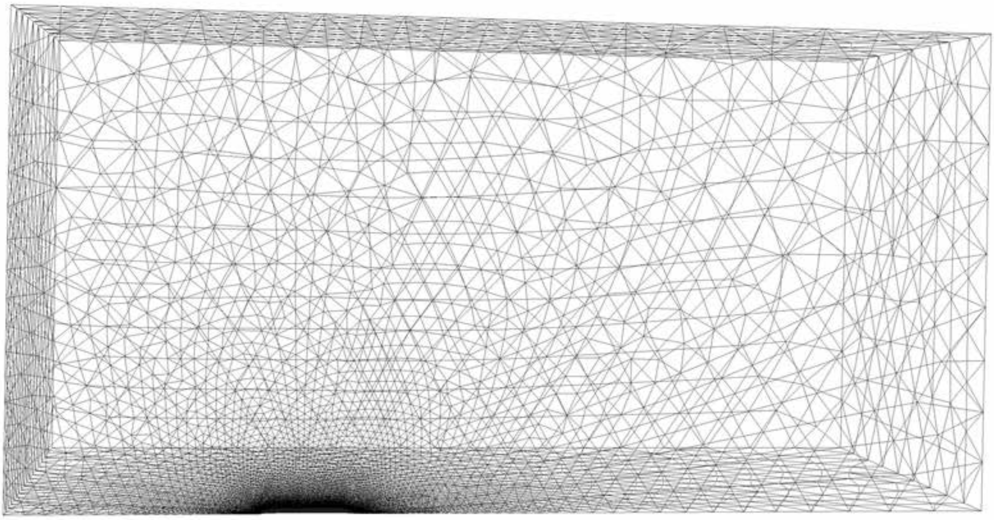


Figure 2: Mesh structure of entire solution domain.

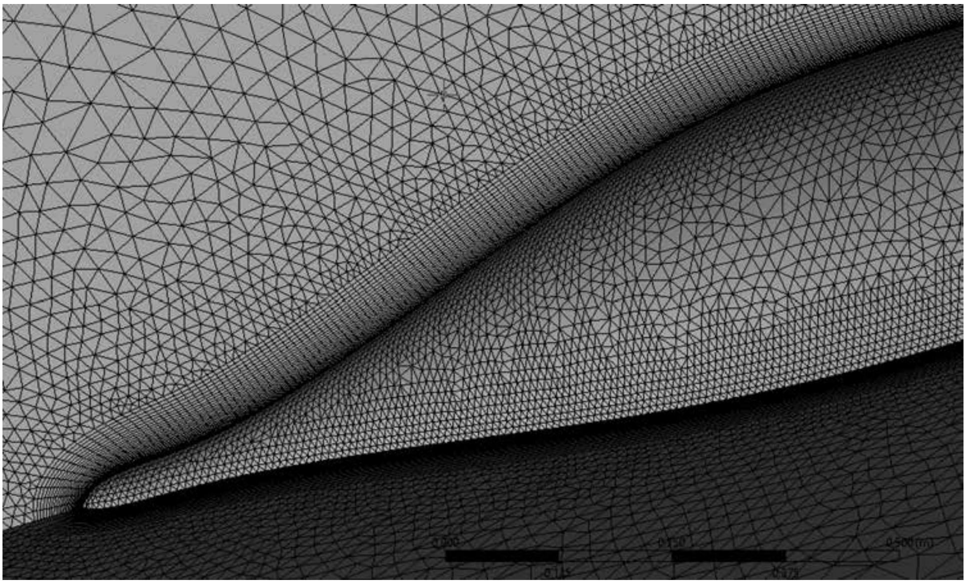


Figure 3: Mesh structure details around the hull form.

A certain expertise in mesh construction is necessary since appropriateness of mesh distribution in the vicinity of the submarine wall is quite important to obtain reliable and accurate resistance values. The mesh distribution adjacent to the wall should be fine enough to resolve the boundary layer flow.

For testing the sensitiveness of computations to the mesh size and ascertaining the convergence of the results to the true values, three different mesh constructions were considered: coarse, medium, and fine. Table 1 lists the number of mesh points generated for each case. After carrying out computations for three different mesh numbers, the mesh size independency of the resistance results was established and, considering the computational time, the medium size grid resolution (1.8 million cells) was selected for all the computations to be carried out.

Resolution	Mesh Number
Coarse	1.25 millions
Medium	1.8 millions
Fine	2.5 millions

Table 1: Mesh number.

In computations it was also quite important to set the y^+ values. A y^+ value is the non-dimensionalized distance between the wall of the submarine form and the first point of the mesh in the immediate vicinity. For a typical run with 1.8 million cells, the variation of y^+ values along the DARPA-SUBOFF model length is shown in Figure 4. The maximum y^+ value did not exceed 130 and for most part of the submarine it remained nearly constant at 80.

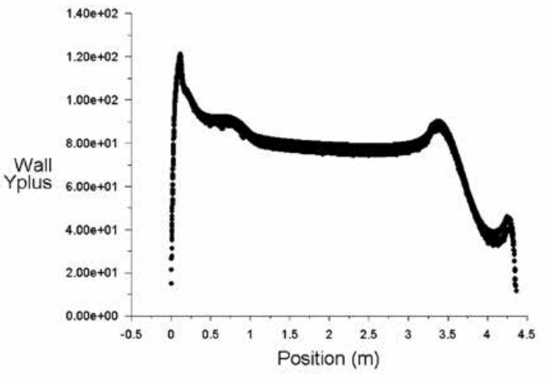


Figure 4: Variation of y^+ values along the model submarine.

The resistance values of DARPA-SUBOFF model for velocities 5.14 m/s, 6.10 m/s, and 7.16 m/s were computed using medium resolution 1.8 million cells while keeping y^+ values within suggested limits. Those limits are $30 \leq y^+ \leq 800$ [Usta and Korkut, 2015]. Experimentally measured and numerically calculated values are depicted in Figure 5. Overall, the computed resistance values are systematically lower than the measured ones. For velocity 5.14 m/s, the difference is about 8%; for velocities 6.10 m/s and 7.16 m/s, the difference is slightly higher and about 9%. These differences are interpreted as systematic errors, which are probably associated with the modelling of turbulence. By their very nature, systematic errors, as opposed to random errors, could not be eliminated by repeated processes or statistical analysis; especially so for deterministic calculations. In the present case, however, the availability of experimental measurements provides quantitative estimates of these errors. Since the difference percentages are approximately constant (8%-9%) within the velocity range (5 m/s-7 m/s) considered, it may be plausible to argue that the resistance computations with newly generated forms would all include nearly the same percentage of systematic error. Consequently, although all computed results would probably be less than the true (experimental) values, they may very well be compared with each other as they all contain nearly the same percentage of error.

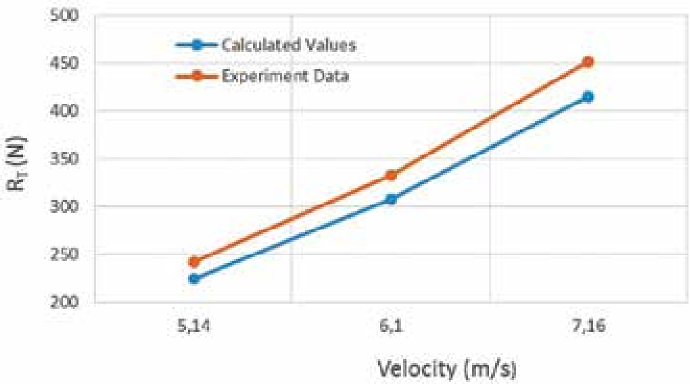


Figure 5: Experimental and calculated resistance values for DARPA-SUBOFF model for three different velocities.

NEWLY GENERATED FORMS

Basically, three different new bow forms and three different stern forms have been generated as slight variants of the original DARPA-

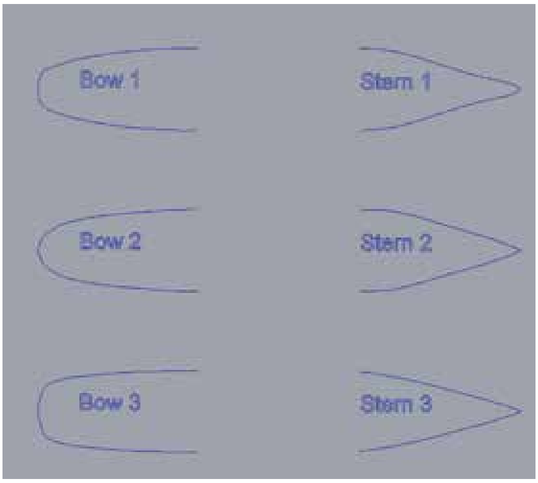


Figure 6: Newly generated bow and stern forms.

SUBOFF model as shown in Figure 6. Different bow and stern patterns were combined with each other so that a total of nine new submarine forms were created. All the new submarine forms have the same parallel body as the parallel body of DARPA-SUBOFF model.

The new forms were first produced by hand as the variants of the generic model and then polynomials with the least square method were used to obtain analytical expressions for the newly generated bow and stern forms. In this way, whenever needed, the forms could be reproduced accurately.

Newly generated bow forms:

$$\begin{aligned}&0 \le x \le k\\&y = a_1x^3 + b_1x^2 + c_1x + d_1\\&k \le x \le 1.016\\&y = a_2x^3 + b_2x^2 + c_2x + d_2\end{aligned} \qquad (1)$$

Parallel body (the same for all forms):

$$\begin{aligned}&1.016 \le x \le 3.245\\&y = 0.254\end{aligned} \qquad (2)$$

Newly generated stern forms:

$$\begin{aligned}&3.245 \le x \le 4.356\\&y = ax^3 + bx^2 + cx + d\end{aligned} \qquad (3)$$

where k is a constant parameter indicating the separation point between domains and set to the values given in Table 2 below. Table 2 and Table 3 give the coefficients for the generated bows and sterns respectively as obtained by the application of the least square method for each case.

Displacement values for the DARPA-SUBOFF model and the newly created forms are given in Table 4. For all the forms, the overall length is L=4.356 m, the mid-section diameter is D=0.508 m, and the slenderness ratio is L/D=8.57.

COMPARISONS

The resistance values of nine newly generated bare hull forms have been computed using the same computational parameters and specifications employed in the resistance calculation of the generic form. For meaningful comparisons, all the resistance values were expressed as non-dimensional resistance coefficients. The non-dimensional resistance coefficient C_T is defined as:

$$C_T = \frac{R_T}{\frac{1}{2}\rho A V^2} \qquad (4)$$

where R_T is the computed total resistance in Newton, ρ = 998.2 kg/m^3 is the fresh water density, V is the velocity in m/s, and A is the total surface area of the submarine form in m^2.

Bow	Bow 1	Bow 2	Bow 3
k	0.01236	0.08988	0.06986
a_1	-2486.9	254.54	784.63
a_2	0.3006	0.2541	0.1972
b_1	-181.41	-48.991	-124.35
b_2	-0.6872	-0.5939	-0.4435
c_1	8.5895	3.7653	7.2913
c_2	0.5591	0.5031	0.3482
d_1	0.00002	0.0014	0.0013
d_2	0.0855	0.0936	0.1529

Table 2: Values of bows.

Stern	Stern 1	Stern 2	Stern 3
a	0.2524	0.1618	0.0507
b	-3.0018	-2.022	-0.6895
c	11.583	8.0824	2.8015
d	-14.348	-10.211	-3.3072

Table 3: Values of sterns.

Form	11	12	13	21	22	23	31	32	33	DS
Δ (tonne)	0.712	0.718	0.701	0.708	0.721	0.698	0.729	0.742	0.719	0.696

Table 4: Displacement values of forms.

The surface areas of all the forms are computed with the aid of the software Rhinoceros.

Since variations in forms necessarily changes the total surface area of the form, use of the non-dimensional resistance values is quite important for reliable comparisons. Otherwise, dimensional resistance would normally be smaller for the smaller surface area. Table 5 gives the computational results with relevant details for the original DARPA-SUBOFF model and five newly generated forms. The results for the remaining four new forms are not shown due to their relatively high resistance values. Figure 7 shows C_T versus the Froude number $Fn=V/\sqrt{gL}$ for six different forms including DARPA-SUBOFF model.

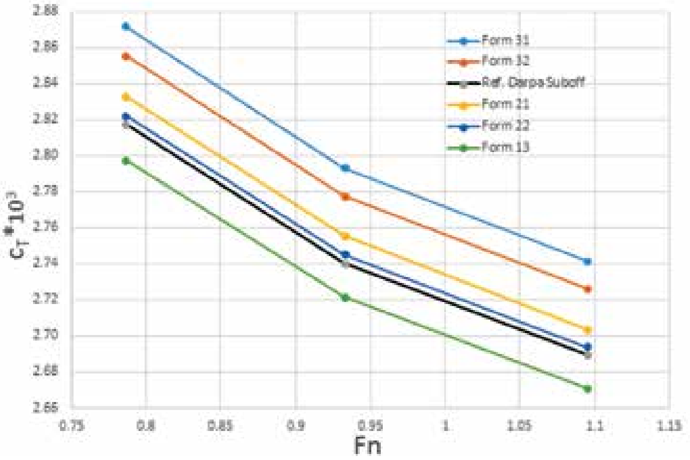
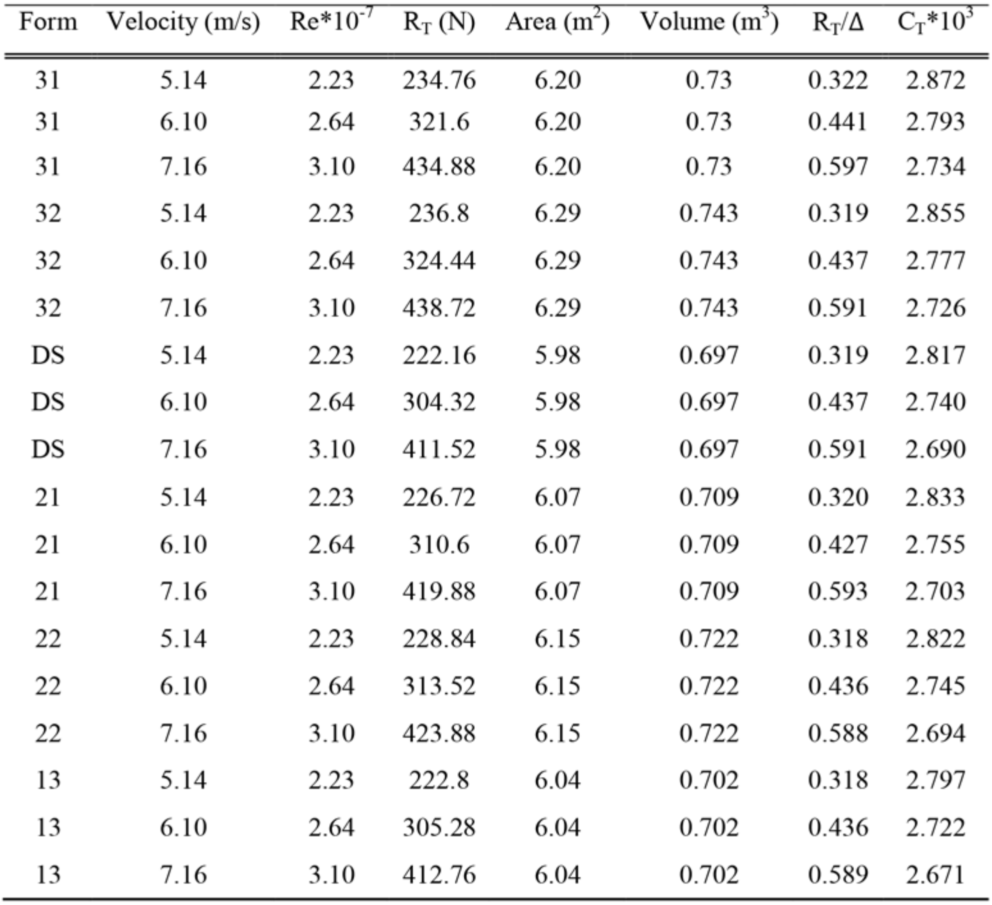


Figure 7: Non-dimensional resistance coefficient versus Froude number *Fn=V/√gL*.

Form numbers are denoted by the bow form number followed by the stern form number. For



Form	Velocity (m/s)	$Re*10^{-7}$	R_T (N)	Area (m^2)	Volume (m^3)	R_T/Δ	C_T*10^3
31	5.14	2.23	234.76	6.20	0.73	0.322	2.872
31	6.10	2.64	321.6	6.20	0.73	0.441	2.793
31	7.16	3.10	434.88	6.20	0.73	0.597	2.734
32	5.14	2.23	236.8	6.29	0.743	0.319	2.855
32	6.10	2.64	324.44	6.29	0.743	0.437	2.777
32	7.16	3.10	438.72	6.29	0.743	0.591	2.726
DS	5.14	2.23	222.16	5.98	0.697	0.319	2.817
DS	6.10	2.64	304.32	5.98	0.697	0.437	2.740
DS	7.16	3.10	411.52	5.98	0.697	0.591	2.690
21	5.14	2.23	226.72	6.07	0.709	0.320	2.833
21	6.10	2.64	310.6	6.07	0.709	0.427	2.755
21	7.16	3.10	419.88	6.07	0.709	0.593	2.703
22	5.14	2.23	228.84	6.15	0.722	0.318	2.822
22	6.10	2.64	313.52	6.15	0.722	0.436	2.745
22	7.16	3.10	423.88	6.15	0.722	0.588	2.694
13	5.14	2.23	222.8	6.04	0.702	0.318	2.797
13	6.10	2.64	305.28	6.04	0.702	0.436	2.722
13	7.16	3.10	412.76	6.04	0.702	0.589	2.671

Table 5: Results of CFD.

instance, Form 13 indicates a form created by the use of bow form 1 and stern form 3, as shown in Figure 6. Comparisons made based on the numerical calculations reveal that Form 13 has the lowest dimensionless resistance coefficient among all forms, including the original generic form. Although the computed resistance of Form 13 would probably be 8%-9% less than the experimental value, following the arguments presented at the end of the previous section, Form 13 is expected to perform best among others. To give a visual demonstration of this conclusion, the pressure values on the hull forms and velocity vectors in the vicinity of Form 13 and generic DARPA-SUBOFF model are depicted in Figure 8. Compared to DARPA-SUBOFF model, the pressure values of Form 13 around the bow and stern are less pronounced and the velocity vectors are more uniform in the entire domain.

CONCLUSION

CFD may be considered as a viable tool in gaining insight into the nature of fluid problems. In this work, with the aid of CFD, a systematic approach of improving the resistance characteristics of a generic submarine form was performed. Starting from DARPA-SUBOFF model and by slightly varying its bow and stern

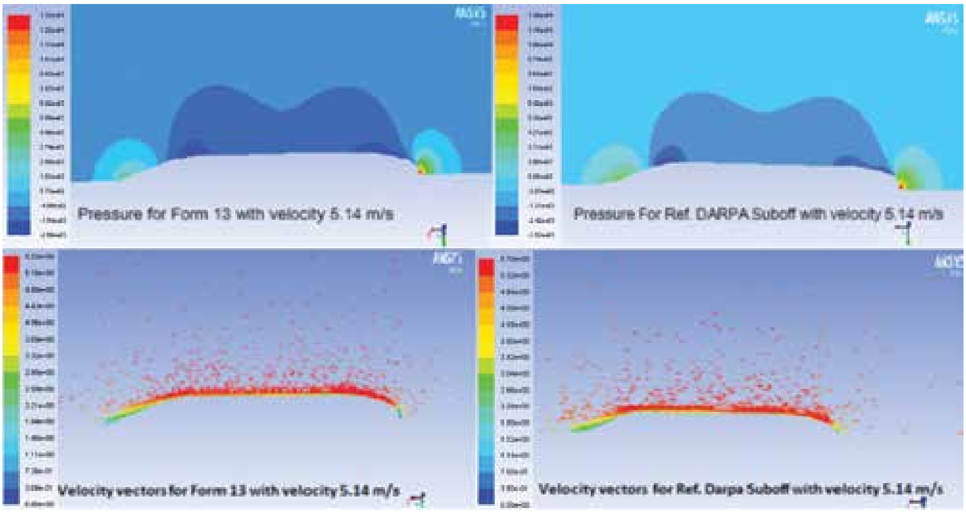


Figure 8: Pressure and velocity field comparisons between Form 13 and DARPA-SUBOFF model.

forms, nine new bare hull forms were generated. Then, keeping the tuned parameter values and computational specifications the same as obtained from the benchmark tests, resistance computations were carried out for the newly generated submarine forms.

Non-dimensional resistance coefficient comparisons show that one of the form variants has the lowest resistance coefficients for all velocities among all others, including the original generic form. While the computed resistance values of this particular form would definitely differ from the experimental values, since all the computations performed under identical conditions have approximately the same percentage of difference, it is expected that the computationally best form would still perform best when tested experimentally as well.

It may then be concluded that by carrying out numerical resistance experiments of a preliminary design variants, the original design may be refined to have better resistance characteristics. The final design must eventually be tested in laboratory.

REFERENCES

Chase, N. [2012]. S*imulations of the DARPA-SUBOFF submarine including self-propulsion with the E1619 propeller*. University of Iowa City, Iowa.

Gross, A.; Kremheller, A.; and Fasel, H.F. [2011]. *Simulation of flow over Suboff bare hull model*. 49th AIAA Aerospace Sciences Meeting, January. Orlando, Florida.

Han-Lieh, L. and Thomas, T.H. [1998]. *Summary of DARPA-SUBOFF experimental program data*. Hydromechanics Directorate, Naval Surface Warfare Center, Carderock Division.

Karim, M.M.; Rahman M.M.; and Alim, M.A. [2011]. *Comparative study between flows around sphere and pod using finite volume method*. Journal of Naval Architecture and Marine Engineering, Vol. 8, pp. 49-58.

Menter, F.R. [1994]. *Two-equation eddy-viscosity turbulence models for engineering applications*. American Institute of Aeronautics and Astronautics Journal, Vol. 32, pp. 1598-1605.

Menter, F.R.; Kuntz, M.; and Langtry, R. [2003]. *Ten years of industrial experience with the SST turbulence model*. Turbulence, Heat and Mass Transfer, Vol. 4.

Moonesun, M.; Javadi, M.; Charmdooz, P.; and Mikhailovich, K.U. [2013]. *Evaluation of submarine model test in towing tank and comparison with CFD and experimental formulas for fully submerged resistance*. Indian Journal of Geo-Marine Sciences, Vol. 42, No. 8.

Usta, O. and Korkut, E. [2015]. A *study for cavitating flow around a NACA foil using RANS approach*. AMT2015, 4th International Conference on Advance Model Measurement Technologies for the Maritime Industry.