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Evaluation of submarine model test in towing tank and comparison with CFD and experimental formulas for fully submerged resistance

Mohammad Moonesun[1], Mehran Javadi[2,*]Pejman Charmdooz[3] & Karol Uri Mikhailovich[4]

[1]National University of Shipbuilding Admiral Makarov (NUS), Faculty of Ship Design,
Isfahan University of Technology (iut), Isfahan, Iran
[2]Aero-Maritime Science & Research Center, Isfahan University of Technology (iut), Isfahan, Iran
[3]Department of Marine Science & Engineering, Malek-Ashtar University of Technology (MUT), Isfahan, Iran
[4]National University of Shipbuilding Admiral Makarov (NUS), Faculty of Ship Design,
Malek-Ashtar University of Technology (MUT), Isfahan, Iran
[*][E-mail: p.charmdooz@yahoo.com]

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Towing tanks experiments were conducted to study the behavior of flow on a model of underwater vehicle with tango shape of nose. Length of model and prototype vehicle is 1 and 32 meters, respectively. First the method of underwater model test is evaluated by unequal Reynolds number. An accurate method has been suggested for scaling of results between model and main submarine in underwater testing. Suitable depth for ignoring the free surface effects has been suggested. After underwater test in towing tank and extracting the results, the CFD results have been compared. At last, for more validation of results, four groups of experimental formula for submarine bare hull resistance in deep water have been presented. Finally, the comparison tables and diagrams show the accuracy of each of these six methods in the calculation of submerged resistance of submarine and present an optimum resistance coefficient for this submarine.

[Keywords: Submarine, Resistance, Fully submerged, Model test, CFD, Experimental result]

Introduction

The most ideal shape for the submerged mode is shown in Fig. 1. In this case, the pressure resistance is only 10 percent of the total resistance showing an efficient body. Other form is parallel middle body (Figure 1) that is more similar to the actual shape of submarines that is easier to construction.

Fully submerged mode is a situation of underwater movement without any effects on the surface i.e. free surface of water can be ignored. For this reason, the shapes of the submarine and aircraft are similar because of absence of free surface effects. Ship moves in the interference of water and air with free surface effects (surface mode) and therefore a sharp stem of bow is suitable. Main different between submerged and surfaced mode is wave making and wave breaking resistance. Fully submerged modes have only viscous pressure resistance (form resistance) and frictional resistance. Variation of frictional and form resistance with L/D variation is shown in Fig. 2 & 3. By increasing L/D, frictional resistance increases and form resistance decreases. Then, the effects of L/D on two items of resistance are paradoxical; thus, there is a unique optimum resistance that total resistance is minimum. Total resistance diagram is shown in Fig. 3. Lowest point of diagram is related to the optimum L/D.

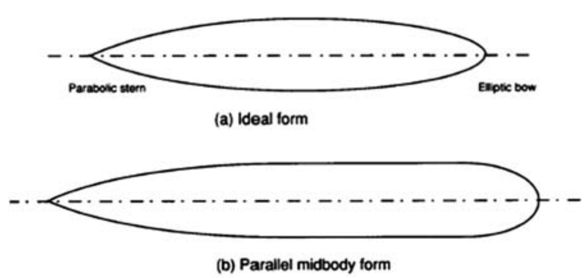

Fig. 1—Suitable Form for Submarine Hull

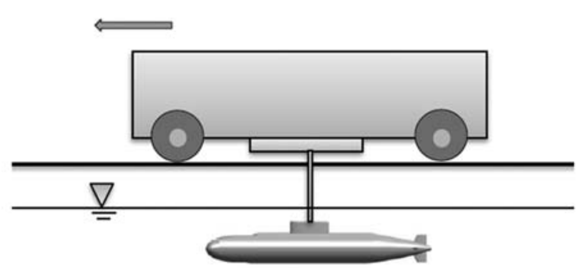

Fig. 2—Schematic of the overall test set-up

For teardrop shape, (ideal shape) the optimum L/D is 6 and in parallel middle body form, the optimum L/D is 10.

In naval submarines, the approximate resistance of main hull and appendages are shown in Table 1. Appendage resistance is 35 percent of total resistance [1].

Materials and Methods

Experiments were conducted in Isfahan University of Technology (IUT) marine laboratory. Towing tank has 108(m) length, 3 (m) width and 2.2 (m) depth. Basin is equipped with a trolley that is able to operate in through 0.05-6 m/s speed that moves by two 7.5 KW electromotors with ±0.02 m/s accuracy. System is prepared with a proper frequency encoder, i.e., 500 pulses in a minute, which decreases the uncertainty of measurements. Dynamometer was calibrated by calibration weights [2]. A three degree of freedom dynamometer is used for force measurements. Data are recorded via an accurate data acquisition system. Dynamometer is equipped with 100 N load cells. An amplifier set is used to raise signals of load cells and to reduce the noise sensitivity of the system. The experiment is conducted with a submarine model that is made by wood

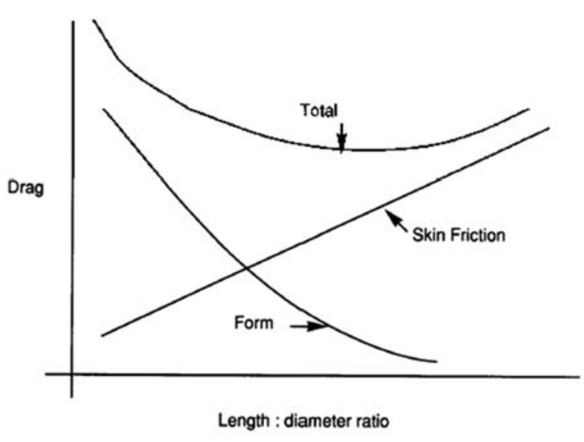

Fig. 3—Variation of Submarine Resistance by L/D Ratio

according to ITTC recommendations [3]. Tango nose submarine is a type of submarine that has been tested in undersurface motion.

All data are filtered to eliminate the undesirable acceleration, primary and terminative motion of trolley. Trolley was controlled in wireless system from control room of lab. Data presented in this paper for each point are an average of several towing tank runs [4]. For each run, at least 750 samples in 15 seconds were collected and the ensemble averaged. Schematic of the model and the overall test set-up are shown in Figure 2.

Dimensions of studied submarine in this paper are shown in Table 2 with parallel middle body form. Relation L/D is equal to 8.88 because of limitation of design and internal arrangements. Hull bow is elliptical and stern is conical. Main submarine has a deck with 28 meters of length, 0.4 meters of height and 1 meter of beam. Also, it has a conning tower of 3.2 meters length and 3 meters of height on top of the main hull. Maximum submerged speed is 14 knots and wetted surface area is 450 square meters. All dimensions of this submarine have been scaled by 1:32.

Fully Submerged Standard Condition

Wave making procedure is in the interference of air and water produced by variation of fluid pressure. When a submarine goes from surface to submerge mode, wave making decreases until fully omitted[1]. Fig. 4 shows that the resistance coefficient (C_D) decreases by increasing submergence depth. In this diagram, h is submerged depth, L is submarine length, and D is submarine diameter.

Standard depth for fully submerged condition is different in several references. In reference[5] this depth is half of submarine length (h=L/2), in reference[6] depth is 3D (h=3D), and in reference [7] depth is 5D (h=5D).

Our experiment shows that h=5D is the best option but there is no difference between the results. Before full submergence of submarine, there are some ripples on the water surface, which are omitted after full submergence of body (Fig. 5).

Table 1—Percentage of Appendages in Submarine Resistance

Main body	Bridge fin	Stern planes	Bow planes	Upper rudder	Lower rudder	Sonar fairing	keel	Total(%)
65.5	7.67	7.61	3.44	5.24	1.71	2.78	6.05	100

Table 2—Main Submarine Dimensions (meter)

Overall length (m)	Hull diameter (m)	Displacement (t)	Bow length (m)	Cylinder length (m)	Conical stern length (m)	Conical stern Angle (deg)
32	3.6	235	5	21	6	16.7

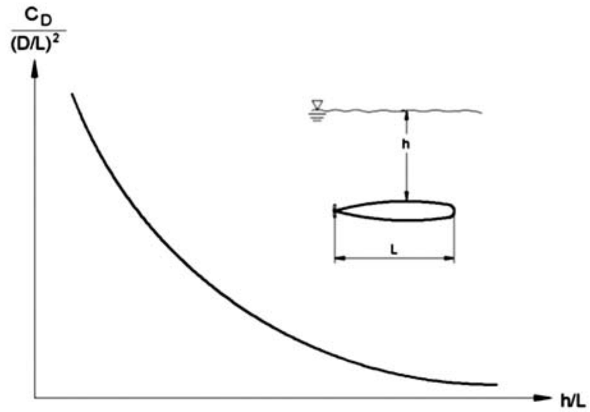

Fig. 4—Total Resistance Coefficient vs Depth

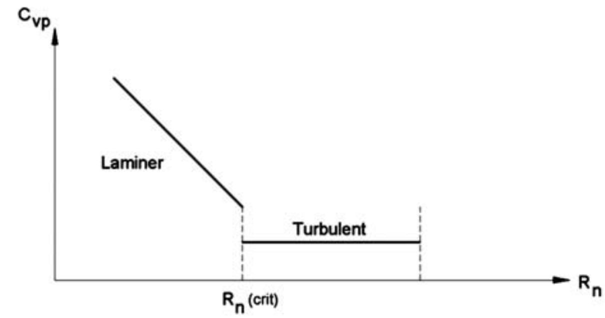

Fig. 6—Variation of Viscous Resistance vs Reynolds Number

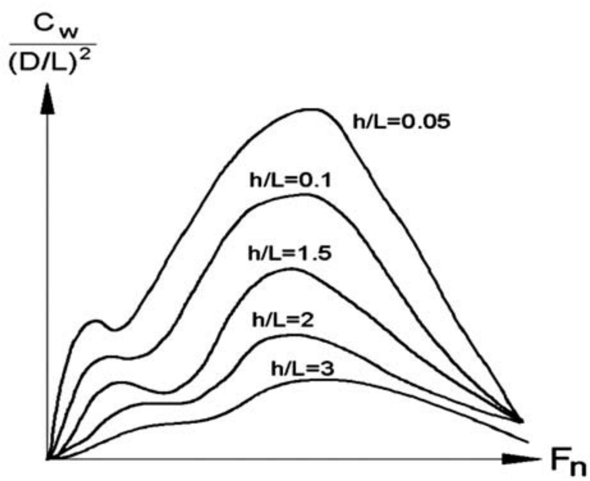

Fig. 5—Wave Making Coefficient vs Froude Number and Depth of Submergence

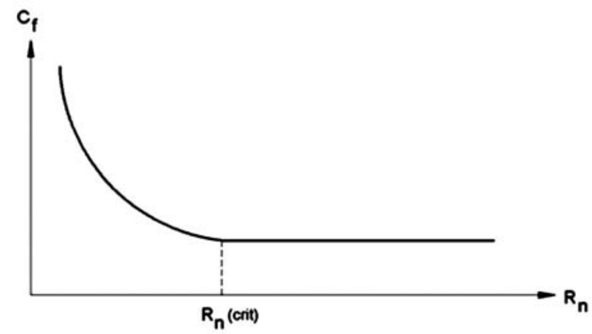

Fig. 7—Variation of Frictional Resistance vs Reynolds Number

Method of Developing Result of Model to Main Submarine at Submerged Test

At submerged mode, Froude equation cannot be used because of absence of free surface effects and waves. Also, the use of Reynolds equation is impossible because model speed will be too large and impossible to provide.

$$(\mathrm{Re})_M = (\mathrm{Re})_S$$

$$V_M = V_S.(L_S/L_M)$$

For this submarine with a speed of 14 knots (7.2 m/s) and scale of 1:32, the speed of model will be 32 times of main submarine, which is equal to 230 m/s that is actually impossible.

Main aid of Reynolds equation is independent from turbulent current on model surface. This turbulence can be provided with several methods such as making roughness of submarine's bow. Thus, we can be sure that the currents on both model and main submarine are turbulent.

In the depth of water, there are only frictional and viscous pressure resistances and there is not a wave resistance. Variation of frictional resistance coefficient and viscous pressure resistance coefficient curve after critical Reynolds (turbulent current) at rough zone is straight horizontal, and shows constant coefficient. Schematic curve of variation is shown in Figures 6, 7. As mentioned before, in beneath stages, model results can be developed to main submarine [8]:

- Making roughness of model's bow and confidence of turbulent flow on the model body
- Calculation of model total resistance $(R_T)_M$
- Calculation of total resistance coefficient $(C_T)_M$
- Calculation of frictional resistance coefficient $(C_F)_M$ by ITTC-1957 method
- Calculation of viscous pressure coefficient: $(C_V)_P = (C_T)_M - (C_F)_M$
- Equalizing viscous pressure coefficients of model and submarine:
- $(C_V)_P = \left((C_V)_P\right)_M = \left((C_V)_P\right)_S$

- Calculation of frictional resistance coefficient of submarine by ITTC-1957 at actual Reynolds of submarine
- Calculation of total resistance coefficient:

$$(C_T)_S = (C_F)_S + (C_V)_P$$

- Calculation of total resistance of submarine:

$$R_T = \frac{1}{2} C_D . \quad . A . V^2$$

The above-mentioned stages can provide a very good estimation for developing the results of model to submarine.

Methods of Resistance Calculation of Fully Submerged Submarine

For calculation of submarine resistance in fully submerged condition, there are some experimental based formula with rather accurate results and small errors.

These methods with model test method and CFD method can provide a suitable estimation of resistance. These results are not exactly equal and similar. By omission of diverged results, the final estimation can be exact and correct.

Method 1) this method is for the calculation of bare hull resistance by several diagrams in Reference[1]

$$C_T = C_F + C_{VP} + C_A$$

In this method resistance coefficient can be extracted from these diagrams. Results of calculations by method 1 are in Table 4.

Method 2) This method is mentioned in Reference [9]. Conditions of use for this method are:

- Length to diameter ratio: $5 \langle L/D \langle 7$
- Depth of submergence more than 5 times of diameter: $h \geq 5D$

After these conditions, bare hull resistance can be calculated as follows:

1- Calculation of frictional resistance coefficient by ITTC-1957

2-Added resistance from surface roughness equal to 5 percent of CF:

$$C_F = 0.05\, C_f$$

$$C_F = C_{F\circ} + \quad C_F$$

3-Calculation of form coefficient (K):

$$K = \left(\frac{D}{L}\right) + 1.5\left(\frac{D}{L}\right)^3$$

4-Viscous pressure coefficient by:

$$C_{VP} = C_{Form} = K.C_{F\circ}$$

5-Total resistance coefficient:

$$C_T = C_F + C_{VP}$$

6-Calculation of total resistance of bare hull:

$$R_T = \frac{1}{2} C_T . \quad . A . V^2$$

where A is wetted surface area. Appendage resistance must be added to the above. Results of calculation by method 2 are shown in Table 5.

$$C_{F0} = \frac{0.075}{(\log \mathrm{Re} - 2)^2}$$

Method 3) This method is in Reference [10] by these stages for bare hull resistance:

1-Frictional resistance coefficient by ITTC-1957

Table 4—Results of Method 1

V (knot)	V (m/s)	Re	$(C_F)_S$	C_R	C_A	C_T	R_T (KN)
1	0.514	14964364	0.0028	0.0007	0.0004	0.0039	0.238
2	1.029	29928727	0.0025	0.0007	0.0004	0.0036	0.881
3	1.543	44893091	0.0023	0.0007	0.0004	0.0035	1.897
4	2.058	59857455	0.0022	0.0007	0.0004	0.0034	3.275
5	2.572	74821818	0.0022	0.0007	0.0004	0.0033	5.005
6	3.086	89786182	0.0021	0.0007	0.0004	0.0032	7.081
7	3.601	104750545	0.0021	0.0007	0.0004	0.0032	9.498
8	4.115	119714909	0.0020	0.0007	0.0004	0.0031	12.252
9	4.630	134679273	0.0020	0.0007	0.0004	0.0031	15.340
10	5.144	149643636	0.0020	0.0007	0.0004	0.0031	18.758
11	5.658	164608000	0.0019	0.0007	0.0004	0.0031	22.505
12	6.173	179572364	0.0019	0.0007	0.0004	0.0030	26.578
13	6.687	194536727	0.0019	0.0007	0.0004	0.0030	30.974
14	7.202	209501091	0.0019	0.0007	0.0004	0.0030	35.692

Table 5—Results of Method 2

V (knot)	V (m/s)	Re	C_{F0}	∂C_F	C_F	k	C_{Form}	C_T	R_T (KN)
1	0.514	14964364	0.0028	0.0001	0.0029	0.1146	0.0003	0.0033	0.199
2	1.029	29928727	0.0025	0.0001	0.0026	0.1146	0.0003	0.0029	0.710
3	1.543	44893091	0.0023	0.0001	0.0025	0.1146	0.0003	0.0027	1.500
4	2.058	59857455	0.0022	0.0001	0.0024	0.1146	0.0003	0.0026	2.553
5	2.572	74821818	0.0022	0.0001	0.0023	0.1146	0.0002	0.0025	3.858
6	3.086	89786182	0.0021	0.0001	0.0022	0.1146	0.0002	0.0025	5.409
7	3.601	104750545	0.0021	0.0001	0.0022	0.1146	0.0002	0.0024	7.200
8	4.115	119714909	0.0020	0.0001	0.0021	0.1146	0.0002	0.0024	9.225
9	4.630	134679273	0.0020	0.0001	0.0021	0.1146	0.0002	0.0023	11.482
10	5.144	149643636	0.0020	0.0001	0.0021	0.1146	0.0002	0.0023	13.965
11	5.658	164608000	0.0019	0.0001	0.0020	0.1146	0.0002	0.0023	16.674
12	6.173	179572364	0.0019	0.0001	0.0020	0.1146	0.0002	0.0022	19.604
13	6.687	194536727	0.0019	0.0001	0.0020	0.1146	0.0002	0.0022	22.754

2-Total frictional resistance coefficient:

$$C_T = C_F\left(1+1.5\left(\frac{D}{L}\right)^{1.5}+7\left(\frac{D}{L}\right)^{3}\right)$$

3-Calculation of total bare hull resistance:

$$R_T = \frac{1}{2} C_T \; . \quad . A . V^2$$

where A is wetted surface area. Appendage resistance must be added to this amount. Results of calculations by method 3 are in Table 6.

Method 4) this method is also in Reference [10]. This method is similar to method 3 with a different way for calculating C_T This coefficient is:

$$C_T = C_F\left(3\left(\frac{D}{L}\right)+4.5\left(\frac{D}{L}\right)^{0.5}+21\left(\frac{D}{L}\right)^{2}\right)$$

where S is cross section area of submarine. Results of method 4 are presented in Table 7.

$$R_T = \frac{1}{2} C_T \; . \quad . S . V^2$$

Method 5) This method is based on model test[11]. For successful experiment of the model, bow part of submarine is made carefully (Fig. 8). These tests are done at fully submerged condition (Figure 9). For turbulent current at low speeds, the bow part of the model is roughed. The results of model test in towing tank are presented in Table 8. As mentioned before, resistance coefficient variation after critical Reynolds will be constant and rather equal to 0.0039. Thus, according to the mentioned stages for developing the results, the resistance of submarine in several speeds is in Table 9.

Table 6—Results of Method 3

V (knot)	V (m/s)	Re	C_{F0}	C_T	R_T (KN)
1	0.514	14964364	0.00280	0.00299	0.182
2	1.029	29928727	0.00250	0.00267	0.651
3	1.543	44893091	0.00235	0.00250	1.374
4	2.058	59857455	0.00225	0.00240	2.338
5	2.572	74821818	0.00217	0.00232	3.533
6	3.086	89786182	0.00212	0.00226	4.954
7	3.601	104750545	0.00207	0.00221	6.593
8	4.115	119714909	0.00203	0.00217	8.448
9	4.630	134679273	0.00200	0.00213	10.515
10	5.144	149643636	0.00197	0.00210	12.789
11	5.658	164608000	0.00194	0.00207	15.270
12	6.173	179572364	0.00192	0.00205	17.953
13	6.687	194536727	0.00190	0.00202	20.838
14	7.202	209501091	0.00188	0.00200	23.922

Table 7—Results of Method 4

V (knot)	V (m/s)	Re	C_{F0}	C_T	R_T (KN)
1	0.514	14964364	0.00280	0.00592	0.361
2	1.029	38533236	0.00240	0.00508	1.238
3	1.543	57799855	0.00226	0.00477	2.619
4	2.058	77066473	0.00216	0.00457	4.460
5	2.572	96333091	0.00209	0.00443	6.745
6	3.086	1.16E+08	0.00204	0.00431	9.460
7	3.601	1.35E+08	0.00200	0.00422	12.597
8	4.115	1.54E+08	0.00196	0.00414	16.146
9	4.630	1.73E+08	0.00193	0.00407	20.101
10	5.144	1.93E+08	0.00190	0.00401	24.456
11	5.658	2.12E+08	0.00187	0.00396	29.206
12	6.173	2.31E+08	0.00185	0.00391	34.346
13	6.687	2.5E+08	0.00183	0.00387	39.872
14	7.202	2.7E+08	0.00181	0.00383	45.780

Fig. 8—Construction of Model and Bow of Submarine

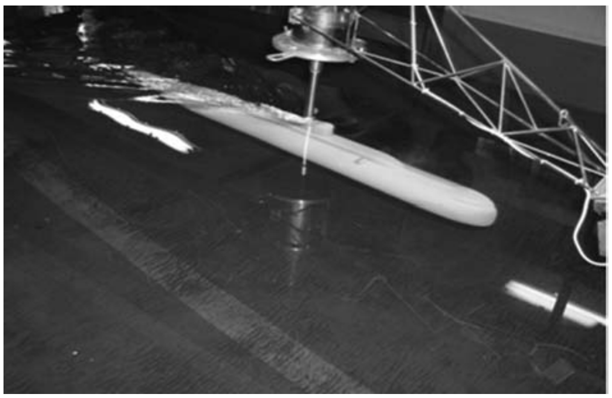

Fig. 9—Submarine Model Test in Towing Tank

Table 8—Results of model test in towing tank

V (knot)	V (m/s)	$(R_T)_M$	$(C_T)_M=(C_T)_S$
2.916019	1.5	4.43	0.003842
2.721617	1.4	3.9	0.003883
2.527216	1.3	3.42	0.003949
2.332815	1.2	2.96	0.004011
2.138414	1.1	2.48	0.003999
1.944012	1	2.05	0.004
1.749611	0.9	1.68	0.004047
1.55521	0.8	1.37	0.004177
1.360809	0.7	1.08	0.004301
1.166407	0.6	0.76	0.004119
0.972006	0.5	0.55	0.004293

Table 9—Model Test Results in Speeds 1-14 knots

V_S(knot)	V_S (m/s)	$(R_T)_S$ (KN)
0	0	0.0000
1	0.5144	0.2380
2	1.0288	0.9520
3	1.5432	2.1420
4	2.0576	3.8080
5	2.572	5.9499
6	3.0864	8.5679
7	3.6008	11.6619
8	4.1152	15.2319
9	4.6296	19.2778
10	5.144	23.7998
11	5.6584	28.7977
12	6.1728	34.2717
13	6.6872	40.2216
14	7.2016	46.6476

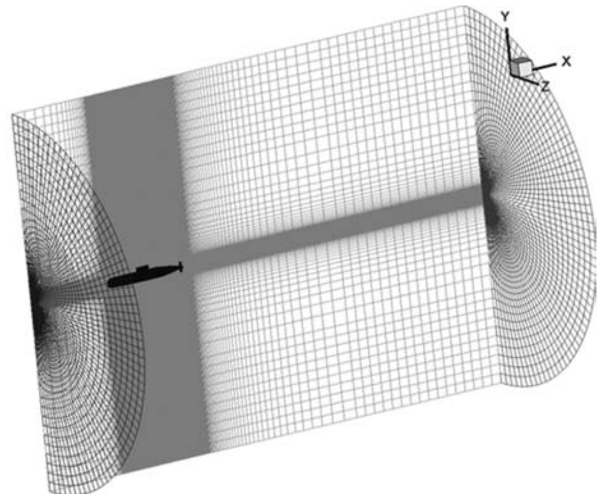

Fig. 10—Submarine Simulation in Fluent

Method 6) CFD method: To evaluate the hydrodynamic performance of the submarine, CFD analyses are utilized and the results are compared with those of the model tests and experimental formula. FLUENT, a commercial CFD code is one of the efficient codes for CFD analyses. Total resistance was estimated and compared with the results of the model tests and experimental Formulas. The simulation in this paper involved solving the incompressible Reynolds Average Navier-Stocks (RANS) equations[12, 13]. At first, CAD geometry, as starting point, has been possible to automate the generation and meshing of a suitable computational domain for test on the basis of vehicle geometry. Also, all tests have been performed using an unstructured hexagonal mesh with prism layer adjacent to the underlying solid surface. Because of depending on the region in space surrounding the submarine, the meshes are refined. Additionally, the left and top boundaries of the domain are modeled as velocity inlet, the right boundary was modeled as an outflow boundary, and the surface of the body itself was modeled as a wall (Fig. 9).

In this work, SST k-ω model is used to simulate turbulent flow past underwater vehicle hull forms [14].

This simulation as shown in Figure 10 is with hull and appendages. Structured and unstructured grids are used to mesh the domain around hull as shown in Figure 10. The results of CFD method are shown in Table 10. Amount of each part of submarine in total resistance at speed 8 knot is shown in Table 11.

Results and Discussion

Before analyzing these methods, it must be noted that methods 1 to 4 are for bare hull, and methods 5, 6 are for hull and appendages. Appendages resistance is about 35 percent of total resistance. Then, results of methods 1 to 4 must be completed. Comparisons of results are shown in Table 12 and Fig. 11.

Table 10—Results of CFD Analysis

V(knot)	R_T(KN)
0	0
1	0.623
2	1.359
3	2.126
4	3.346
5	4.637
6	6.368
7	8.863
8	12.5553
9	19.24
10	23.552
11	26.982
12	30.567
13	34.254
14	37.386

Table 11—Total Resistance in Speed 8 Knot

Pressure force (N)	Viscous force (N)	Total force (N)
6749.1628	5804.1003	12553.2631

According to them, except method 1 and 4, results of other methods are rather near and similar with less than 20 percent difference. Therefore, the total resistance of 45 KN can be a good estimate for this model.

The best way for calculating a submarine resistance is to evaluate the methods such as experimental base formula, CFD, & towing tank tests together. Best method that most of the time has acceptable errors is experimental test in towing tank (of course if the test conditions are not applied in a correct way, the unacceptable error will be inevitable) but towing tank test is not always possible or available, so with considering the errors the other methods can be used[15].

To show the competence of the methods for such these models, comparison of the other methods with towing tank test results can be extracted from Table 12.

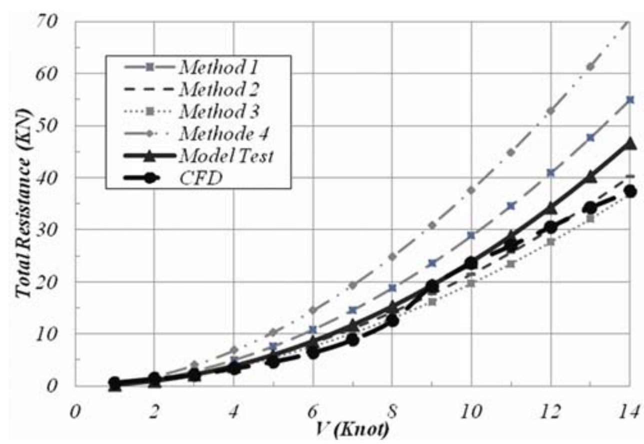

Fig. 11—Resistance-Speed Diagrams for 6 Methods

Table 12—Total Resistance of Main Submarine (KN)

V (knot)	R_T Method 1	R_T Method 2	R_T Method 3	R_T Method 4	R_T Method 5	R_T Method 6
1	0.36677514	0.30590877	0.2801496	0.5549127	0.2379978	0.623
2	1.35476246	1.09280212	1.0007824	1.9051925	0.9519911	1.359
3	2.91871624	2.30798527	2.1136407	4.0286747	2.14198	2.126
4	5.03809373	3.92753338	3.5968143	6.861308	3.8079645	3.346
5	7.69959057	5.93595174	5.4361133	10.376349	5.9499446	4.637
6	10.893471	8.32190174	7.6211537	14.554213	8.5679202	6.368
7	14.6121165	11.0765105	10.14381	19.379562	11.661891	8.863
8	18.8493033	14.1925298	12.997444	24.839863	15.231858	12.5553
9	23.5997927	17.6638582	16.176468	30.924559	19.27782	19.24
10	28.8590756	21.4852444	19.676073	37.624564	23.799778	23.552
11	34.6232042	25.6520906	23.492049	44.931916	28.797732	26.982
12	40.8886748	30.1603163	27.620659	52.839551	34.271681	30.567
13	47.6523432	35.0062596	32.058548	61.341124	40.221625	34.254
14	54.9113617	40.1866041	36.80268	70.430891	46.647565	37.386

For reference speed of 12 knots, errors percentages are as follows:

- Method 1: 19%
- Method 2: 11%
- Method 3: 19%
- Method 4: 54%
- Method 6: 10%

So, according to these results, in the case of a similar model as described (parallel middle body), and suitable scaling method, various models resistance (model with different diameter, length, length of parallel body and…) can be calculated.

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