Journal of the Korean Society of Marine Engineering, Vol. 38, No. 10 pp. 1217~1224, 2014
J. Korean Soc. of Marine Engineering (JKOSME)
http://dx.doi.org/10.5916/jkosme.2014.38.10.1217
ISSN 2234-7925 (Print)
ISSN 2234-8352 (Online)
Original Paper

Practical scaling method for underwater hydrodynamic model test of submarine

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(Received June 16, 2014 ; Revised July 7, 2014 ; Accepted November 4, 2014)

Abstract: This paper provides a practical scaling method to solve an old problem for scaling and developing the speed and resistance of a model to full-scale submarine in fully submerged underwater test. In every experimental test in towing tank, water tunnel and wind tunnel, in the first step, the speed of a model should be scaled to the full-scale vessel (ship or submarine). In the second step, the obtained resistance of the model should be developed. For submarine, there are two modes of movement: surface and submerged mode. There is no matter in surface mode because, according to Froude's law, the ratio of speed of the model to the full-scale vessel is proportional to the square root of lengths (length of the model on the length of the vessel). This leads to a reasonable speed and is not so much for the model that is applicable in the laboratory. The main problem is in submerged mode (fully submerged) that there isn't surface wave effect and therefore, Froude's law couldn't be used. Reynold's similarity is actually impossible to implement because it leads to very high speeds of the model that is impossible in a laboratory and inside the water. According to Reynold's similarity, the ratio of speed of the model to the full-scale vessel is proportional to the ratio of the full-scale length to the model length that leads to a too high speed. This paper proves that there is no need for exact Reynold's similarity because after a special Reynolds, resistance coefficient remains constant. Therefore, there is not compulsion for high speeds of the model. For proving this finding, three groups of results are presented: two cases are based on CFD method, and one case is based on the model test in towing tank. All these three results are presented for three different shapes that can show; this finding is independent of the shapes and geometries. For CFD method, Flow Vision software has been used.

Keywords: Submarine, Resistance, Fully submerged, Model test, Computational fluid dynamics, Towing tank

Nomenclature

A_W	Wetted area surface (m^2)
C_d	Total resistance coefficient
C_f	Frictional resistance coefficient
C_{vp}	Viscous pressure resistance coefficient
CFD	Computational Fluid Dynamics
L_M	Total length of model (m)
L_S	Total length of submarine (m)
$(Fn)_M$	Froude number of model
$(Fn)_S$	Froude number of submarine
$(Re)_M$	Reynolds of model
R	Total resistance (N)
R_f	Frictional resistance (N)
R_{vp}	Viscous pressure resistance (N)
$(Re)_S$	Reynolds of submarine
V_M	Speed of model (m/s)
V_S	Speed of ship (m/s)

1. Introduction

In every experimental test in towing tank, water tunnel and wind tunnel, in the first step, the speed of the model should be developed to the full-scale vessel (ship or submarine). In the second step, the obtained resistance of the model should be developed. For submarine, there are two modes of movement: surface and submerged mode. There is not any problem in surface mode because, according to Froud's law, the ratio of speed of the model to the full-scale vessel is proportional to the square root of lengths (length of the model on the length of the vessel) **[1]-[3]**. This leads to a reasonable speed and is not so much for the model that is applicable in the laboratory.

$$(F_n)_M = (F_n)_s \quad V_M = V_s(\sqrt{L_M/L_S})$$

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For example, for a submarine at surface mode with a speed of 10 m/s and a scale of 1:100, the required speed of the model in towing tank will be 1m/s that is easily possible. The main problem is in submerged mode (fully submerged). At submerged mode, Froude equation cannot be used because of absence of free surface effects and waves. In the depth of water, there is frictional and viscous pressure resistance and there is not wave resistance **[4][5]**. Furthermore, the use of Reynold's equation is impracticable because model speed will be too large and impossible to provide **[6]**.

$$(R_e)_M = (R_e)_S \quad V_M = V_S \cdot (L_S / L_M)$$

For example, for a submarine with a speed of 10 m/s and a scale of 1:100, the required speed of the model in towing tank will be 100 times of main submarine, which means 1000 m/s that is actually impossible. The related dynamic effects are evaluated in **[7]-[11]**. Classification of resistance in marine applications is shown in **Figure 1**, which presents the different levels of resistance. A popular and well known classification in marine engineering for total resistance (R) is the summation of wave resistance, viscous pressure resistance (R_{vp}) and friction resistance (R_f) **[12][13]**. There is not wave resistance for fully submerged submarine. Total resistance coefficient (C_d), friction resistance coefficient(C_f), viscous pressure resistance coefficients (C_{vp}) are defined as:

$$C_d = \frac{R}{0.5\rho A_W V^2} \quad C_f = \frac{R_f}{0.5\rho A_W V^2} \quad C_{vp} = \frac{R_{vp}}{0.5\rho A_W V^2}$$

Which V is the velocity in (m/s), and Aw is wetted area surface in m^2.

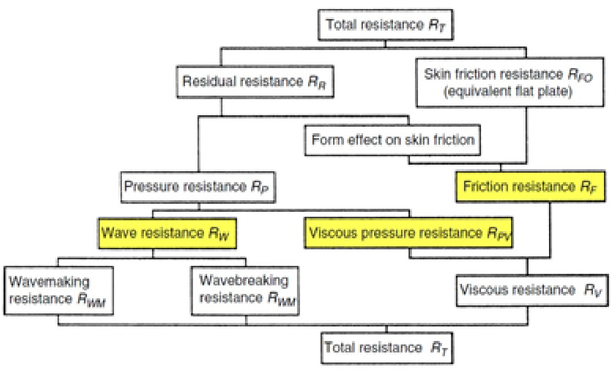

Figure 1: Decomposition and classification of resistance in marine applications **[10][11]**

There are three important notes about critical Reynolds and resistance coefficients that are described below.

Note 1: Reynolds of model and submarines do not have to be exactly equal. Main aid of Reynold's equation is to ensure from the existence of a turbulent flow on the surface of the model because the flow regime on real submarines is turbulence. Critical Reynolds is different from 300,000 to about 1000,000 that depend on another condition such as roughness of model, initial flow turbulence, vibration and heat transfer. Here is an important note that says, "providing turbulent flow can be done by many parameters not only by the Reynolds". By providing these parameters that mentioned above, the required critical Reynolds decreases steeply. For example, by setting a wire or pin on the bow of model, turbulence can be happened at critical Reynolds less than 500,000. Thus, we can be sure that the flow on the model is turbulent even in low Reynolds. Apart from that, providing Reynolds equal to one millions is not difficult and is not out of access because the kinematic viscosity coefficient is about 0.000001 that it means, for example, in a model with 1 meter length, and speed of 1 m/s the Reynolds is equal to one millions.

Note 2: Variation of the curves of frictional resistance coefficient and viscous pressure resistance coefficient after critical Reynolds (turbulent current) is almost horizontal, and shows the constant coefficient. Total resistance in fully submerged mode is equal to frictional resistance plus viscous pressure resistance. Schematic curve of variation is shown in **Figures 2** and **3**. The diagram of variations of frictional resistance coefficients versus Reynold's number for pipes is presented in all fluid dynamic books as "Moody diagram" thus it is an accepted obvious origin. This paper wants to prove that this origin can be extended to be used in fully submerged resistance of submarine. For this purpose C_f and C_{vp} diagrams versus Reynolds are plotted for three analyses. These diagrams will show that "after a special Reynolds, these coefficients are almost constant".

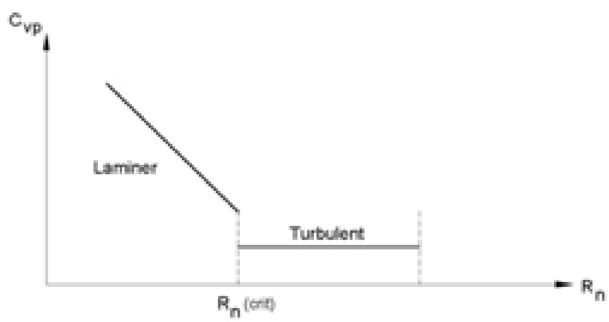

Figure 2: Schematic variations of the viscous pressure resistance coefficients versus Reynold's number

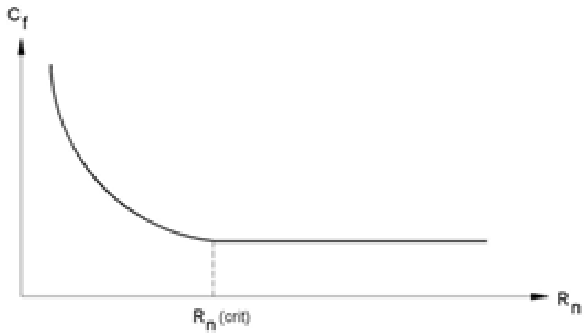

Figure 3: Schematic variations of the frictional resistance coefficients versus Reynold's number

Note 3: The variations of resistance coefficients versus Reynold's number are independent of the geometry and the shape of objects. For proving this concept, the three samples have the different shape from each other.

In the next section, the results of analysis of three studied cases are presented that contains two cases by CFD method and one case by experimental test in towing tank.

Many extensive studies have been done about resistance (drag) in aerospace engineering such as Ref **[14]**, but none of them didn't any suggestion for developing the model test results to main object for submerged vehicles. Critical Reynolds depends on the shape of object, velocity and environment. There are main differences between specifications of marine and aerial vehicles such as sharp nose, sub and super sonic speed and compressibility of air. Our focus in this paper is finding a critical Reynolds for developing the result of the model to the main vehicle for marine crafts.

2. Case 1: CFD analysis for a submarine

This analysis is done by Flow Vision 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 speed, five different amount of meshes were selected and the results were compared insofar as the results remained constant, and it shows that the results are independent of meshing. 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. 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). The turbulence model is K-Epsilon. The considered flow is incompressible fluid (fresh water) in 20 degrees centigrade.

The dimensions of the submarine are presented in **Figure 4**, and The modeling in Flow Vision is shown in **Figure 5**. Wetted area is 29.27 m2 and the specifications of fresh water are considered. According to Iranian Hydrodynamic Series of Submarines (IHSS) the code of this shape is: IHSS.1001565-30108025. Therefore, the foil section of the tower is NACA0025. The specifications of IHSS are described in **[13][14]**. Architecture, and general arrangements have a very important role in the selection of the hydrodynamic shape **[17][21]**.

Results are presented in **Table 1**, and the diagram is shown in **Figures 6** and **7**.

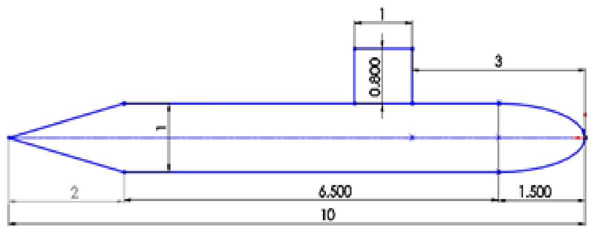

Figure 4: Dimensions of the model in case 1

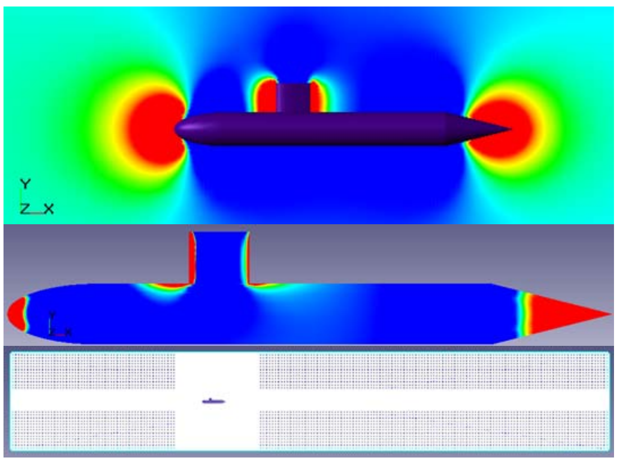

Figure 5: Modeling of case 1 in the Flow Vision software

Table 1: Total resistance coefficient of case 1 by CFD method

V (m/s)	Resistance (N)	Rn	Cd
1	182.5	10000000	0.012470106
1.5	305.17	15000000	0.009267585
2	524.84	20000000	0.008965494
2.5	800.91	25000000	0.008756105
3	1136	30000000	0.008624682
5	2742	50000000	0.007494363
7	5544	70000000	0.007730978
9	9309	90000000	0.007852814
11	13738	110000000	0.007757922
13	18995	130000000	0.007679976
15	25034	150000000	0.007602475
17	31951	170000000	0.007554294

Table 2: Viscous pressure resistance coefficient of case 1 by CFD method

V (m/s)	Resistance (N)	Rn	Cd
1	99.3	10000000	0.006785104
1.5	106.48	15000000	0.003233648
2	187.8	20000000	0.003208063
2.5	292.11	25000000	0.00319355
3	456	30000000	0.00346202
5	1245	50000000	0.003402802
7	2575	70000000	0.003590777
9	3717	90000000	0.003135558
11	5562	110000000	0.003140891
13	7762	130000000	0.003138298
15	10274	150000000	0.00312007
17	13195.8	170000000	0.003119932

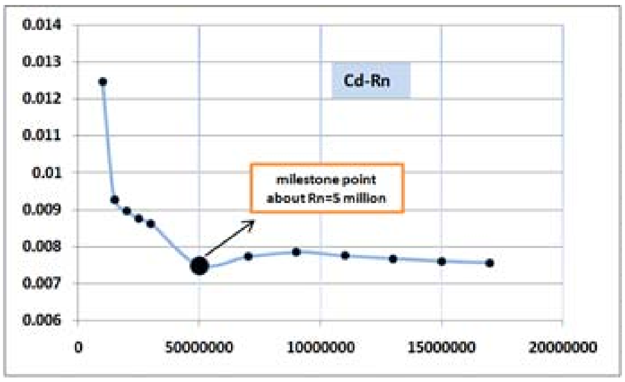

Figure 6: The diagram of variations of total resistance coefficients versus Reynold's numbers in case 1

Study on the results shows that for the total resistance coefficient, there is a millstone in Reynold's 5 millions because after this point, the variations are less than 5% (in maximum) that meant almost constant resistance coefficient after this Reynold's. The diagram of variations of viscous pressure resistance coefficients versus Reynold's, shows a millstone after Reynold's 1 millions. In both above-mentioned diagrams, there is a local hump around Reynold's 8 millions.

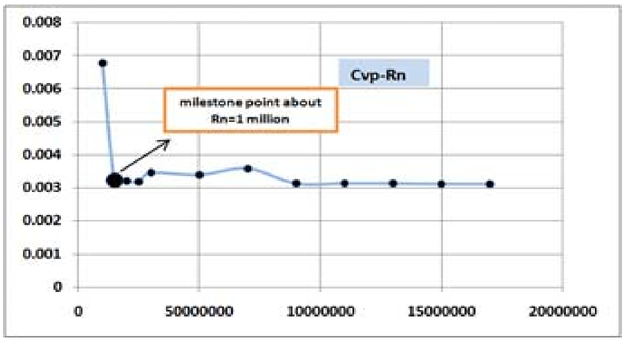

Figure 7: The diagram of variations of viscous pressure resistance coefficients versus Reynold's numbers in case 1

3. Case 2: CFD analysis for a torpedo

The specifications of the model are shown in **Figure 8**, and the modeling in Flow Vision is presented in **Figure 9**. All modeling conditions are as mentioned in case 1. Wetted area is 7.87 m2 and the specifications of fresh water are considered. According to Iranian Hydrodynamic Series of Submarines (IHSS) **[16]** the code of this shape is: IHSS.8336058.

Study on the results shows that for the total resistance coefficient, there is a millstone in Reynold's 5 millions because after this point, the variations are less than 4% (in maximum) that meant almost constant resistance coefficient after this Reynold's. The diagram of variations of viscous pressure resistance coefficients versus Reynold's, shows a millstone after Reynold's 1 and 5 millions. Such as mentioned formerly in case 1, here in both diagrams, there is a local hump around Reynold's 9 millions.

Results are presented in **Table 3**, and the diagram is shown in **Figure 10** and **11**.

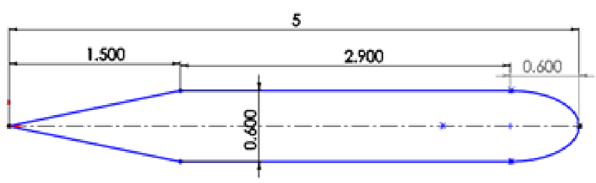

Figure 8: Dimensions of model in case 2

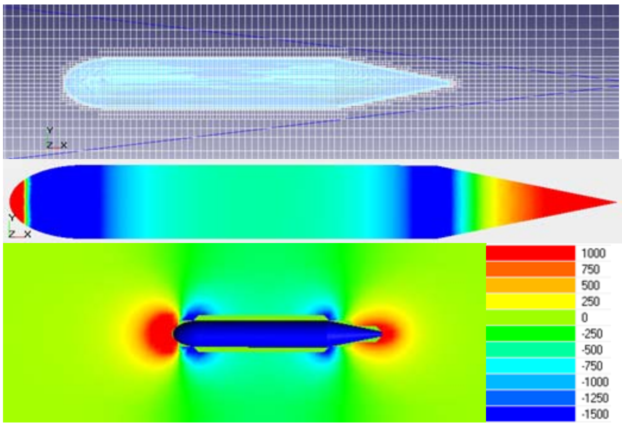

Figure 9: Modeling of case 2 in the Flow Vision software

Table 3: Total resistance coefficient of case 2 by CFD method

V (m/s)	Resistance (N)	Rn	Cd
0.05	0.092	250000	0.00935197
0.2	1.33	1000000	0.008449809
0.5	6.78	2500000	0.006891995
1	23.83	5000000	0.006055909
2	89.1	10000000	0.005660737
4	342	20000000	0.00543202
6	756	30000000	0.005336722
8	1297	40000000	0.005150095
10	1970	50000000	0.005006353
12	2836	60000000	0.005004941
14	3803	70000000	0.004930892
16	4950	80000000	0.004913834
18	6250	90000000	0.004902191
20	7595	100000000	0.004825286
26	13124	130000000	0.004933723

Table 4: Viscous pressure resistance coefficient of case 2 by CFD method

V (m/s)	Resistance (N)	Rn	Cd
0.05	0.042	250000	0.00426938
0.2	0.65	1000000	0.00412961
0.5	3.18	2500000	0.00323253
1	11.1	5000000	0.00282084
2	43.7	10000000	0.00277637
4	179.8	20000000	0.00285578
6	397.5	30000000	0.00280601
8	713.4	40000000	0.00283275
10	1094	50000000	0.00278018
12	1598	60000000	0.00282013
14	2156	70000000	0.00279543
16	2835	80000000	0.00281429
18	3650	90000000	0.00286288
20	4401	100000000	0.00279606
26	7750	130000000	0.00291347

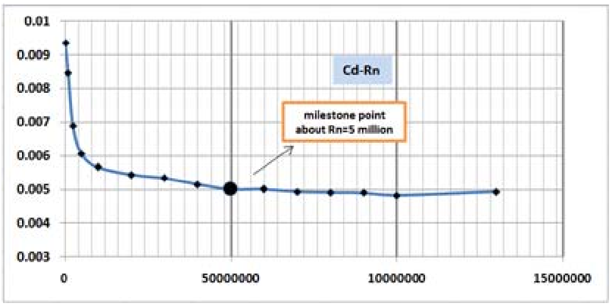

Figure 10: The diagram of variations of total resistance coefficients versus Reynold's numbers in case 2

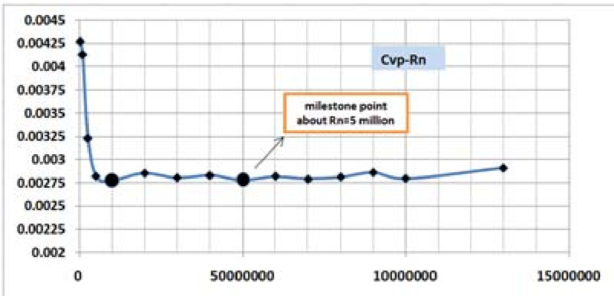

Figure 11: The diagram of variations of viscous pressure resistance coefficients versus Reynold's numbers in case 2

4. Case 3: model tests in towing tank

Experiments were conducted in the marine laboratory of Isfahan University of Technology (IUT) in Iran. The towing tank has 108(m) length, 3 (m) width and 2.2 (m) depth. The basin is equipped with a trolley that can operate in through 0.05-6 m/s speed that moves by two 7.5 KW electro-motors with ±0.02 m/s accuracy. The system is prepared with a proper frequency encoder, i.e., 500 pulses in a minute, which decreases the uncertainty of measurements. The dynamometer was calibrated by calibration weights **[22]**. A three degree of freedom dynamometer is used for force measurements. Data are recorded via an accurate data-acquisition system. The 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 materials according to ITTC recommendations **[23]**. Tango nose submarine is a type of submarine that has been tested in underwater mode. All data are filtered to eliminate the undesirable acceleration, primary and terminative motion of trolley. The trolley was controlled in a wireless system from control room of lab. The data presented in this paper for each point are an average of a lot of towing tank runs according to **[24]**. For each run, at least 750 samples in 15 seconds were collected and the ensemble averaged. Schematic of the model and the overall test stand is shown in **Figure 12**. General considerations for submarine model test are described in **[25]-[31]**.

Dimensions of studied submarine in this paper are shown in **Table 5** with parallel middle body form. Relation L/D is equal to 8.88. Hull bow has Tango shape and stern is conical. Main submarine has a deck with 28 meters of length, 0.4 meters of height and 1 meter of the beam. In addition; 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 the wetted surface area is 450 square meters. All dimensions of this submarine have been scaled by 1:32.

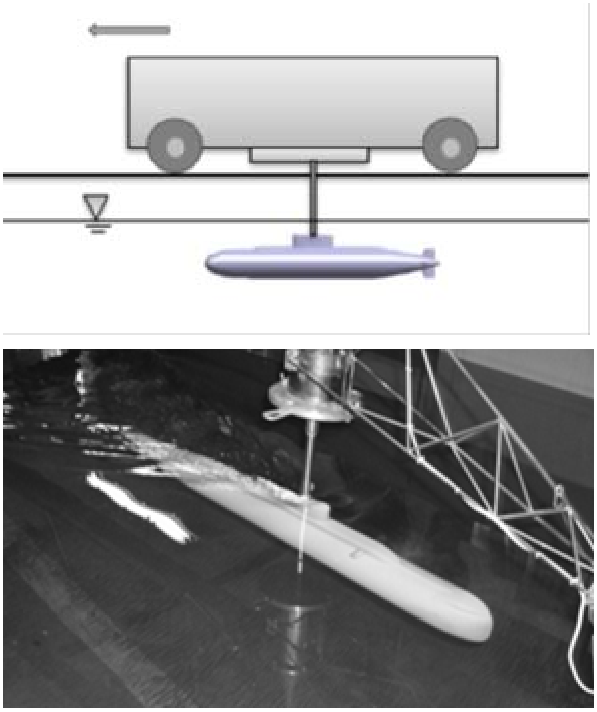

Figure 12: Schematic shape of the test stand

Dimensions of studied submarine in this paper are shown in **Table 5** with parallel middle body form. Relation L/D is equal to 8.88. Hull bow has Tango shape and stern is conical. Main submarine has a deck with 28 meters of length, 0.4 meters of height and 1 meter of the beam. In addition; 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 the wetted surface area is 450 square meters. All dimensions of this submarine have been scaled by 1:32.

By study on the experimental results, it is shown that for the total resistance coefficient, there is a millstone in Reynolds 5 millions because after this point, the variations are less than 5.1% (in maximum) that meant almost constant resistance coefficient after this Reynolds. In experimental results, such as mentioned for CFD results, there is a local hump around Reynolds 7-8 millions.

Table 5: Main Submarine Dimensions (meter)

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

Table 6: Results of model test in towing tank

V	Rn	Cd
0.2	200000	0.0065
0.5	500000	0.004293
0.6	600000	0.004119
0.7	700000	0.004201
0.8	800000	0.004177
0.9	900000	0.004047
1	1000000	0.004
1.1	1100000	0.003999
1.2	1200000	0.004011
1.3	1300000	0.003949
1.4	1400000	0.003883
1.5	1500000	0.003842

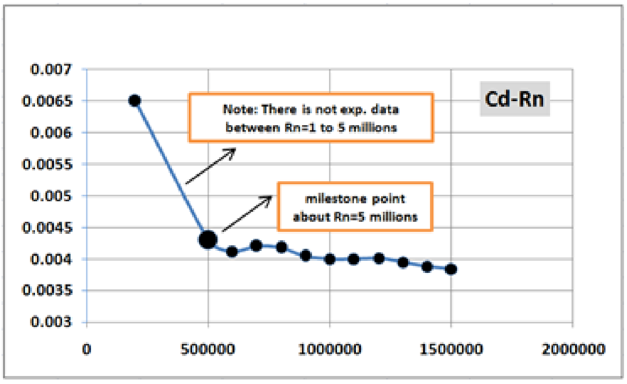

Figure 12: The diagram of variations of resistance coefficients versus Reynold's numbers for model test in towing tank

2. Analysis and Conclusion

In this paper, a practical solution was presented for solving an old problem about developing the results of the experimental model to the full-scale submarine in fully submerged mode. In every experimental test, in the first step, the speed of the model should be developed to full-scale submarine. In the second step, the obtained resistance of the model should be developed. The main problem is providing the speed of the model in the laboratory, based on Reynold's similarity. It leads to a very high and impossible speed for model.

Based on the findings of this paper, if the Reynold's of submarine at submerged test be more than 5,000,000 it can be actually supposed that total resistance coefficient of the model and full-scale submarine is equal (CTS=CTm) for every speed in the region of the mentioned Reynold's. It means that the both problems for finding "corresponded speed" and "related resistance coefficient" were simultaneously solved. For Reynold's number 5,000,000, the error of this assumption can be less than 5 percent.

If providing this Reynold's be difficult, setting some wire or pin on the bow, can be used for providing turbulent flow. Furthermore, many other ways to providing turbulent flow can be used. In every method that we be confident about turbulent flow, the total resistance coefficient is constant in every related speed.

For example, in case 3, for full-scale submarine with length 32 meters, in every speed greater than 0.16 m/s, the Reynold's number is more than 5,000,000 thus the flow regime is certainly turbulent. According to the model test results, in all speeds larger than 0.5 m/s the Reynolds are more than 5,000,000 with constant total resistance coefficients equal to 0.004. Therefore, for full-scale submarine for every speed more than 0.16 m/s, we can suppose that total resistance coefficient is constant and equal to 0.004. It should be noted that the maximum speed of the model which was tested was only 1.5 meters that are easily possible for doing.

Another interesting subject, is unexpected local hump in the resistance coefficient diagram in Reynold's number of about 7-9 millions. This phenomenon is seen in both CFD and experimental results but now, there is not any scientific reason for that.

We can summarize the findings of this paper as below:

1. Total resistance coefficient after Reynolds 5,000,000 is almost constant.

2. There is not any need for highs speed for model test in towing tank because "corresponding speed" (such as in ship model and base on Froud's law) doesn't define here. On the other hand, Reynold's similarity for finding "corresponding speed" is an unnecessary process.

3. There is a local hump in the resistance coefficient diagram in Reynold's number of 7-9 millions.

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