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Wave making system in submarines at surface condition

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In this paper the critical Froude numbers of the wave making system of submarines are evaluated at surface condition.. Focus of this paper is on finding out the hump and hollow of the wave making diagram, and related critical Froude number. Range of maximum Froude number in submarines is extracted statistically. For the study of this phenomenon, three methods are employed; CFD method, Experimental method and Analytical formulas. CFD analysis is performed for a bare hull of a submarine by Flow Vision (V.2.3) software, which is based on the solution of RANS equations. Experiments are conducted in the towing tank of Isfahan University of Technology (IUT) on two models with appendages and different bows (Tango and DREA).

[Key world: *submarine, wave making, resistance, Froude number, hump, hollow***]**

Introduction

Ship waves are believed to be due to Lord Kelvin idea (1904). He considered a single pressure point traveling in a straight line over the surface of the water, sending out waves. This consists of a system of transverse waves following behind the point, together with a series of divergent waves radiating from the point, the whole pattern being contained within two straight lines starting from the pressure point and making angles of 19 degrees and 28 minutes on each side of the line of motion[1]. The Kelvin wave pattern illustrates and explains many features of the wave system of ship or submarine. Near the bow of a ship or submarine, the most noticeable waves are a series of divergent waves that starts with a large wave at the bow and followed by others arranged on each side along a diagonal line. Between the divergent waves on each side of the body, transverse waves are formed having their crest lines normal to the direction of motion near the hull, bending back as they approach the divergent-system waves and finally coalescing with them. These transverse waves are most easily seen along the middle portion of a ship or submarine with parallel body or just behind a vehicle running at high speed. It is easy to see the general Kelvin pattern in such a bow system. Similar wave systems are formed at the shoulders, if any, and at the stern, with separate divergent and transverse patterns, but these are not always so clearly distinguishable because of the general disturbance already present from the bow system[1]. Since the wave pattern as a whole moves with the ship, the transverse waves are moving in the same direction as the ship at the same speed *V,* and might be expected to have the length appropriate to free waves running on the surface at that speed, $L_w = 2\pi V^2/g$. Conventional naval submarines are periodically obliged to transit near the surface or, at the surface of water for surveillance and recovery affairs such as: intake fresh air, charge the high pressure air capsules and starting the diesel-generators for recharging the batteries. The process of charging the batteries is the most time-consuming task at near-surface depth or snorkel depth for usually 6 to 10 hours. This time depends on the specification of the electric power system and the battery storage system. Submarines have usually 220 to 440 battery cells that should be charged in the period of snorkeling. Minimizing the resistance of a submarine, moving close to the ocean surface, is very important, because a submarine must save the energy for earlier charging the batteries and lesser need to stay at snorkel depth. For every submersible, the more resistance is equal to the additional power requirement and thus the minor range and lesser duration of operation or endurance. In critical Froude numbers, wave making resistance can make up more than 50% of the total resistance. Whenever a submarine ascents from the deep depth to the surface of water, the free surface effects cause a steep increase in the resistance because of the appearance of wave making resistance. Wave making system in ships and submarines is different because of differences in the bow shapes and Froude numbers. Rounded or elliptical bow shapes of submarines generate a high bow wave. An ideal bow form for free surface condition is a steep bow, such as ships, but for fully submerged condition without free surface effect, the suitable bow form is an elliptical shape with rounded nose, meanwhile this rounded bow is a very bad design in free surface condition. Collective studies about the bow and stern shape of submarines are performed by M.Moonesunet.al in[2,3,4,5,6,7&8] and K.N.Suman et.al[9]. Hydrodynamic aspect in submarine design is discussed by P.N.Joubert[13,14], R.Burcher and L.J.Rydill[15], Y.N.Kormilitsin and O.A.Khalizev[16], U.Gabler[17], L.Greiner[18] and in[19] by a group of authorities. In surfaced mode of navigation, such as ships, the body interferes with the free surface of water. In surface mode in calm water, the wave making resistance is an important part of resistance that depends on the Froude number. Overall discussions about wave making system (wave profile and resistance) in ships and surface vehicles are presented in many naval architecture engineering books such as[1,20&23]. Scientific materials about wave making in submarines are presented in[24,24,25,26,27,28,29,30&31]. Experimental formula for wave-making resistance achieved by submarine at snorkel depth (submerged depth just near the surface) is presented in[27,28]. This article is intended to evaluate the wave profile induced by submarine at surface condition and deck flooding occurred by the added wave-making due to the bow and the added frictional resistance caused by it.

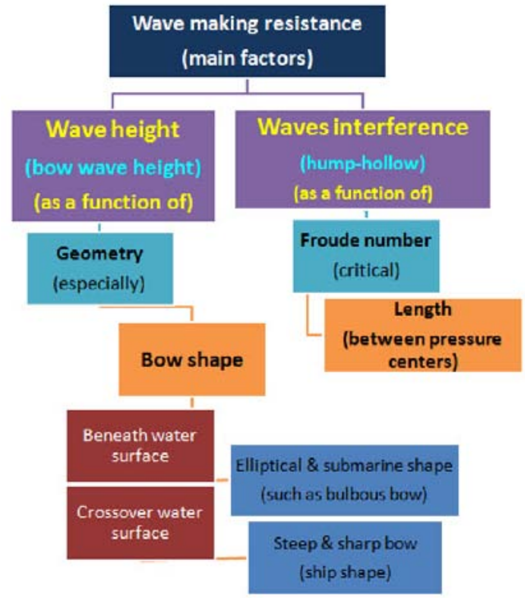


Fig. 1—Important factors in wave making resistance

Materials and Methods

A review study about critical Froude number in wave making resistance diagram

In wave making resistance diagram, there are some hump and hollow that show the interference effects of the bow and stern waves. The related Froude numbers corresponding to the hollow and hump points are named "critical Froude numbers". As shown in Fig. 1, the height of wave is a function of body shape, especially the bow shape, but the location of bow and stern wave is a function of Froude number, especially the value of "length" in Froude formula. Froude Number depends on the speed and length. In scientific references, length term has different definitions, but it is usually considered as the distance between the pressure centers of the bow and stern. Because of that, the critical Froude numbers are different in ships and submarines. It notes that; $R_T=R_{f0}+R_R=R_f+R_w+R_{vp}$. Resistance coefficient for each component is equal to $C=R/(0.5\rho.A.V2)$. The focus of this paper is on finding out the hump and hollow of the wave making diagram and related critical Froude number. Fig. 2, shows the total resistance coefficient for a model ship as a result of an experiment in towing tank[1]. The related Froude numbers are visible in Fig.2.

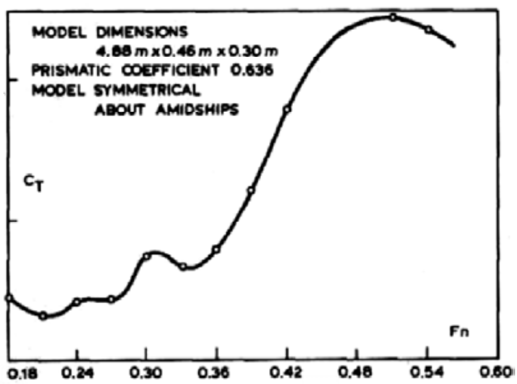


Fig. 2— Typical resistance curve for a ship, showing interference effects of waves[1]

According to[22], the related length is defined as L=0.9(LBP). Based on this assumption, the critical Froude numbers are shown in Fig. 3.

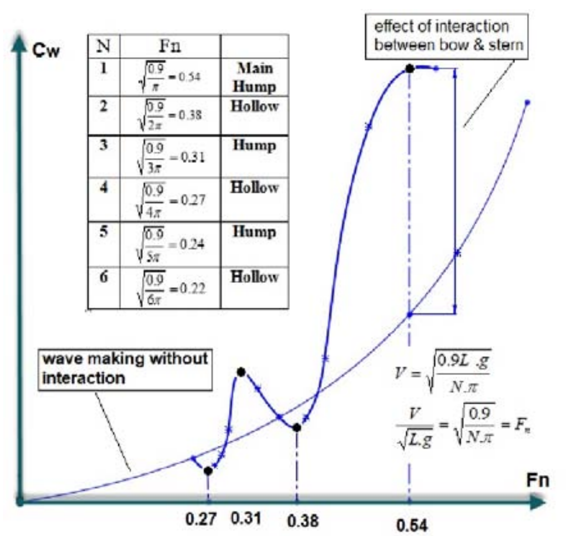


Fig. 3—variations of wave resistance coefficient versus Froude number for ships [extracted from[22]]

Regarding the wave making resistance, the first reference was presented in 1982,[30]. Fig. 4 shows the variations of wave resistance coefficient versus Froude number. In this diagram, two important factors, "L/D" and "depth of immerge" are considered. As shown in Fig. 4, it is clear that the critical Froude numbers are the same in different depth of immerge. Moreover, the wave making resistance will decrease as the depth is increased until it disappears. Fig. 5 shows the wave resistance coefficient for a tear drop shape submarine by Boundary Element Method (BEM)[31]. The related Froude numbers are visible in Fig. 5.

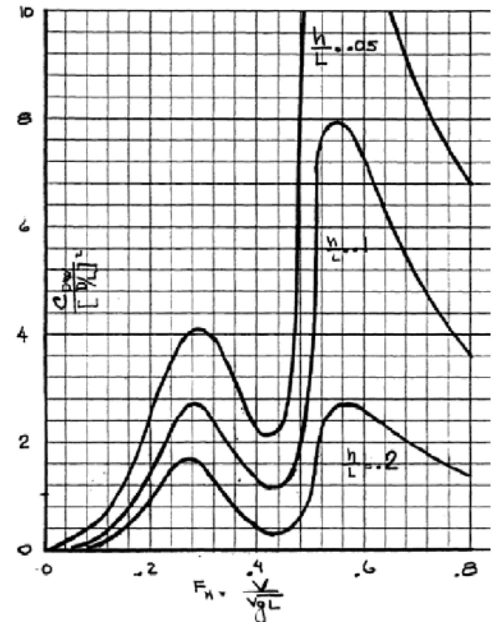


Fig. 4—variations of wave resistance coefficient versus Froude number in several depth from sea surface for submarines [28, 30]

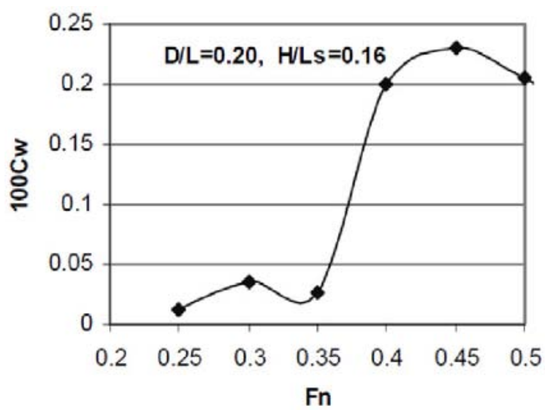


Fig. 5—Wave making resistance of a tear drop shape submarine[31]

Range of Froude number in submarines

For estimating the range of the usual Froude number in submarines, statistical values have been collected (Tab.1). The usual range of the Froude number of naval submarines is 0.15~0.25 but for torpedoes and high speed UUVs can be more than 2. Submarine is a low-speed marine vehicle. As written in Tab.1, usually maximum surface speed is approximately 45~60% of maximum submerged speed, and by average of 55%. It means 55% loss speed, due to free surface effect and wave making resistance. On the other hand, the total resistance coefficient of surface condition is more than submerged condition. It can be described so, as the total power of submarine is constant, then: Psubmerge=Psurface=constant, and $R = 0.5C_T\rho AV^2$ and P=k.R.V then: $P=K.C_T.V^3$. For comparison between surface and submerge condition, it can be said: $C_{T1}.V_1^3 = C_{T2}.V_2^3$ (or) $\frac{C_{T2}}{C_{T1}} = \left(\frac{V_1}{V_2}\right)^3$. If it be supposed that, the surface speed of a submarine be 50% of submerged speed, thus; $V_2=0.5V_1$, $\frac{C_{T2}}{C_{T1}} = (2)^3 = 8$. It meant that, total resistance coefficient in surface condition is 8 times the total resistance in submerged condition. If we suppose that frictional and form resistance are constant in snorkel depth and surface condition, then the wave making resistance is 7 times of them. It shows the huge effect of wave making resistance.

Table 1— Maximum Froude number in some naval submarines

Submarine Class	L (m)	Submerge speed (V1) (knot)	Surface speed (V2) (knot)	V2/V1 %	Fn
TRIOMPHANT	138	25	20	80	0.28
DELTA	167	24	14	59	0.18
TYPHOON	172	25	12	48	0.15
OSCAR II	144	32	16	50	0.22
COLLINS	78	20	10	50	0.19
DOLPHIN	57	20	11	55	0.24
GOTLAND	67	20	11	55	0.22
KILO	73	17	10	59	0.19
TUPI	67	24	10	42	0.20
VICTORIA	70	20	12	60	0.24
AKULA	110	33	10	30	0.16
U206	49	17	10	56	0.23
U209	64	22.5	11.5	51	0.24
Fateh	45	14	11	79	0.27
Torpedo	8	35	-	-	2.03

Wave making principles in submarine

In ships or submarines, at low speeds, the waves made by the vehicle are very small and the resistance is almost wholly viscous in character. Since the frictional resistance varies with a power of the speed (a bit less than 2), the coefficient of total resistance (C_T), when plotted to a base of Froude number, at first decreases by the increase of speed (Fig.2) and then with the increase in speed, the value of C_T begins to increase more and more rapidly. As Froude number approaches to 0.45, the resistance will vary with the sixth power of the speed (or more). However, this general form of increase in C_T is usually accompanied by a number of humps and hollows in the resistance curve. As the speed of the ship increases, the wave pattern will change in order to increase the length of the waves and alter the relative positions of their crests and troughs. In this process, there will be a succession of speeds when the crests of the two systems reinforce one another, separated by other speeds at which crests and troughs tend to cancel one another. The former condition leads to higher wave heights, the latter to lower ones, and as the energy of the systems depends upon the square of the wave heights, this means alternating speeds of higher and lower than average resistance. The humps and hollows in the C_T curve are due to the mentioned interference effects between the wave systems. Obviously, it is a good design practice, whenever possible, to ensure that the vehicle will be running under service conditions at a favorable speed. As will be seen later, the dependency of humps and hollows on Froude number is the subject that accounts for the close relationship between economic speeds and ship lengths[1]. The classification of resistance at the free surface condition is as: $R_T=R_P+R_f=(R_W+R_{VP})+R_f$. When a body travels through a fluid, the pressure field, varies over the body. While a body is moving in a stationary fluid, the waves travel at the same speed as the body. On the other hand, While a vehicle moves in a free surface, a part of dynamic energy will be lost in generating waves. At fully submerged depth, there is not a free surface. Thus, in relation to action and reaction system, the dynamic energy will be utilized for driving ahead. Indeed, the surface wave absorbs a part of energy. Obviously, the pressure fields at surface and submerged conditions are somewhat different. However, in this work, the fully submerged pressure field is considered for explaining the wave system. The wave system around a submarine is approximately according to Tab.2. Wave crest in bow tip and stern tail is expected, and wave trough between them.

Table 2— Wave system around a submarine

Part of bare hull	Location from bow tip (x/L)	Description
Bow tip	0~0.03	Stagnation point- very high pressure
Bow curvature	0.03~0.15	Very low pressure
cylinder	0.15~0.65	moderate pressure
Aft part (stern shoulder)	0.65~0.75	Low pressure
Tail of stern	0.75~1	High pressure

CFD Method

The base model considered in this work is an axis-symmetric body (similar to torpedo) without any appendages. It is because that the bare hull is only intended to be studied in this study. It helps to model half of the body (in CFD model) and saving the time. Here, one model at draft of 0.7D is analyzed. The specifications of the model are presented in Tab.3 and Fig.6.

Table 3— Main assumptions of models

v (m/s)	Fn	L (m)	D (m)	L/D	S (m^2)
1.4~3.22	0.2~0.46	5	0.6	8.33	7.87

The speeds of the model's motions are so considered that the usual range of Froude numbers in submarines could be covered. Froude numbers less than 0.2 are not studied because, the wave height is so little, that wave making resistance will be very little and there is not any hump and hollow in wave resistant coefficient diagram.

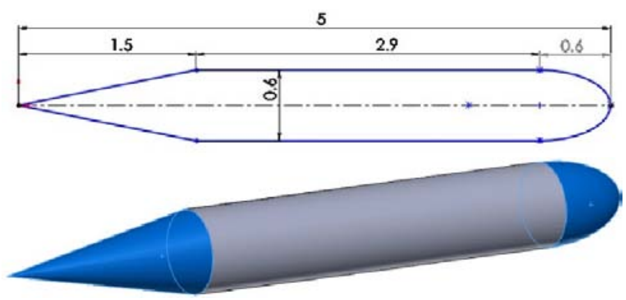


Fig. 6— General configuration of the model

The CFD analysis is performed by Flow Vision (V.2.3) software, which is based on the solution of RANS equations. The validity of the results of this software has been done by several experimental test cases and, nowadays, this software is accepted as practicable and reliable software in CFD activities. Finite Volume Method (FVM) is used for modeling the cases considered in this paper. A structured mesh with cubic cell has been used for mapping the space around the submarine. For modeling the boundary layer near the solid surfaces, the selected cells near the object are tiny and very small compared to the other parts of domain. For selecting the proper number of the cells, six different amounts of meshes were selected and the results were compared insofar as the results remained almost constant after 300 thousand meshes, and it shows that the results are independent of mesh size (Fig.7). In all modeling cases, the total number of cells is considered more than 350 thousand.

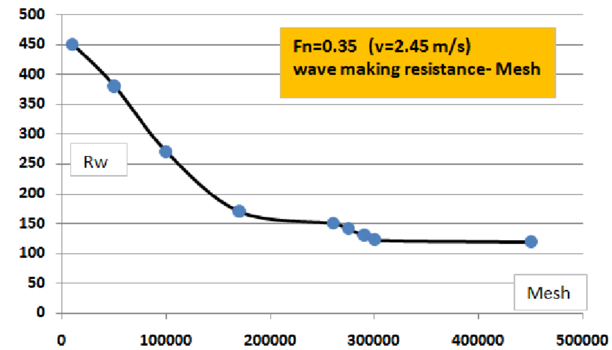
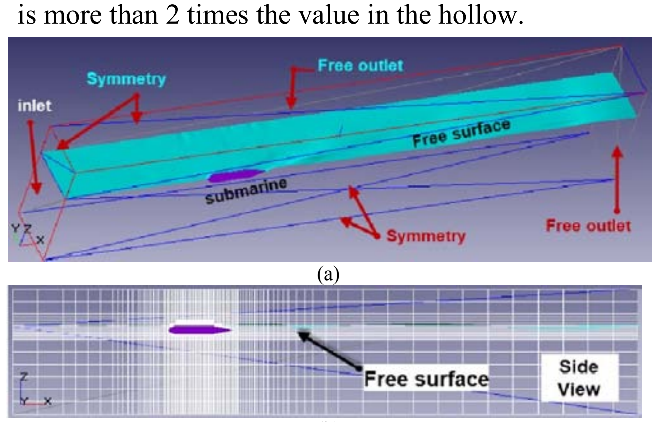
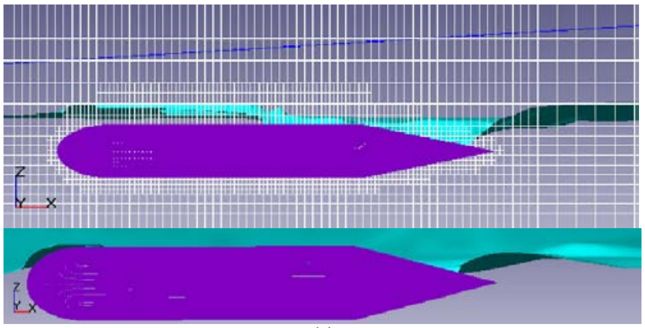


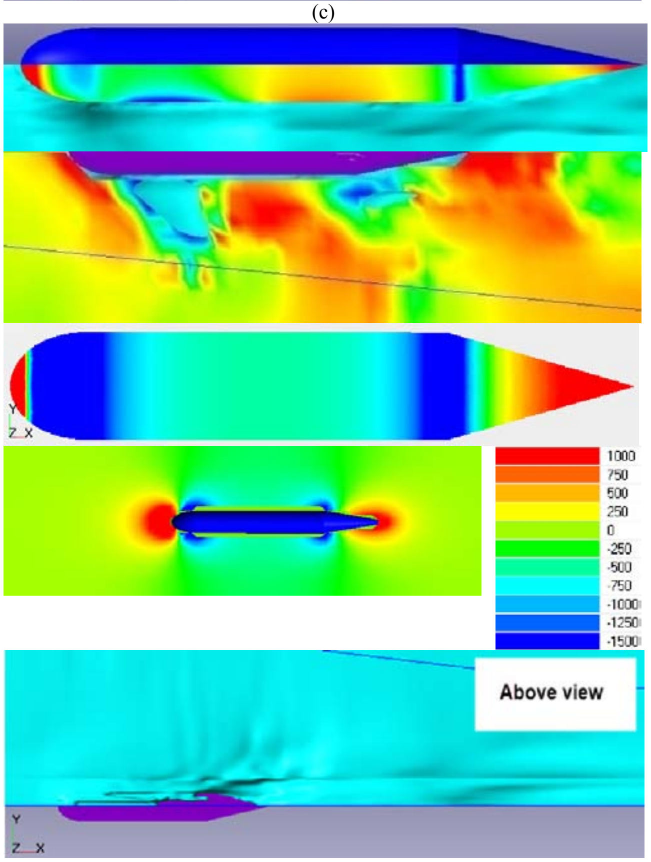
Fig. 7— Mesh independency evaluations

The domain as shown in Fig.8, has inlet (with uniform flow), Free outlet, Symmetry and Wall (for the body of submarine). Dimensions of cubic domain are 50m length (that frontal distance of the model is 12.5 m), 5m beam and 10m height (7m for water depth). Pay attention to that only half of the body is modeled because of axis-symmetric shape and symmetric flow. Therefore, the domain is modeled by half. The base model of analysis is "Free surface" with the method of "Volume of Fluid" and turbulence model is K-Epsilon and minimum y+ is considered equal to 30. The considered fluid is fresh water at 20 degrees centigrade. Modeling of free surface is shown in Fig.8. The results of analysis are shown in Fig.9. This diagram shows the wave making resistance coefficient in the Froude number range 0.2-0.46. It is because of that the wave making effects in Froude numbers less than 0.2 are negligible, and ultimate value is so considered that can cover the hollow point of diagram. The first hump is happened in Froude number of 0.29, and hollow in Froude number of 0.4. The value of wave resistance coefficient in the hump is more than 2 times the value in the hollow.





(c)



(d)

Fig.8— (a) Domain and parts (b) structured grid and tiny cell around free surface (c)Very tiny cells near the wall for boundary layer modeling and keeping y+ about 30 (d) pressure distribution upon the hull and fluid

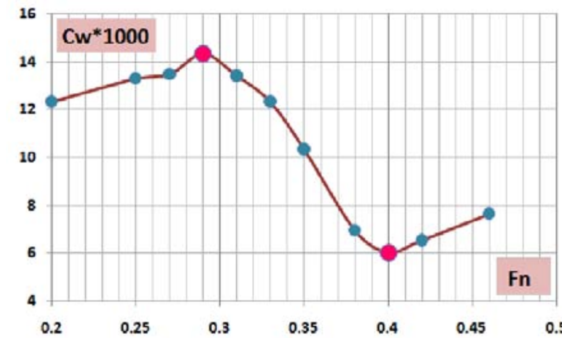
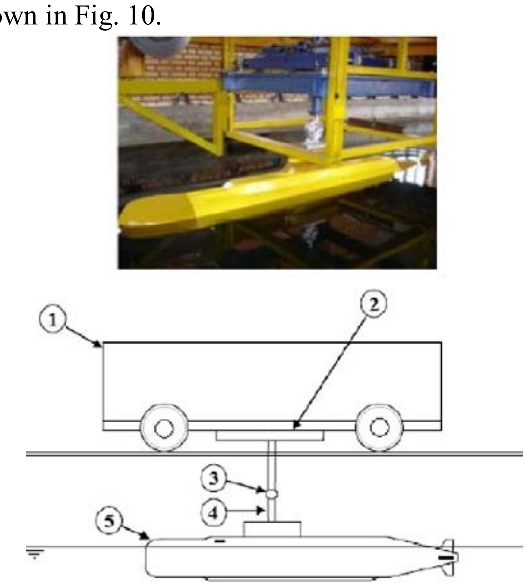


Fig. 9— Results of CFD analysis for wave making resistance

Experimental Method

Towing tank and test condition

Experiments were conducted in the towing tank of Isfahan University of Technology, which has 108(m) length, 3 (m) width and 2.2 (m) depth. The basin is equipped with a trolley that able to operate in 0.05-6 m/s speed with ±0.02 m/s accuracy. A three degree of freedom dynamometer is used for force measurements. The dynamometer was calibrated by calibration weights. The dynamometer equipped with 100 N load cells and it has 1 percent uncertainty. Schematic of the model and the overall test set up is shown in Fig. 10.

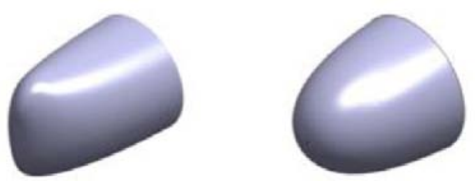


1. Trolley; 2. Dynamometer;
3. Change trim angle mechanism; 4. Strut; 5. Model
Fig. 10—Model setup in the towing tank

As indicated, the main purpose of the present work is to explore the effect of bow wave shape. The experiment conducted with a submarine model that is made by wood according to ITTC recommendations. For the study of bow wave effect, two bows with the same length are manufactured. Fig. 11 shows the profiles of bows. Profile A and B are Tango and DREA bow shape respectively. Tango bow shape has, to some extent, tapered shape such as ships. DREA bow shape is according to Fig.12, which is somewhat similar to elliptical bow. Table 4 provides a summary of the scale model characteristics.

Table 4: A summary of model characteristics

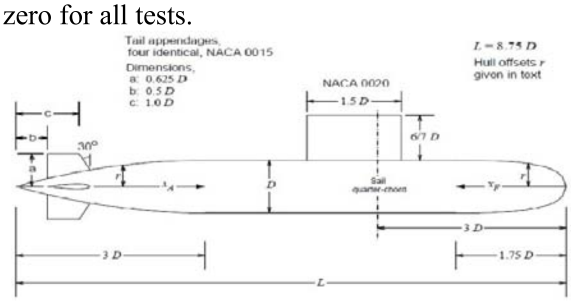
Characteristics	Quantity
Length	2110 mm
Maximum Diameter	233 mm
Length of each bows	390 mm
Draft	183 mm
Mass	32 kg



A B

Fig. 11—The Bows profiles; Tango shape (A) and DREA shape (B)

Furthermore, Model was connected to the dynamometer with a strut rigidly to restrict yaw, pitch, heave and other uninvited motions. The forced transition (laminar to turbulence) was achieved by installation of trip strips on the model. Trip strips (10 mm width) are installed on the bow at 5% overall length. The trim angle of the model is adjusted equal to zero for all tests.



$$\frac{r}{D} = 0.8685\sqrt{\frac{x_F}{D}} - 0.3978\frac{x_F}{D} + 0.006511\left(\frac{x_F}{D}\right)^2 + 0.005086\left(\frac{x_F}{D}\right)^3$$

Fig. 12— Parameters of DREA submarine hull and equation of bow form [28]

Investigation of resistance coefficient

In this diagram, CF is earned from ITTC-57 and other parts of resistance are gathered in C_R so as to satisfy equation $C_T=C_F+C_R$. These diagrams are plotted for two different bow shapes.

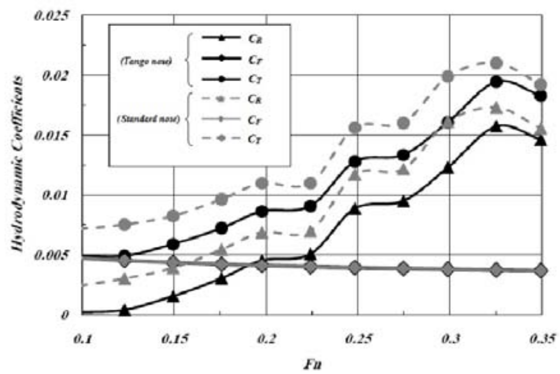


Fig.13— Variations of hydrodynamic coefficients resistance by Froude number

This diagram shows a steep increase in the residual resistance coefficient in Froude numbers of 0.225 and 0.275, and variation after Froude numbers of 0.2 and 0.25 is approximately horizontal and mild. Therefore, it can be considered, Therefore, Froude numbers of 0.25 and 0.28 can be considered as hump and hollow points, respectively. As mentioned before, interference of bow wave and stern wave, causes the creation of hump and hollow points in the resistance coefficient diagram of wave making or residual. The effect of bow wave is dominant. According to Figs. 14 and 15, the location of bow wave in both types of bow is approximately constant at a given Froude number. The reason can be seen from Fig. 1 and explained as follows: the wave length is a function of Froude number but wave height is a function of bow shape and Froude number. This condition is more visible in Fig.15.

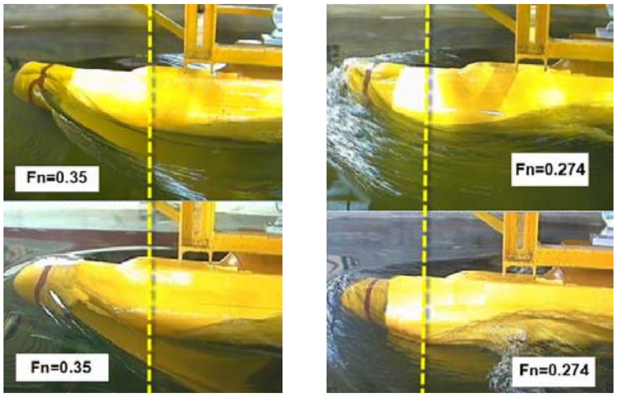


Fig. 14— Comparison the center of bow wave in to the different bow shapes

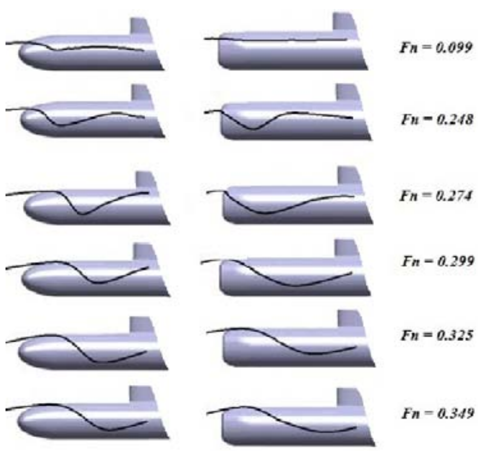


Fig. 15— the trajectories of the waves from bow to stern of the model with the both types of bows at different velocities

Analytical formula Method

An approximate formula for estimating the wave resistance of submarines is presented in[27,28]. The length in this formula, is the length overall or maximum length of the hull (LOA). This formula is extracted from the experimental results on several models of submarines at snorkel depth. General shape of the submarine is "tear drop" or "Albacore" shape. The wave making resistance coefficient (C_{DW}), is the result of this formula as below:

$$F_n = \frac{V}{\sqrt{g.LOA}} \quad (1)$$

$$C_{DW} = 561.3Fn^6 - 8812.6Fn^5 + 8148.4Fn^4 - 3454.3Fn^3 + 654.09Fn^2 - 40.235Fn + 0.2726 \quad (2)$$

$$C_w = \frac{C_{DW}}{4\left[\left(\frac{LOA}{D}\right) - 1.3606\right]\left(\frac{LOA}{D}\right)} \quad (3)$$

For example, the diagram is plotted for L/D=8.33 in Fig.16 and critical points are marked on them.

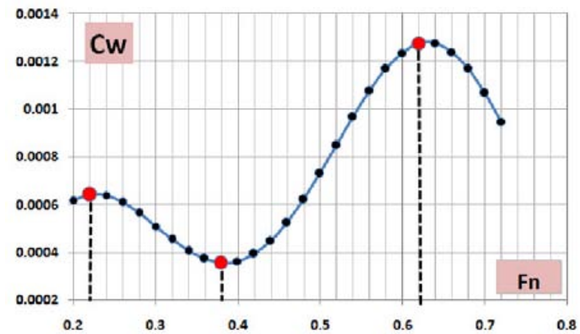


Fig. 16— Diagram of wave making resistance in snorkel depth[27&28]

Results and Discussion

This paper, offered the evaluation of the critical Froude numbers of wave making system of the submarines at surface condition. According to studies conducted in this paper, based on Fig. 17, the results can be summarized as follows:

1- The usual value of the Froude number of naval submarines isin the range of 0.15 to 0.25.

2- The usual value of maximum surface speed is approximately in the range of 45-60% of maximum submerged speed with an average value equal to 55%.

3- The ratio of the resistance coefficients in surface and submerged conditions is proportional to the cube of the inversed speeds.

4- The form of submarine can affect the wave height, but have little effect on the wave length.

5- The hump and hollow points and the wave length are strongly related to Froude numbers.

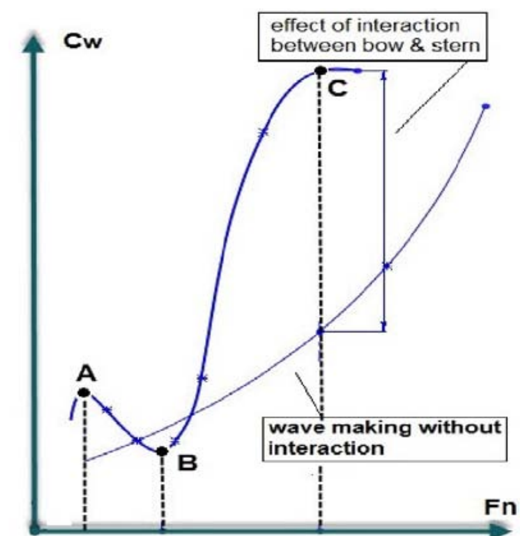
6- Critical Froude numbers of submarines can be suggested as follows: (Fn)A=0.23~0.25, (Fn)B=0.4. The Froude number of 0.58 is inaccessible, but, if available, can be a major hump.

7- In the wave resistance diagram, the range of variations at critical points can be stated as:

$\frac{(C_W)_B}{(C_W)_A} = 1.5\sim2.5$, $\frac{(C_W)_C}{(C_W)_B} = 4\sim12.$

8- In submarines,because of the maximum Froude number is usually less than 0.25, then, for Froude numbers less than 0.2, the variations of wave resistance coefficient versus Froude number can be estimated by a simple linear interpolation between the points (0, 0) and A. The error of this method can be less than 10%.

9- At critical Froude numbers of A, B and C,the general form of the interference between bow and stern wave systems is represented in Fig.18.



0.23~0.25	0.41~0.42	0.56~0.58	According to [30]	**Submarine**
0.22	0.38	0.62~0.64	According to formula of [27,28]	
0.3	0.34	0.46	According to [31]	
0.28	0.4	--	According to CFD	
0.25	0.28	--	According to model test	
0.31	0.34	0.51	According to [1]	**Ship**
0.31	0.38	0.53	According to [21]	
0.27	0.31	0.54	According to [22] Based on 0.9LBP	
0.25	0.29	0.51	According to [22] Based on LBP	
0.23~0.25	**0.4**	**0.58**	**Expected for submarine**	

Fig. 17— Estimation of critical Froude number in submarine

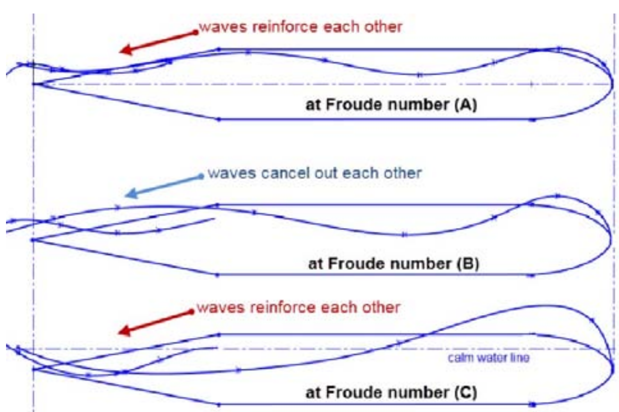


Fig. 18— General form of interference of bow and stern waves in critical Froude numbers of A, B, C

Nomenclature

CFD	Computational Fluid Dynamics
C_T	Total resistance coefficient
C_{T1}	Total resistance coefficient (submerge)
C_{T2}	Total resistance coefficient (surface)
D	maximum diameter of the outer hull (m)
EFD	Experimental Fluid Dynamics
Fn	Froude number- $Fn = v/\sqrt{g.L}$
h	Submergence depth (m)
H*	non-dimensional depth
IHSS	Iranian Hydrodynamic Series of Submarines
L	overall length of hull (m)
LOA	Length overall or maximum length (m)
R	maximum radius of the outer hull (m)
Rt	Total resistance (N)
Rf	Frictional resistance (N)
R_{f0}	Flat plate frictional resistance (N)
Rp	Pressure resistance (N)
Rvp	Viscous resistance (N)
Rw	Wave resistance (N)
ROB	Reserve of Buoyancy (%) $ROB = \frac{surface\ displacement}{submerge\ displacent} * 100$
S	Wetted surface area (m^2)
v	Speed of submarine (m/s)
V1	Maximum submerged Speed (m/s)
V2	Maximum surfaced Speed (m/s)

References

1 Edward.V. Lewis, *Principles of Naval Architecture, Vol.II*; *Resistance Propulsion and Vibration* (The Society of Naval Architects and Marine Engineers, USA), 1988, pp.256.

2 Moonesun.M, Introduction of Iranian Hydrodynamic Series of Submarines (IHSS), *J. of Taiwan society of naval architecture and marine engineering*, 33(3) (2014), 155-162.

3 Moonesun.M, M.Korol.Y, *Concepts in submarine shape design*, 16th Marine Industries Conference (MIC2014), Bandar Abbas, Iran, (2014), 269-275.

4 Moonesun.M, Korol.Y, Dalayeli.H, CFD analysis on the submarines bow shapes, *Int. J. of Naval Architecture and Ocean Engineering*, In press.

5 Moonesun.M, Korol.Y, Brazhko.A, CFD analysis on the equations of submarine stern shape, *J. of Taiwan Society of Naval Architects and Marine Engineers*, 34(1) (2015), 21-32.

6 Moonesun.M, Korol.Y, Tahvildarzade.D, Optimum L/D for Submarine Shape, *16th Marine Industries Conference (MIC2014),* Bandar Abbas, Iran (2014), 436-442.

7 Moonesun.M, Korol.Y, Tahvildarzade.D, M.Javadi, Practical scaling method for underwater hydrodynamic model test of submarine, *J. of the Korean Society of Marine Engineering*, 38(10) (2014), 217-1224. https://sites.google.com/site/jkosme76/archives/back-issues.

8 Moonesun.M, Javadi.M, Charmdooz.P, Korol.U, Evaluation of submarine model test in towing tank and comparison with CFD and experimental formulas for fully submerged resistance, *Indian J. of Geo-Marine Science*, 42(8), (December 2013), 1049-1056 http://nopr.niscair.res.in/handle/123456789/25467.

9 Suman.K.N.S, Nageswara Rao.D, Das.H.N, Bhanu Kiran.G, Hydrodynamic Performance Evaluation of an Ellipsoidal Nose for High Speed Underwater Vehicle, *Jordan J. of Mechanical and Industrial Engineering (JJMIE)*, 4(5), (November 2010), 641-652.

10 Praveen.P.C, Krishnankutty.P, study on the effect of body length on hydrodynamic performance of an axi-symmetric underwater vehicle, *Indian J. of Geo-Marine Science*, 42(8), (December 2013), 1013-1022.

11 Budiyono.A, Advances in unmanned underwater vehicles technologies: modeling, control and guidance perspectives, *Indian Journal of Geo-Marine Science*, 38(3) (September 2009), 282-295.
12 Lee.J.M, Park.J.Y, Kim.B, Baek.H, Development of an Autonomous Underwater Vehicle IsiMI6000 for deep sea observation, *Indian J. of Geo-Marine Science*, 42(8) (December 2013), 1034-1041.
13 Joubert.P.N, *Some aspects of submarine design: part 1: Hydrodynamics* (Australian Department of Defence), 2004, pp.43.
14 Joubert.P.N, *Some aspects of submarine design: part 2: Shape of a Submarine 2026*, (Australian Department of Defence), 2004, pp.69.
15 Burcher R, Rydill L J, *Concept in submarine design*, (Cambridge university press), 1998, pp. 295.
16 Kormilitsin.Yuri.N, Khalizev.Oleg.A, *Theory of Submarine Design*, (Saint Petersburg State Maritime Technical University, Russia), 2001, pp.185-221.
17 Gabler.U, *Submarine Design*, (Bernard & Graefe Verlag), 2000, pp.238.
18 Greiner.L, *Underwater missile propulsion : a selection of authoritative technical and descriptive papers*, (SSGR Ltd), 1968, pp.86.
19 A group of authorities, *Submersible vehicle system design*, (Society of naval architects and marine engineers), 1990, pp.185.
20 Bertram.V, *Practical Ship Hydrodynamics*, (Butterworth-Heinemann Linacre House, Oxford OX2 8DP) 2000, pp.65.
21 Molland.A.F, Turnock.S.R, Hudson.D.A, *Ship Resistance and Propulsion*, (Cambridge University Press), 2011, pp.14.
22 Rawson.K.J, Tupper.E.C, *Basic Ship Theory-vol.2*, (Oxford OXD 8D2), 2001, pp.685.
23 Hoerner.S.F, *Fluid Dynamic Drag*, (STRAS-USA), 1965, pp.265.
24 Javadi Mehran, Manshadi.M.D, Kheradmand.S, Moonesun.M, Experimental investigation of the effect of bow profiles on resistance of a submarine in free surface motion, *Journal of Marine Science and Application*, 14(1), 2015, 53-60.
25 Bao-ji Zhang, Shape optimization of bow bulbs with minimum wave-making resistance based on Rankine source method, *J. of Shanghai Jiaotong University,* 17(1) (2012), 65-69.
26 Alvarez A, Bertram V, Gualdesi V, Hull hydrodynamic optimization of autonomous underwater vehicles operating at snorkeling depth. *Jordan J. of Ocean Engineering*,36(1), (2009), 105–112.
27 Desta Alemayehu, *Design Report Guided Missile Submarine SSG(X)*, (Virginia Tech), 2006, pp.75.
28 Grant.B.Thomton, *A design tool for the evaluation of atmosphere independent propulsion in submarines*, (Massachusetts Ins), 1994, pp.45.
29 Sukas.O.F, Kinaci.O.K, Sakir Bal, *Computation of total resistance of ships and a submarine by a RANSE based CFD*, (Sim Ltd), 2009, pp.66.
30 Jackson.H.A, *Submarine Design Notes*, (Massachusetts Institute of Technology),1982, pp.148.
31 Ghasemi.H, Shahifar.H, Computations of Wave - Making Drag for Underwater Vehicle, *International Journal of Maritime Technology,* Iran, 4 (6) (2007), 39-48.
"http://www.ijmt.ir/browse.php?a_id=39&slc_lang=en&sid=1&ftxt=1 ".