



## RESEARCH ARTICLE

### WAVE PROFILE AND DECK WETNESS OF SUBMARINE AT SURFACE CONDITION

\*<sup>1</sup>Mohammad Moonesun, <sup>2</sup>Hosein Dalayeli, <sup>3</sup>Mehran Javadi, <sup>4</sup>Mousavizadegan, S.H.,  
<sup>5</sup>Alexander Ursalov and <sup>6</sup>Gharachahi, A.,

<sup>1</sup>National University of Shipbuilding Admiral Makarov (NUOS), Faculty of Ship Design, Ukraine and Faculty of marine collage of MUT, Shahin Shahr, Iran

<sup>2</sup>Faculty of Mechanical Engineering collage of MUT, Shahin Shahr, Iran

<sup>3</sup>Isfahan University of Technology, Marine Laboratory, Isfahan, Iran

<sup>4</sup>Amirkabir University of Technology, Naval Architecture & Marine Engineering, Iran

<sup>5</sup>National University of Shipbuilding Admiral Makarov (NUOS), Faculty of Ship Design, Ukraine

<sup>6</sup>Chabahar Marine University, Chabahar, Iran

#### ARTICLE INFO

##### Article History:

Received 5<sup>th</sup> October 2015

Received in revised form

18<sup>th</sup>, November 2015

Accepted 15<sup>th</sup> December 2015

Published online 30<sup>th</sup>, December 2015

##### Keywords:

Submarine,  
Hydrodynamic,  
Wave making,  
Bow wave,  
Deck wetness,  
Resistance.

#### ABSTRACT

This paper describes the evaluation of the wave profile of submarine at surface condition and deck flooding which occurred by the wave making pattern at the bow. Movement of ships and submarines on the free surface of calm water creates the surface wave. Because of the difference in the bow shape and freeboard height, the wave making system in ships and submarines is different. Rounded or elliptical bow shape of submarines generates a high bow wave which causes deck and bow wetness. This is because of the fact that, in submarines this situation arises a small freeboard. In submarines, Deck wetness (because of deck flooding) is a very important subject that has some remarkable consequences, such as increase in resistance and added weigh. The focus of this paper is on the added frictional resistance in the deck wetness condition. Two methods are employed in this study in order to evaluate this phenomenon; CFD method and experimental method. In the first stage of the investigation, the bow wave profile, deck wetness and added resistance are studied in several Froude numbers by CFD method. In the next stage, the bow wave profile is studied in two different bow shapes (Tango and DREA) by the experimental method. This analysis is performed for a bare hull model at two different drafts by Flow Vision (V.2.3) software based on CFD method and solving the RANS equations. Experiments are conducted for two models with appendages and different bow shapes (Tango and DREA) in the towing tank of Isfahan University of Technology (IUT).

#### INTRODUCTION

Movement of ships and submarines on the free surface of calm water creates the surface wave. Submarines have two modes of navigation: surfaced mode and submerged mode. 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 battery is the most time-consuming task at near surface depth or snorkel depth for usually 6~10 hours that depends on the specifications of electric power system and battery storage. Submarines have usually 220~440 battery cells that should be charged in the period of snorkeling. Minimizing the resistance of a submarine, transiting 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 additionally

\*Corresponding author: Mohammad Moonesun,  
National University of Shipbuilding Admiral Makarov (NUOS),  
Faculty of Ship Design, Ukraine and Faculty of marine collage of  
MUT, Shahin Shahr, Iran.

power requirement and thus, minor range and lesser duration of operation or endurance. In contrast to a surface vessel, a deeply submerged submarine, does not encounter the penalty of wave making resistance. Wave making resistance, in critical Froude numbers, can make up more than 50% of total resistance. Whenever a submarine ascends from the deep depth to the surface of water, the free surface effect causes a steep increase in the resistance because of appearance of wave making resistance. The wave making system in ships and submarines is different because of difference in the bow shape and freeboard height. Rounded or elliptical bow shape of submarines generates a high bow wave. An ideal bow form for free surface condition is a ship-like 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.Moonesun *et al.* in Refs (Moonesun, 2014; Moonesun and Korol, 2014; and Moonesun *et al.*, 2014) and K.N.Suman *et al.* (2010). Hydrodynamic aspect in submarine design is discussed by P.N.Joubert (Joubert, 2004 and Joubert, 2004), Burcher and Rydill (1998), Kormilitsin and Khalizev, (2001), Gabler, (2000), Greiner, (1968) and in Ref, (1990) by a

group of authorities. In surfaced mode of navigation, such as ships, the body interferes with free surface of water. In surface mode in calm water, the wave making resistance is a main part of resistance that depends on the Froude number. For a submarine at the deep depth of water, there is not wave-resistance problem because the effects of free surface of water are eliminated. Overall discussions about the wave making characteristics of ships and surface vehicles (wave profile and resistance) are presented in many naval architecture engineering books such as Refs (Lewis, 1988; Bertram, 2000; Molland, 2011; Rawson, 2001 and Hoerner, 1965). Scientific materials about the wave making characteristics of submarines are presented in Refs (Mehran Javadi, 2014; Bao-ji Zhang, 2012; Alvarez, 2009; Desta Alemayehu, 2006; Grant Thomson, 1994 and Sukas, 2005). Experimental formula for wave making resistance of submarine in snorkel depth (submerged depth just near the surface), is presented in Refs (Grant, Thomson 1994 and Sukas *et al.*, 2005). Dynamic modeling of submarines is discussed in Refs (Jang, 2006; Sohn *et al.*, 2006). This article wants to evaluate the wave profile of submarine at surface condition and deck flooding (occurred by the wave making pattern at the bow) and its corresponding added frictional resistance.

**Freeboard and reserve of buoyancy in submarines**

One of the main reasons of deck wetness and bow flooding in submarines is low values of ROB (Reserve of Buoyancy) and as a result, low freeboard height. As mentioned in Refs, (Burcher *et al.*, 1998; Yuri, 2001 and Ulrich Gabler, 2000) the common values of ROB in submarines, according to the volume of Main Ballast Tanks (MBT), is between 10 and 15%. These values of ROB results in an approximately freeboard between 0.1D and 0.17D as shown in Fig.1.

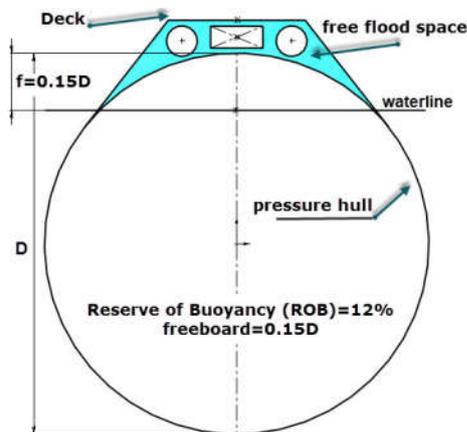


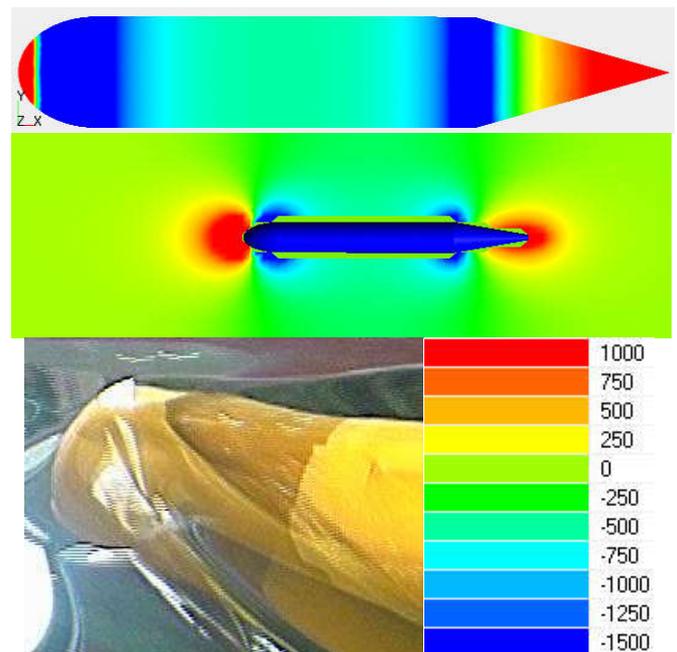
Figure 1. Free board, deck and free flooding space in submarine

It means a very low freeboard which can be flooded easily by bow wave making system. As shown in Fig.1, the pressure hull is watertight while space between the pressure hull and deck

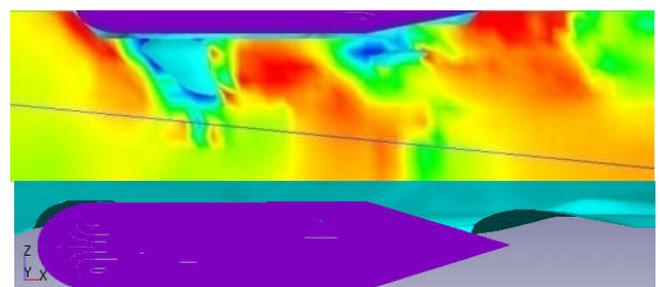
does not have this characteristic and has several flooding holes. Based on this fact, this space is named "free-flooding space". Since the deck is not watertight, the freeboard height is the distance from waterline to the top of the pressure hull. Usually, the height of the deck is considered so small that produce minimum resistance in submerged navigation mode. The whole bow part becomes wetted and flooded too. When deck wetness happens, a large amount of water can enter the free flooded spaces. It causes added resistance due to the added wetted surface. Weight variation is very significant for submarine from floating and stability point of view. Apart from that, the dynamic properties of submarine are important too.

**Wave making principles in submarine**

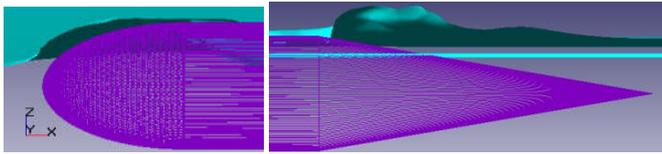
The classification of resistance in free surface condition is as:  $R_T = R_p + R_f = (R_w + R_{vp}) + R_f$ . When a body travels through a fluid, the pressure field, varies over the body. Figure 2(a) shows the pressure field around a sample submarine at fully submerged depth. It is the general form of pressure distribution around a submarine. Near a free surface (Figure 2-b), the pressure variations manifest themselves by changes in the fluid level and creating waves. With a body moving through a stationary fluid, the waves travel at the same speed as the body. While a vehicle moves in a free surface, a part of dynamic energy is lost in generating waves. At fully submerged depth, there is not a free surface, thus, the dynamic energy will be utilized in action and reaction system, for driving ahead. Indeed, surface wave absorbs a part of the energy.



(a) Pressure field around a submarine at fully submerged depth



(b) Free surface elevation according to the pressure field



(c) Bow and stern wave in high pressure area

Figure 2. Pressure field and wave shape

Obviously, pressure field at submerged and surfaced conditions are somewhat different, but fully submerged pressure field is considered for explaining the wave system. As shown in Fig.2(a), it can be derived that the wave system around a submarine is approximately according to Tab.1. Wave crest in bow tip and stern tail is expected, and wave trough between them.

Table 1. 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 cylinder	0.03~0.15	Very low pressure
Aft part (stern shoulder)	0.15~0.65	moderate pressure
Tail of stern	0.65~0.75	Low pressure
	0.75~1	High pressure

Because of essential differences in the shape of submarines and ships, the pressure field and wave system around the hull is very different. The lesser wave height means the better form design and lesser resistance. Wave crest at the bow of submarine is higher than the bow wave of ship because of higher wave height. It means that sharp edge bow is better than elliptical bow in free surface condition. Because of submarines usually have long conical stern that helps to gradual pressure variation, the amplitude of wave trough in its stern shoulder is less than the ship's one (Fig.3).

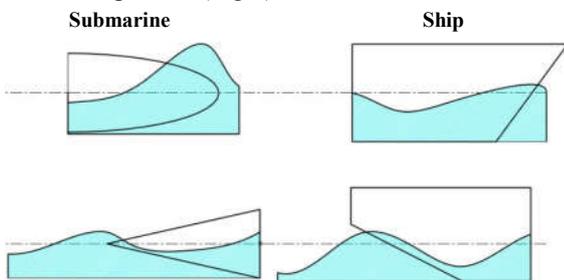


Figure 3. Comparison of wave system in submarines and ships

4- Common Froude number in submarines

For estimating the range of the usual Froude number in submarines, statistical values have been collected (Tab.2). Submarine is a low-speed marine vehicle. As written in Tab.2, 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. 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.

CFD Modeling

Assumptions for the Model of CFD analysis

The base models that considered here, is an axis-symmetric body similar to torpedo, without any appendages because in this study, only bare hull, wants to be studied. It helps to half

CFD modeling of the body and saving the time. Here, one model at two drafts is considered. The specifications of the model are presented in Tab.3 and Fig.4.

Table 2. Common Froude number in naval submarines

Submarine Class	length (m)	Submerge speed (knot)	Surface speed (knot)	V2/V1 %	Fn
Triumphant	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		0.23
U209	64	22.5	11.5		0.24
Fateh	45	14	11		0.27
Torpedo	8	35	-	-	2.03

Table 3. Main assumptions of models

Model	v (m/s)	Fn	L (m)	D (m)	L/D	S (m <sup>2</sup> )
A	1.4~7	0.2~1	5	0.6	8.33	7.87

The speed of models is considered so that the usual range of Froude numbers in submarines could be covered. Froude numbers less than 0.2 are not studied here. It is for this reason that the wave height would be too small so that the deck wetness does not occur and wave making resistance adopts a very low value.

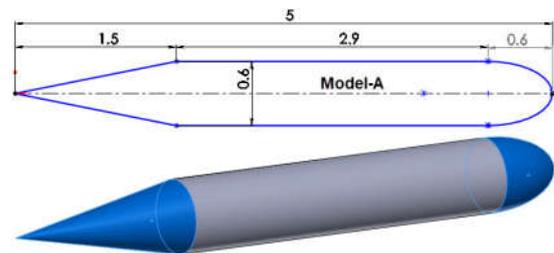


Figure 4. General configuration of the model

Two different drafts are considered; h=0 and 0.1m. At draft h=0, the hull axis is located on the free surface level. This situation is equal to ROB=50%, that is not according to the real demand of submarines. This case is considered only for evaluation of the extremes of the deck wetness. The draft of 0.1m is equivalent to ROB=12% that is related to the real naval submarines. This situation is consistent with the fact.

CFD Method of Study

The analysis is performed by Flow Vision (V.2.3) software based on CFD method and solving the RANS equations. Generally, the validity of the results of this software has been done by several experimental test cases, and nowadays, this software is accepted as a practicable and reliable software in CFD activities. For modeling these cases in this paper, Finite Volume Method (FVM) is used. A structured mesh with cubic cell has been used to map the space around the submarine. For modeling the boundary layer near the solid surfaces, the selected cell near the object is tiny and very small compared to the other parts of domain. For selecting the proper quantity of the cells, six different amounts of meshes were selected and the results were compared insofar as the results remained almost constant after 300 thousands meshes, and it shows that the

results are independent of meshing (Fig.5). In all modeling the mesh numbers are considered more than 350 thousands.

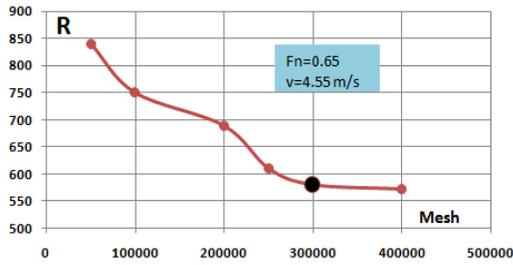


Figure 5. Mesh independency evaluations

The domain as shown in Fig.6, 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 in 20 degrees of centigrade. Free surface modeling is shown in Fig.6. Note that, in all modeling in this paper, the model and its draft are fixed and there is not a sea wave.

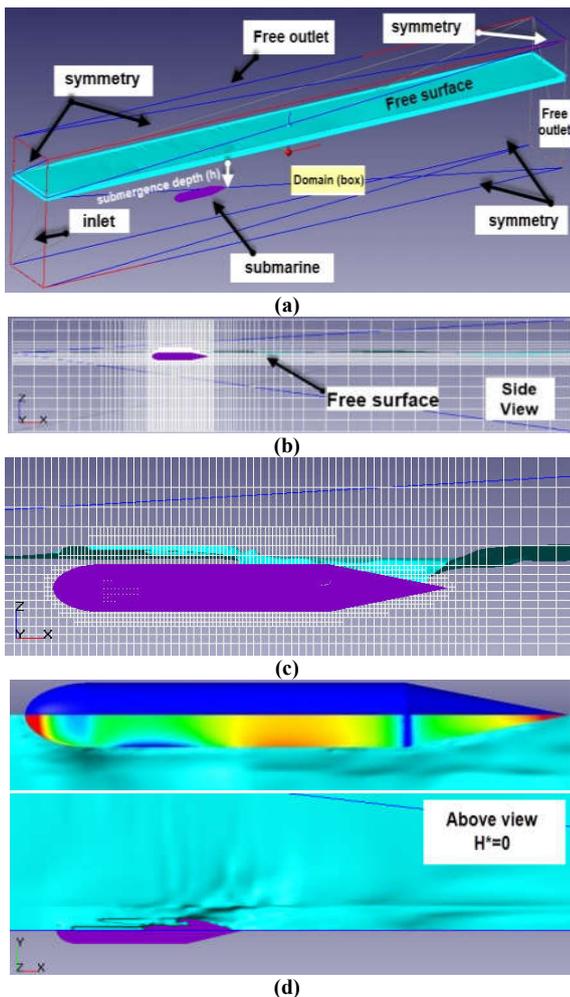


Figure 6. (a) Domain and structured grid (b) tiny cell around free surface (c) Very tiny cells near the wall for boundary layer modeling and keeping  $y^+$  about 30 (d) Half modeling because of axis-symmetry and free surface variations

CFD Results and Analysis

Model at  $h=0$

In this study, the model is analyzed in several Froude numbers of 0.2~1 at the draft  $h=0$ . In this draft, only half of the body is submerged. For evaluating the added resistance due to deck and bow wetness, and comparing the results, the model is analyzed in fully submerged condition without free surface effects. Because of symmetry in the model and flow direction, only a quarter of submarine and domain is modeled (Fig.7). The results of bow wave profile at each Froude number are shown in Fig.8.

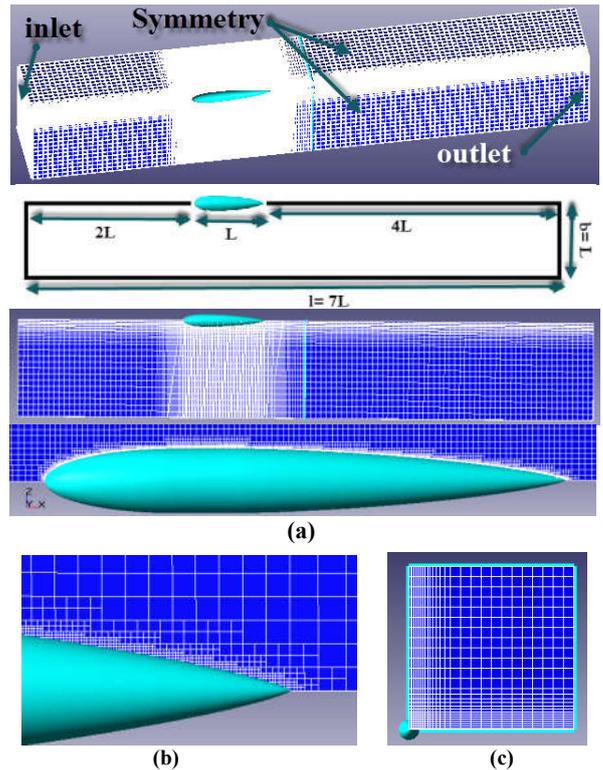
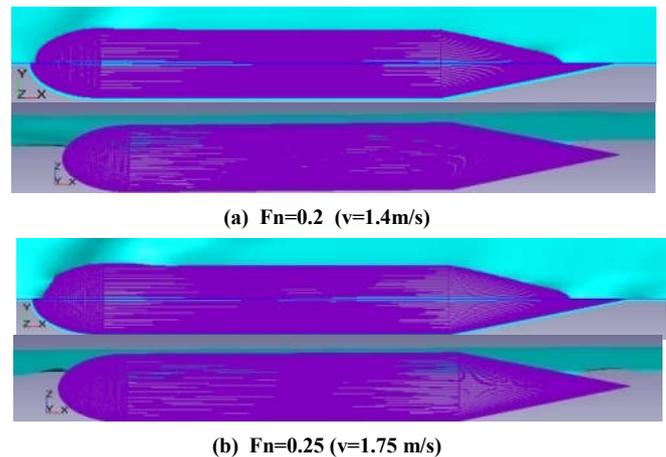
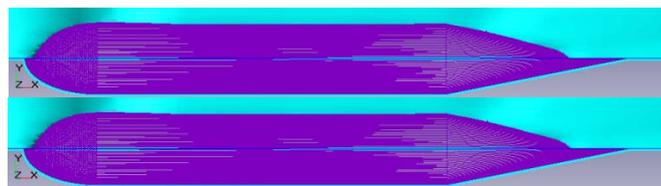


Figure 7. Quarterly modeling because of axis-symmetry at fully submerged condition (without free surface effect)

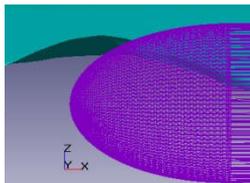
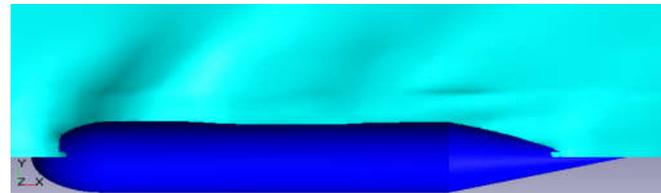
Then, one-quarter of this resistance is compared to the resistance in free surface condition. It is for this reason that, at free surface condition only half of the body is being modeled and in this modeling only half of the model is submerged. It means that in the free surface condition, only a quarter part of body is the wetted part. Frictional resistance is proportional to wetted area.



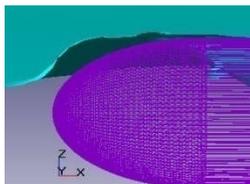
(b)  $Fn=0.25$  ( $v=1.75$  m/s)



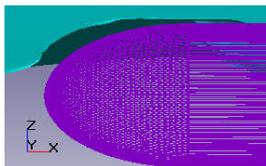
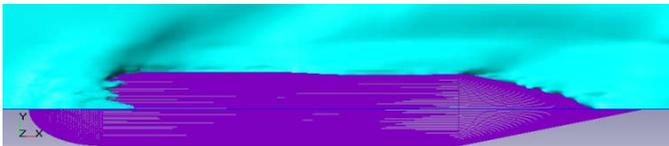
(c) Fn=0.29 (v=2.03 m/s)



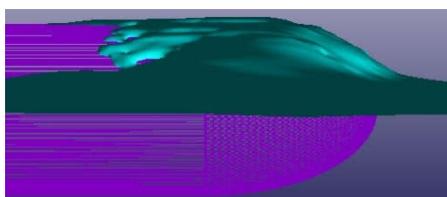
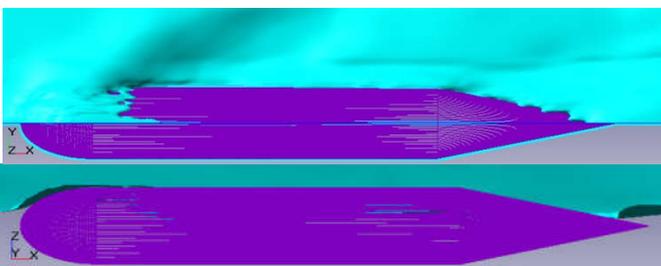
(d) Fn=0.33 (v=2.31 m/s)



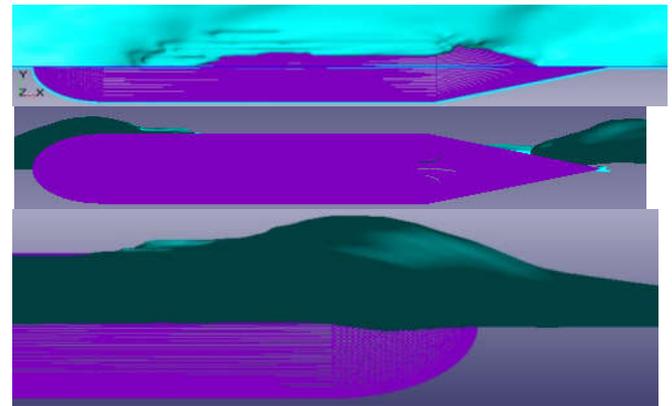
(f) Fn=0.38 (v=2.66 m/s)



(g) Fn=0.42 (v=2.94 m/s)



(h) Fn=0.46 (v=3.22 m/s)



(i) Fn=0.5 (v=3.5 m/s)

Figure 8: Up view and side view of free surface at h=0m

This portion of the draft is unusual in submarines, but here, it is considered for studying the frictional resistance. According to Fig.8-a,b, the bow wave appears at Froude numbers above 0.2. By increasing the Froude number (Fn), bow is partially flooded (Fig.8-c-d) until a value of Fn 0.35 is reached. At this value, the bow is completely flooded (Fig.8-e). At Froude number of 0.5, deck wetness is complete. Added resistance due to deck wetness is presented in Tab.4. This table shows the considered Froude number, related velocity, a quarter of the resistance in submerged mode (without free surface effects) and half of the resistance in free surface condition. The last column in tab. 4 is “difference”. This term is difference in the frictional resistance between fully submerged mode and free surface condition and is defined as:

$$\begin{aligned} \text{Added frictional resistance (\%)} &= \frac{\left( \begin{array}{l} \text{half of frictional resistance in free surface} \\ - \text{quarter of frictional resistance in submerged} \end{array} \right)}{\text{quarter of frictional resistance in fully submerged}} \\ &= \frac{\frac{1}{2} R_{f2} - \frac{1}{4} R_{f1}}{\frac{1}{4} R_{f1}} * 100 \end{aligned}$$

Table 4. Added frictional resistance due to deck wetness

Test condition	Fully Submerged (1)	Free Surface (2)		Difference (%)		
		1/4 Rt	1/2 Rt			
Fn	V (m/s)	1/4 Rf	1/2 Rf			
0.2	1.4	10	6	21	6	0.0
0.25	1.75	15.3	9	37.2	9.2	2.2
0.27	1.89	18	11	49.4	11.4	3.6
0.29	2.03	20.4	12	65	13	8.3
0.31	2.17	23.1	13.6	86	14	2.9
0.33	2.31	26	15.1	103	17	12.6
0.35	2.45	29	16.9	120	21	24.3
0.38	2.66	34.5	19.7	165	24	21.8
0.4	2.8	37.7	21.7	115	26	19.8
0.42	2.94	41.3	23.6	125	30	27.1
0.46	3.22	49	28	186	36	28.6
0.5	3.5	57.5	32.5	203	34	4.6
0.54	3.78	66.5	37.5	235	40	6.7
0.57	3.99	74	41.5	267	44	6.0
0.6	4.2	81.7	45.7	250	47	2.8
0.65	4.55	95.2	53.2	290	59	10.9
0.71	5	114	64	305	73	14.1
0.8	5.6	141.8	78.3	403	85	8.6
0.9	6.3	178	97	519	99	2.1
1	7	218	118	581	124	5.1

As shown in tab. 4, the frictional resistance is increased in all speeds from 0 to 30 percent (approximately). In Froude number of 0.2, the added resistance is almost equal to zero because the bow and deck flooding is not happening. The increase in the added frictional resistance is not regular because of variation in wave profile in different Froude numbers.

Again, it needs to be mentioned that the model is fixed and there is no change in the draft. It can affect the results in real floating condition and causes more resistance. Pressure resistance represents the resistance without viscosity. In free surface condition, the pressure resistance is equal to the summation of the wave resistance and the form resistance. Nevertheless, there is no wave resistance in fully submerged condition. Therefore, the pressure resistance is equal to the form resistance. The amount of the total, pressure and frictional resistance are shown in Fig.9 for fully submerged condition. It shows that total resistance includes 55% for frictional and 45% for pressure resistance.

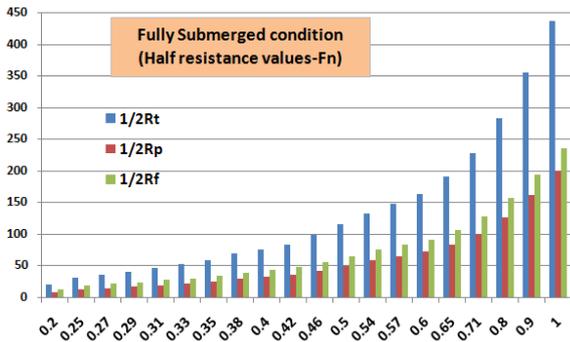


Figure 9. Resistance versus Froude numbers in fully submerged condition

The amount of the total, pressure and frictional resistance are shown in Fig.10 for free surface condition. It shows that the quota of frictional and pressure resistance depends on the Froude number. But compared to the submerged condition, the frictional resistance in most of the speeds has been decreased, because of the bow and deck wetness.

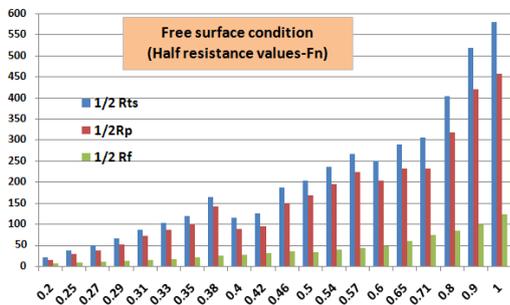
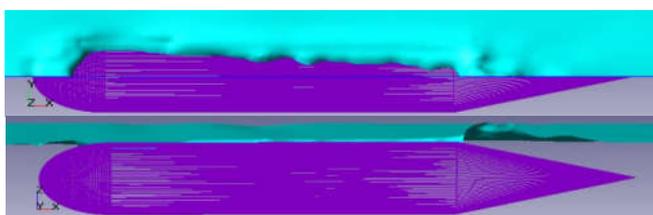


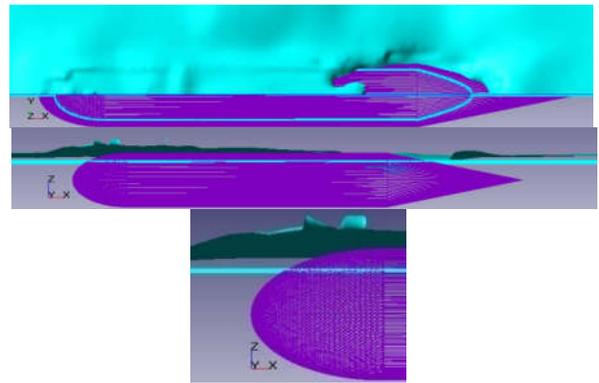
Figure 10. Resistance versus Froude numbers in free surface condition

Model at h=0.1m

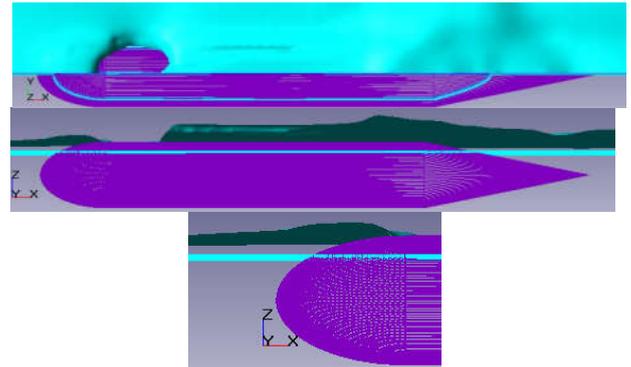
In this part, the model is analysed in several Froude numbers of 0.2~0.27 at the draft h=0.1. This draft is in the range of real submarine draft and ROB. The results of bow wave profile at each Froude number are shown in Fig.11. This figure shows that at Froude number 0.2, the wave profile is visible. At Froude number of 0.27, the most part of the deck is flooded and fully deck wetness is happened.



Fn=0.2 (v=1.4 m/s)



Fn=0.25 (v=1.75 m/s)



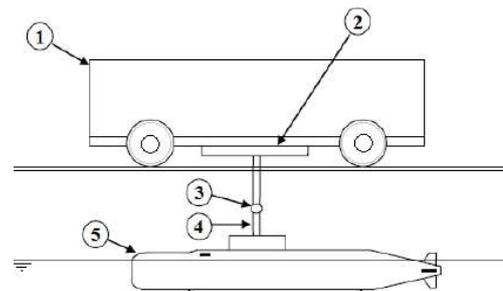
Fn=0.27 (v=1.89 m/s)

Figure 11. Up view and side view of free surface at h=0.1m

Experimental Analysis

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 that have 1 percent uncertainty. Schematic of the model and the overall test set-up are shown in Fig.12.



1. Trolley; 2. Dynamometer; 3. Change trim angle mechanism; 4. Strut; 5. Model

Figure 12. 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 of wood according to ITTC recommendations. For the study of bow wave effect, two bows with the same length are manufactured. Fig.13 shows the profiles of bows. Profiles 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 according to Fig.14 is somewhat similar to elliptical bow. Table 5 provides a summary of the scale model characteristics.

Table 5. 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

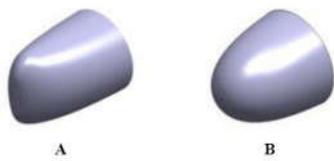


Figure 13. The Bows profiles; Tango shape (A) and DREA shape (B)

Furthermore, Model was connected to the dynamometer with a strut rigidly to restrict yaw, pitch and other unwanted 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 percent of the overall length from bow tip. The trim angle of the model is adjusted equal to zero for all tests.

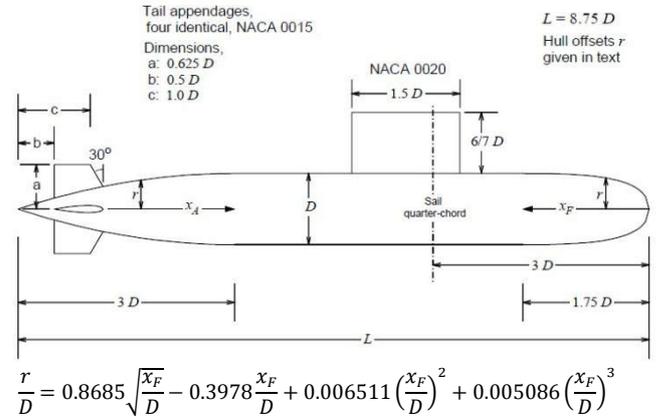


Figure 14: Parameters of DREA submarine hull and equation of bow form is named as Standard bow [28]

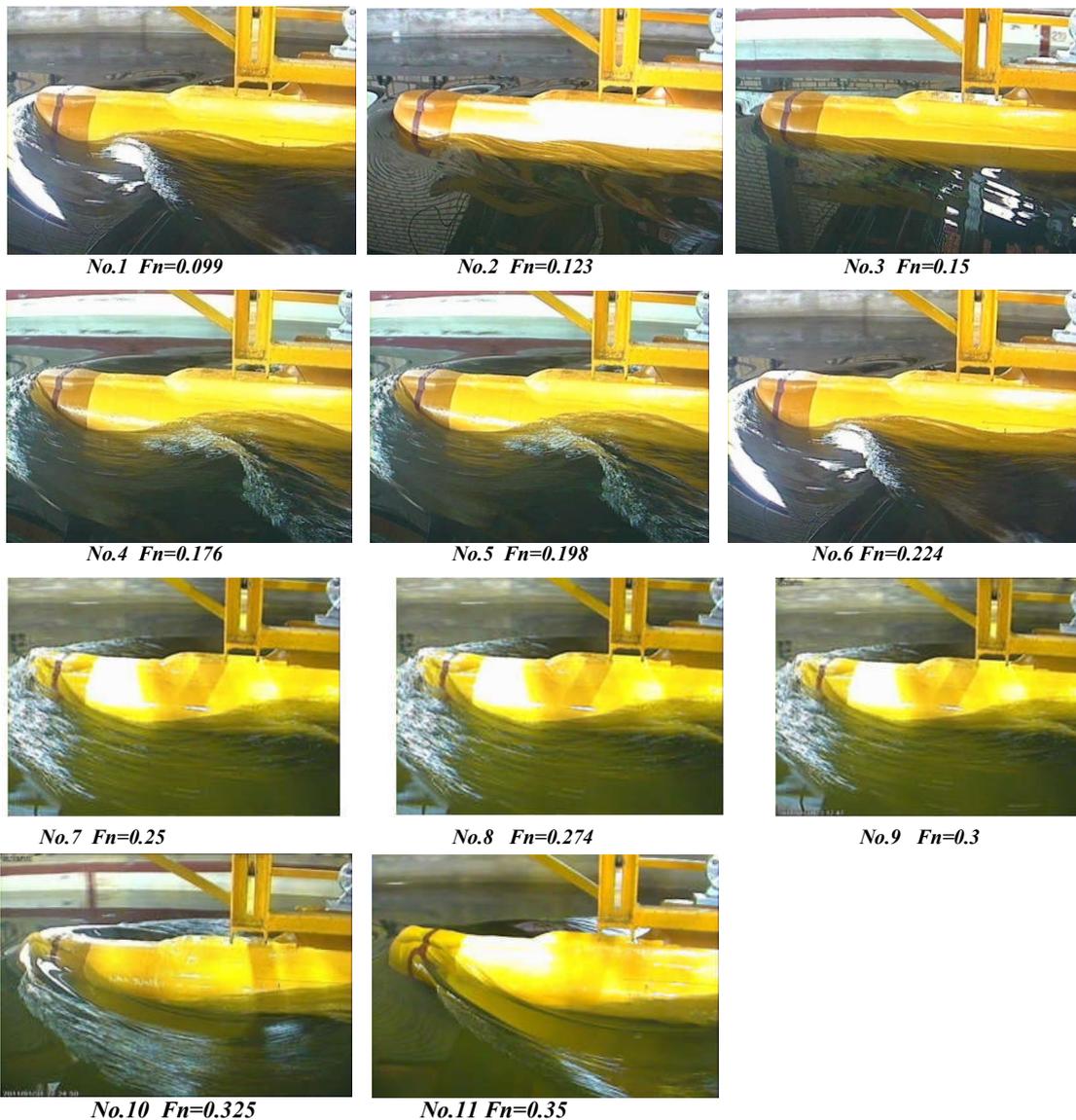


Figure 15. Flow investigations of waves made by tango bow in different Froude number

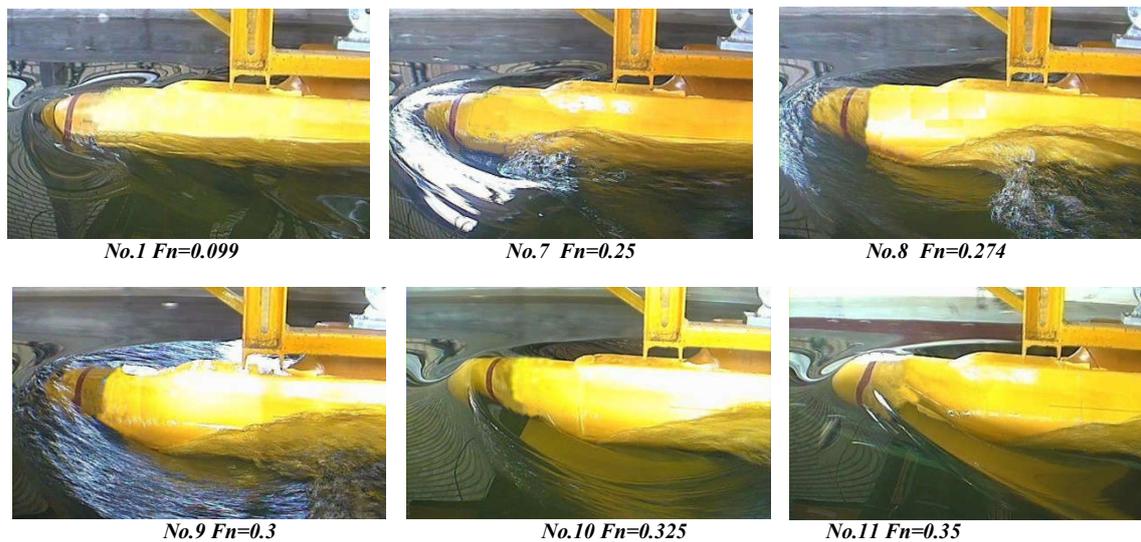


Figure 16. Flow investigations of waves made by standard bow in different Froude number

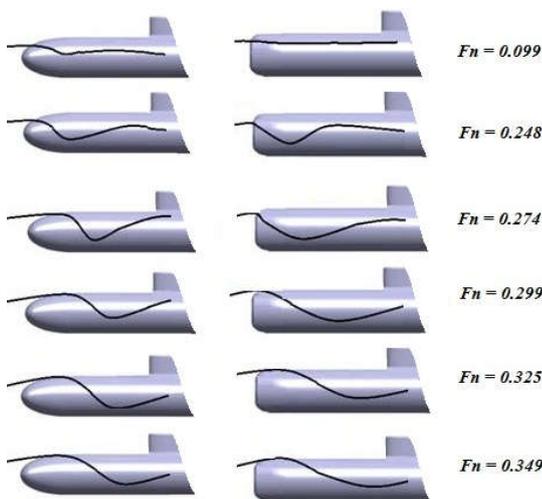


Figure 17. The trajectories of the waves from bow to stern of the model with the both types of bows at different velocities

**Investigation of flow**

Investigation of Flow pattern is a significant method for fluid studies. The ability to see flow patterns around an underwater vehicle under experimental investigations often gives insight into design and optimization process. Here, the investigation of flow experiments is performed to realize the fluid physics on and around the model with different bows. Figure 15 and Fig.16 show the wave induced by both of the bows shapes at different Froude numbers. Fig.17 show the comparison of waves made by the bows of the models. It can be seen, bow wave, begins with wave crest, because the bow is a high pressure area. According to these figures, bow height in Tango shape is less than Standard (DREA) shape.

The lesser bow wave, meant the lesser resistance and the lesser deck flooding. As a result, in surface navigation, Tango shape is better than the Standard bow shape. On the contrary, for submerged navigation, the Standard bow has better results and lesser resistance. Bow wave profile is very small in Froude numbers less than 0.2 but, after that, bow wave comes more visible, especially in Standard bow. Deck wetness in Standard form, happens at Froude numbers more than 0.25, and bow part

is flooded completely, and in Froude number of more than 0.27, deck wetness can encompass the often parts of the deck. Deck wetness in Tango shape, happens at Froude numbers more than 0.3 and fully deck wetness condition at Froude numbers more than 0.35. Indeed, deck wetness and added resistance in real condition can be happened at lesser Froude number because, here vertical position of the model is fixed to the carriage, but real submarines have dynamic behavior due to variation in momentum and buoyancy. Note that, in this study, there is not a sea wave. In Froude number of more than 0.35, sailing wetness can be expected, but it is out of range of Froude number in naval submarines.

**Conclusion**

This paper studied the bow wave profile and deck wetness of submarines by CFD and experimental methods. The bow wave and deck wetness depends on three main parameters: 1- draft 2- Speed (or the corresponding Froude number) 3-bow shape. In CFD modeling, two drafts ( $h=0$  and  $0.1m$ ) were modeled, and in experimental method, two bow shapes (standard and Tango shape) were studied. For defining the draft, usual reserve of buoyancy (ROB) in submarines should be regarded. Common ROB in submarines is between 10 and 15 percent, according to the volume of Main Ballast Tanks (MBT). This ROB results in a freeboard that is approximately equal to  $0.1D \sim 0.17D$ . By increasing the speed and Froude number, the height of bow wave increases. The usual Froude number in naval submarines is in the range of  $0.15 \sim 0.25$ . Usually, the maximum surface speed is approximately 45~60% of the maximum submerged speed, and by an average of 55%. It means 55% speed loss, due to free surface effect and wave making resistance.

At the draft  $h=0$ , the bow wave appears at Froude number above 0.2. By increasing the Froude number, bow is partially flooded until a value of Froude number 0.35 is reached. At this value, the bow is completely flooded. In Froude number of 0.5, deck wetness is occurred completely. At draft of  $0.1m$ , at Froude number 0.2, wave profile is sensible. At Froude number 0.27, the most part of the deck is flooded, and fully deck wetness is happened. In the experiments, it was shown that the bow wave profile is very small at Froude numbers less than 0.2

but, after that, bow wave comes more visible, especially at the standard bow shape. Deck wetness, in standard form, happens at Froude numbers more than 0.25, and bow part is flooded completely. At Froude numbers more than 0.27, deck wetness can encompass the often part of the deck. Deck wetness, in Tango shape, happens at Froude numbers more than 0.3 and fully deck wetness condition happens at Froude numbers more than 0.35.

## REFERENCES

- A group of authorities, "Submersible vehicle system design", The society of naval architects and marine engineers, 1990.
- Alvarez, A., Bertram, V., Gualdesi, V. 2009. "Hull hydrodynamic optimization of autonomous underwater vehicles operating at snorkeling depth". *Jordan Journal of Ocean Engineering*, 36(1), 105–112.
- Bao-ji Zhang, 2012. Shape optimization of bow bulbs with minimum wave-making resistance based on Rankine source method. *Journal of Shanghai Jiaotong University*, 17(1), 65-69.
- Bertram, V. 2000. "Practical Ship Hydrodynamics", Butterworth-Heinemann Linacre House, Oxford OX2 8DP, page 65.
- Burcher, R., Rydill, L.J. 1998. "Concept in submarine design", (The press syndicate of the University of Cambridge., Cambridge university press), pp. 295.
- Desta Alemayehu, *et al*, 2006. "Design Report Guided Missile Submarine SSG(X)", Virginia Tech, page 75.
- Grant, B. Thomson, 1994. "A design tool for the evaluation of atmosphere independent propulsion in submarines", page 205.
- Greiner, L. 1968. "Underwater missile propulsion : a selection of authoritative technical and descriptive papers".
- Jang, J.H. and Park, W.G. 2006. "The Variation of Flow Field and Hydrodynamic Coefficients of Submarine by Changes of Angle of Attack and Yaw Angle", *Journal of the Society of Naval Architects of Korea*, 43(4), pp.460-466.
- Joubert, P.N. 2004. "Some aspects of submarine design: part 1: Hydrodynamics", Australian Department of Defence.
- Joubert, P.N. 2004. "Some aspects of submarine design: part 2: Shape of a Submarine 2026", Australian Department of Defence.
- Lewis, E.V. 1988. (Editor), "principles of naval architecture", Vol II-resistance.
- Mackay, M., 2003. "The Standard Submarine Model: A Survey of Static Hydrodynamic Experiments and Semiempirical Predictions", Defence R&D Canada, pp.30, June.
- Mehran.Javadi, M.D.Manshadi, S. Kheradmand, Mohammad Moonesun, 2014. "Experimental investigation of the effect of nose profiles on resistance of a submarine in free surface motion", *Journal of Marine Science and Application*.
- Mohammad Moonesun, Yuri Mikhailovich Korol, Hosein Dalayeli, "CFD analysis on the submarines bow shapes", *International Journal of Naval Architecture and Ocean Engineering*, under publication.
- Molland, A.F., Turnock, S.R., Hudson, D.A. 2011. "Ship Resistance and Propulsion", Cambridge University Press, page 14.
- Moonesun, M. 2014. " Introduction of Iranian Hydrodynamic Series of Submarines (IHSS)", *Journal of Taiwan society of naval architecture and marine engineering*, Vol.33, No.3, pp.155-162, 2014.
- Moonesun, M. Korol, Y.M and Anna Brazhko, 2014. "CFD analysis on the equations of submarine stern shape", The 16th Marine Industries Conference (MIC2014), Bandar Abbas, Iran.
- Moonesun, M., Korol, Y.M and Davood Tahvildarzade, 2014. "Optimum L/D for Submarine Shape", The 16th Marine Industries Conference (MIC2014), Bandar Abbas, Iran.
- Moonesun, M., Korol, Y.M., Tahvildarzade, D and Javadi, M. 2014. "Practical scaling method for underwater hydrodynamic model test of submarine", *Journal of the Korean Society of Marine Engineering*, Vol. 38, No. 10 pp. 850~857.
- Moonesun, M.Y.M.Korol, " Concepts in submarine shape design", The 16th Marine Industries Conference (MIC2014), Bandar Abbas, Iran, 2014.
- Rawson, K.J., Tupper, E.C., 2001. "Basic Ship Theory-vol.2", Oxford OXD 8D2, page 685.
- S.F.Hoerner, "Fluid Dynamic Drag", 1965.
- Sohn, K.H. Lee, S.K. and Ha, S.P., 2006. "Mathematical Model for Dynamics of Manta-Type Unmanned Undersea Vehicle with Six Degrees of Freedom and Characteristics of Manoeuvrability Response". *Journal of the Society of Naval Architects of Korea*, 43(4), pp.399-413.
- Sukas, O.F., Kinaci, O.K and Sakir Bal, 2005. "Computation of total resistance of ships and a submarine by a RANSE based CFD".
- Suman, K.N.S., Nageswara Rao, D., Das, H.N., Bhanu Kiran, G., 2010. "Hydrodynamic Performance Evaluation of an Ellipsoidal Nose for High Speed Underwater Vehicle", *Jordan Journal of Mechanical and Industrial Engineering (JJMIE)*, Volume 4, Number 5, pp.641-652, November.
- Ulrich Gabler, 2000. "Submarine Design", Bernard & Graefe Verlag.
- Yuri, N. Kormilitsin, Oleg. A. Khalizev, 2001. "Theory of Submarine Design", Saint Petersburg State Maritime Technical University, Russia, pp.185-221.

\*\*\*\*\*