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# Computational fluid dynamics analysis on the added resistance of submarine due to Deck wetness at surface condition

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**Abstract**

This article 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 article is on the added frictional resistance in the deck wetness condition. The bow wave profile, deck wetness and added resistance are studied in several Froude numbers by computational fluid dynamics method. This analysis is performed for a bare hull model at two different drafts by Flow Vision (V.2.3) software based on computational fluid dynamics method and solving the Reynolds-averaged Navier–Stokes equations.

**Keywords**

Submarine, hydrodynamic, wave making, bow wave, deck wetness, resistance

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## 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 h 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 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.

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Whenever a submarine ascents 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 Moonesun and colleagues.[1–6] and Suman et al.[7] Hydrodynamic aspect in submarine design is discussed by Joubert,[8,9] Burcher and Rydill,[10] Kormilitsin and Khalizev,[11] Gabler,[12] Greiner[13] and in A Group of Authorities[14] 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 no 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 Lewis,[15] Bertram,[16] Molland et al.,[17] Rawson and Tupper[18] and Hoerner.[19] Scientific materials about the wave making characteristics of submarines are presented in Javadi et al.,[20] Zhang,[21] Alvarez et al.,[22] Alemayehu et al.,[23] Thomton[24] and Sukas et al.[25] Experimental formula for wave making resistance of submarine in snorkel depth (submerged depth just near the surface) is presented in Thomton[24] and Sukas et al.[25] Dynamic modeling of submarines is discussed in Jang and Park[26] and Sohn et al.[27] 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 reserve of buoyancy (ROB) and as a result, low freeboard height. As mentioned in Burcher and Rydill,[10] Kormilitsin and Khalizev[11] and Gabler,[12] the common values of ROB in submarines, according to the volume of main ballast tanks (MBT), are between 10 and 15%. These values of ROB result in an approximately freeboard between 0.1D and 0.17D as shown in Figure 1. It means a very low freeboard which can be flooded easily by bow wave making system. As shown in Figure 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.

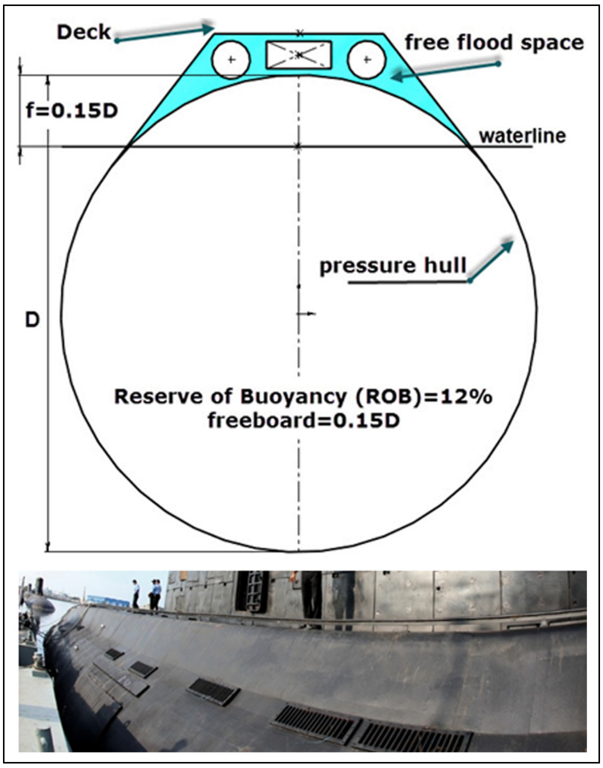


**Figure 1.** Freeboard, deck and free-flooding space in submarine.

## 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 no free surface; thus, the dynamic energy will be utilized in action

**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 | 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 |

and reaction system, for driving ahead. Indeed, surface wave absorbs a part of the energy.

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 Figure 2(a), it can be derived that the wave system around a submarine is approximately according to Table 1. Wave crest in bow tip and stern tail is expected, and wave trough between them.

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 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 (Figure 3).

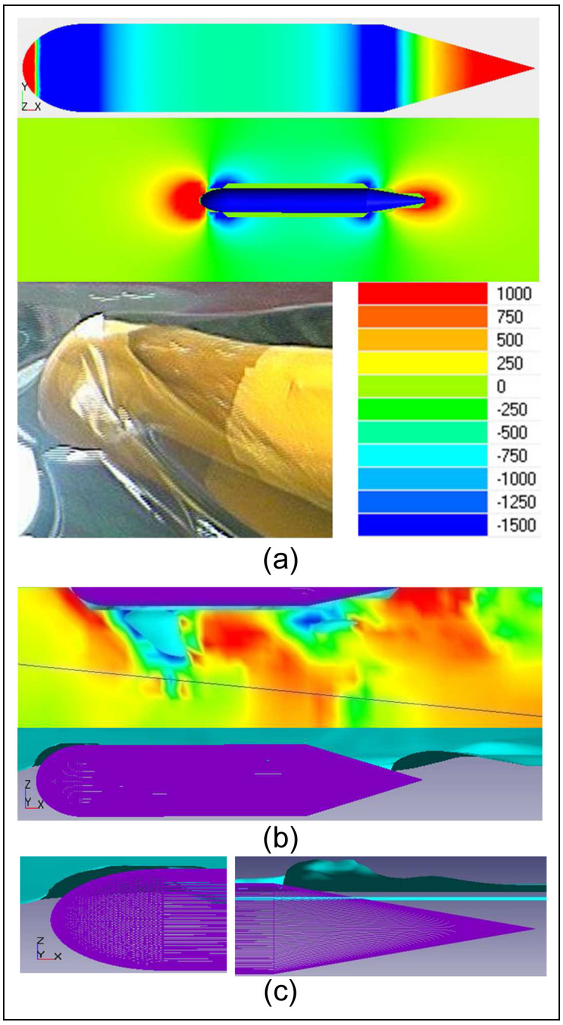


**Figure 2.** Pressure field and wave shape: (a) pressure field around a submarine at fully submerged depth, (b) free surface elevation according to the pressure field and (c) bow and stern wave in high pressure area.

## Common Froude number in submarines

For estimating the range of the usual Froude number in submarines, statistical values have been collected (Table 2). Submarine is a low-speed marine vehicle. As written in Table 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 Unmanned Underwater Vehicle (UUVs) can be more than 2.

## Computational fluid dynamics modeling

### *Assumptions for the model of computational fluid dynamics 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 computational fluid dynamics (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 Table 3 and Figure 4.

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.

Two different drafts are considered: h = 0 and 0.1 m. 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 0.1 m is equivalent to ROB = 12% that is related to the real naval submarines. This situation is consistent with the fact.

**Table 2.** Common Froude number in naval submarines.

| Submarine class | length (m) | Submerge speed (knot) | Surface speed (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 | | 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 ($m^2$) |
|---|---|---|---|---|---|---|
| A | 1.4–7 | 0.2–1 | 5 | 0.6 | 8.33 | 7.87 |

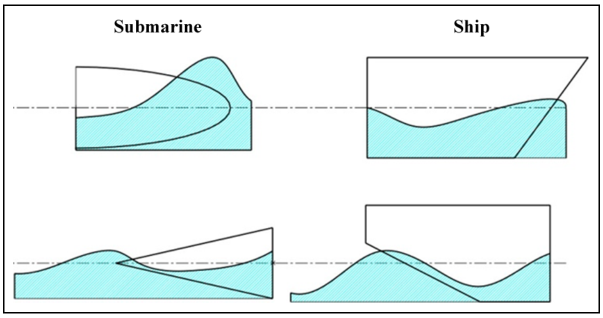


**Figure 3.** Comparison of wave system in submarines and ships.

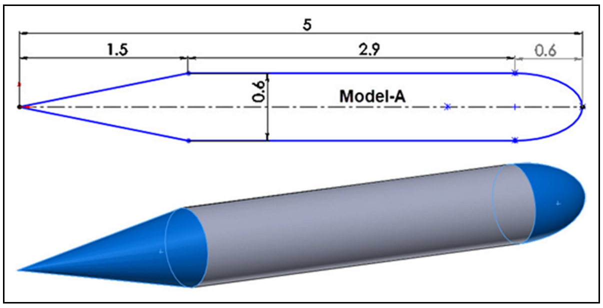


**Figure 4.** General configuration of the model.

## *CFD method of study*

The analysis is performed by Flow Vision (V.2.3) software based on CFD method and solving the Reynolds-averaged Navier–Stokes (RANS) equations. Nowadays, this software is accepted as a practicable and reliable software in CFD activities. For modeling these cases in this article, 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 300,000 meshes, and it shows that the results are independent of meshing (Figure 5). In all modeling, the mesh numbers are considered more than 350,000.

The domain, as shown in Figure 6, has inlet (with uniform flow), free outlet, symmetry and wall (for the body of submarine). Dimensions of cubic domain are 50 m length (that frontal distance of the model is 12.5 m), 5 m beam and 10 m height (7 m 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° of centigrade. Free surface modeling is shown in Figure 6. Note that in all modeling of this article, the model and its draft are fixed and there is no sea wave.

## *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

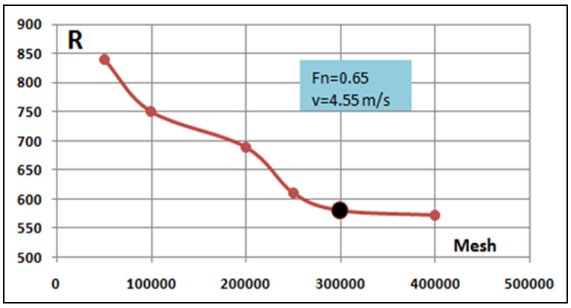


**Figure 5.** Mesh independency evaluations.

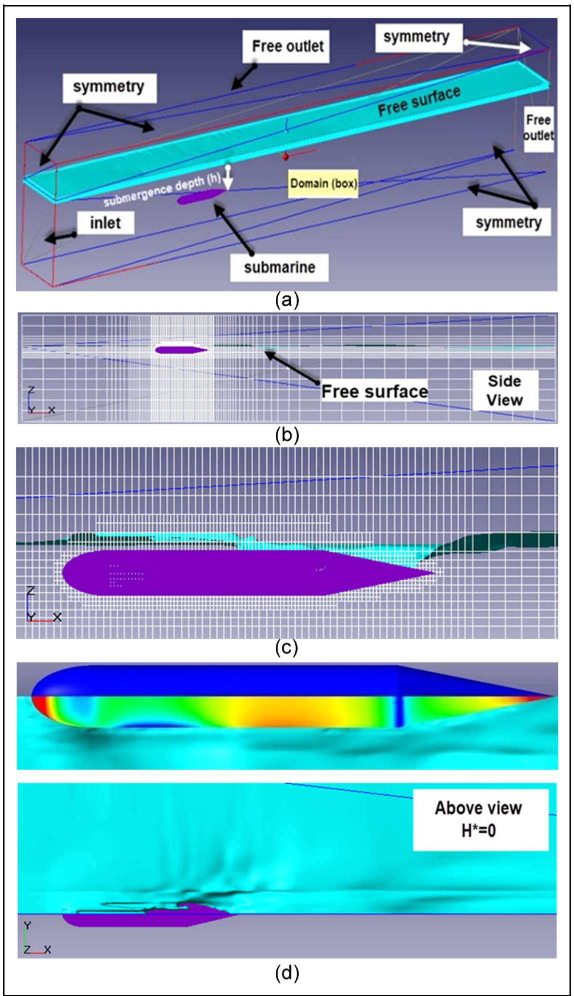


**Figure 6.** (a) Domain and structured grid, (b) tiny cell around free surface, (c) very tiny cells near the wall for boundary layer modeling and keeping $y^+$ about 30 and (d) half modeling because of axis-symmetry and free surface variations.

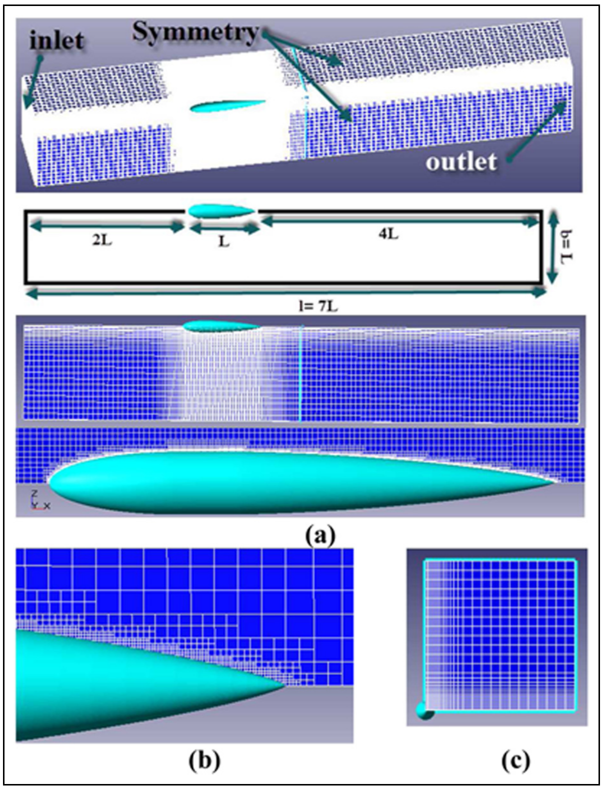


**Figure 7.** Quarterly modeling because of axis-symmetry at fully submerged condition (without free surface effect). (a) dimensions of domain (b) fine meshes around the body (c) quarterly modeling of the domain.

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 (Figure 7). The results of bow wave profile at each Froude number are shown in Figure 8.

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. This portion of the draft is unusual in submarines, but here, it is considered for studying the frictional resistance. According to Figure 8(a) and (b), the bow wave appears at Froude numbers above 0.2. By increasing the Froude number (Fn), bow is partially flooded (Figure 8(c) and (d)) until a value of Fn 0.35 is reached. At this value, the bow is completely flooded (Figure 8(e)). At Froude number of 0.5, deck wetness is complete.

Added resistance due to deck wetness is presented in Table 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 Table 4 is "difference." This term is difference in the frictional resistance between fully submerged mode and free surface condition and is defined as

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

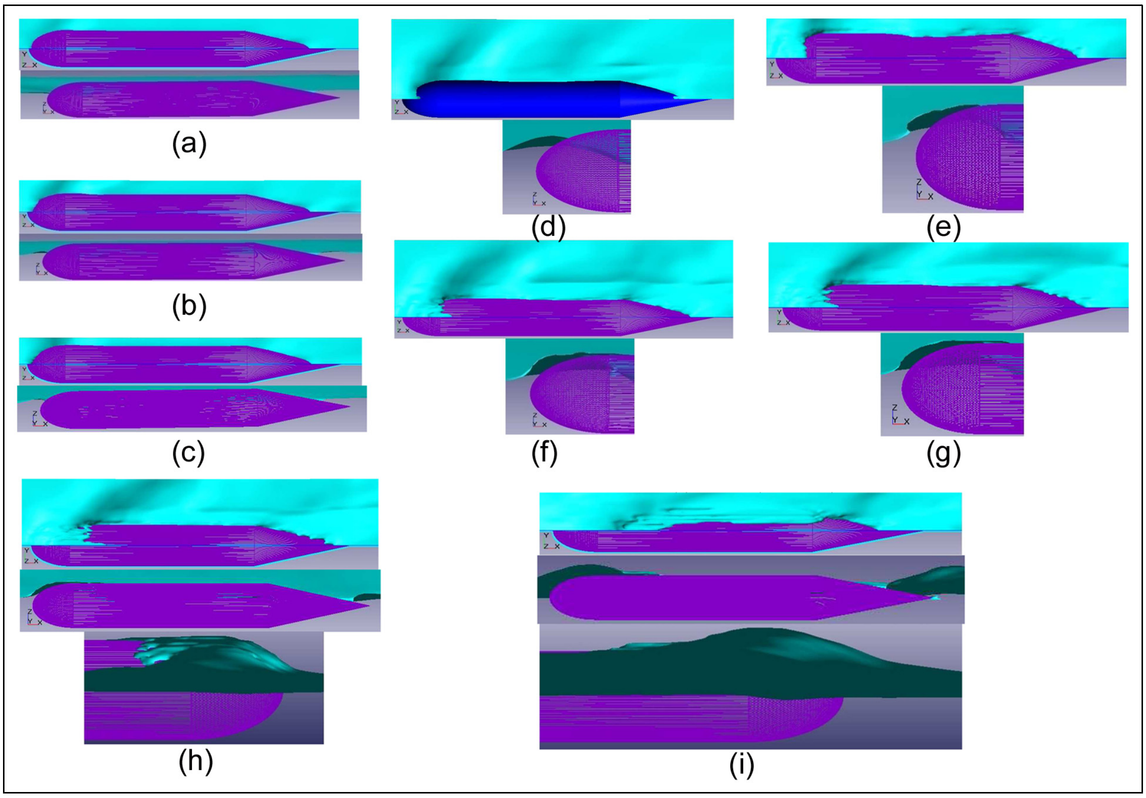


**Figure 8.** Up view and side view of free surface at h = 0 m: (a) Fn = 0.2 (v = 1.4m/s), (b) Fn = 0.25 (v = 1.75 m/s), (c) Fn = 0.29 (v = 2.03 m/s), (d) Fn = 0.33 (v = 2.31 m/s), (e) Fn = 0.35 (v = 2.45 m/s), (f) Fn = 0.38 (v = 2.66 m/s), (g) Fn = 0.42 (v = 2.94 m/s), (h) Fn = 0.46 (v = 3.22 m/s) and (i) Fn = 0.5 (v = 3.5 m/s).

**Table 4.** Added frictional resistance due to deck wetness.

| Test condition | | Fully submerged (1) | | Free surface (2) | | Difference (%) |
|---|---|---|---|---|---|---|
| Fn | V (m/s) | 1/4 Rt | 1/4 Rf | 1/2 Rt | 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 Table 4, the frictional resistance is increased in all speeds from 0% to 30% (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

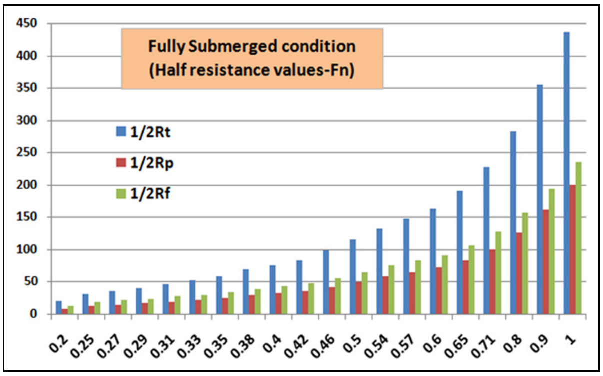


**Figure 9.** Resistance versus Froude numbers in fully submerged condition.

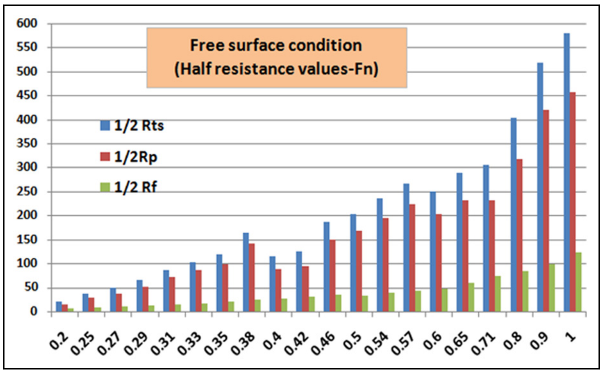


**Figure 10.** Resistance versus Froude numbers in free surface condition.

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 Figure 9 for fully submerged condition. It shows that total resistance includes 55% for frictional and 45% for pressure resistance.

The amount of the total, pressure and frictional resistance is shown in Figure 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.

*Model at h = 0.1 m.* In this part, the model is analyzed 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 Figure 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.

## Conclusion

This article studied the bow wave profile and deck wetness of submarines by CFD method. The bow wave and deck wetness depend on three main parameters: (1) draft, (2) speed (or the corresponding Froude number) and (3) bow shape. In CFD modeling, two drafts (h = 0 and 0.1 m) were modeled. For defining the draft, usual ROB in submarines should be regarded. Common ROB in submarines is between 10% and 15%, according to the volume of MBT. This ROB results in a freeboard that is approximately equal to 0.1D–0.17D.

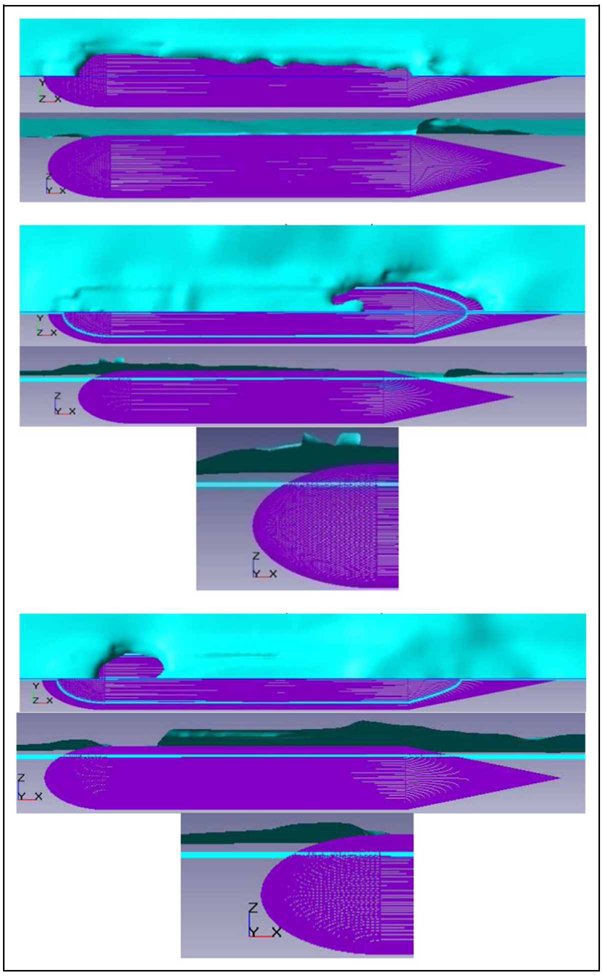

**Figure 11.** Up view and side view of free surface at h = 0.1 m.

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 0.15–0.25. 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 0.1 m, 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.

## Declaration of conflicting interests

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# Appendix 1

## *Notation*

| | |
|---|---|
| CFD | computational fluid dynamics |
| D | maximum diameter of the outer hull (m) |
| EFD | experimental fluid dynamics |

| | |
|---|---|
| Fn | Froude number ($Fn = v/\sqrt{g \cdot L}$) |
| h | Submergence depth (m) |
| H* | non-dimensional depth |
| IHSS | Iranian hydrodynamic series of submarines |
| L | overall length of hull (m) |
| R | maximum radius of the outer hull (m) |
| Rf | frictional resistance (N) |
| ROB | reserve of buoyancy (%), $ROB = (surface\ displacement/submerge\ displacent) \times 100$ |
| Rp | pressure resistance (N) |
| Rt | total resistance (N) |
| Rvp | viscous resistance (N) |
| Rw | wave resistance (N) |
| S | wetted surface area ($m^2$) |
| v | speed of submarine (m/s) |