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# Experimental and numerical investigation of the effects of incorporation of one and two steps to a mono-hull planing vessel on its performance in calm water

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**Abstract.** In the current study, two different vessels with single and two steps were experimentally and numerically studied. The experimental tests were conducted at 7.5, 8.025, 8.5, and 9.5 m/s, i.e., at beam Froude numbers from 3.22 to 4.09. The measured parameters include bow rise-up, trim angle, and resistance. Followed by validating the numerical setup against the experimental measurements, simulations of the fluid flow around the vessel at 10 m/s and 12 m/s speeds were conducted using STAR-CCM+ software. Two-phase flow was analyzed using the finite volume method as well as volume of fluid technique considering the overset meshing scheme. Based on the experimental results, addition of the transverse step enhanced the stability of the vessel and reduced its trim. It was also concluded that the resistance of the single-step high-speed vessel was considerably reduced compared to that with no step. Of note, both single-step and two-step models were stable at speeds up to 12 m/s. Finally, based on Taguchi test design method, a number of numerical models were extracted and the interaction of the three parameters of the first and second step length and the speed at two levels was investigated. Based on these findings, as the length of the second step increased, the resistance increased as well.



## 1. Introduction

An increase in the speed and progress in seakeeping capability have always been one of the main goals of naval architects in designing different vessels. Achieving these goals through development of displacement vessels poses serious challenges mainly due to the fact that from the viewpoint of design, there is a peak or sharp slope in the resistance-speed plot under any circumstances. Therefore, reaching and passing this peak to increase the design speed requires huge costs, thus making the accomplishment of these goals completely non-economical. To overcome this difficulty, the concept of planing vessel was proposed. A great deal of attention has been paid to this type of vessel considering different approaches described in the following.

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### *1.1. Analytical and semi-empirical studies*

In the 1920s, a majority of researches related to planing hulls were first conducted by Von Karman [1]. Given that analytical methods can easily provide suitable information on the behavior of these vessels, mathematical modeling can be considered as one of the main research areas in the field of planing hulls that has been widely adopted by many researchers. Martin [2] proposed a theoretical method to predict the responses of planing hull in the presence of waves. However, his method only took into account the linearized response characteristics of constant deadrise hulls. Zarnick [3] also contributed to mathematical modeling of the motions of a planing vessel and primarily focused on the vessel motion in regular waves. Later, Sebastiani et al. [4] employed a 2D approach and determined the heave, pitch, and roll motions of a high-speed craft using the momentum and wedge theories. Ghadimi et al. [5] investigated the heave, pitch, and roll motions in regular waves with their main focus on the less studied areas. Ghadimi et al. [6] studied the spray generated by the motion of planing hulls and developed a computer program to predict its dynamic behavior. Moreover, Ghadimi et al. [7] took into consideration the pressure distribution and analytically calculated the resistance of a prismatic planing hull in calm water. In addition, Ghadimi et al. [8] proposed a mathematical model to find the roll motion of warped planing hulls. This model, which was validated by the empirical data, could consider the water entry in asymmetric condition. Tavakoli et al. [9] carried out a study to find the roll motion coefficients of a planing hull through 2D+t and potential theories. Hasse et al. [10] employed the 2D+t method as an efficient solution to predict the performance of high-speed crafts. They also established a model using 2D+t and employed the Boundary Element Method (BEM) to study the prismatic hull in head waves. Later, Ghadimi et al. [11] analyzed the behavior of the heeled planing hulls in clam water using 2D+t theory. They calculated the trim angle, rise-up at the Center of Gravity (CG), and resistance by integrating the pressure distribution with the wedge sections which were fixed at the heel angle and free to rise and trim. Ghadimi et al. [12] also developed a method based on the 2D+t theory to predict the hard-chine vessels in semi-planing and planing regimes, considering three resistance types of frictional, induced, and spray.

### *1.2. Numerical and experimental studies*

Alongside these analytical efforts, Computational Fluid Dynamics (CFD) methods are widely used as powerful application tools for analyzing the behavior of vessels under different geometries and conditions owing to the arrival of advanced computer processors. Kazemi and Salari [13] demonstrated how the loading condition and weight distribution could affect the performance of a planing hull using Finite Volume Method (FVM). Given that the meshing of the domain around the vessel with different degrees of freedom is always a challenge to naval architects, Faruk et al. [14] conducted a study to evaluate the overset technique to be used in this specific sector. Recently, Judgea et al. [15] considered a deep V planing hull as their case study, performed some experimental and numerical investigations, and gained detailed information. Although the FVM method in CFD has highly attracted the designers' attention in planing-hull sectors, it is not the only computational method. Ghassemi and Kohansal [16] demonstrated that BEM method could also be effectively employed to evaluate the performance of vessels as well as their effect on the free surface. However, the high dependence of hydrodynamics on the empirical measurement has encouraged researchers to carry out empirical tests alongside numerical studies. Ghadimi et al. [17] investigated the wedge effect on the performance of planing vessels in calm water with two different wedge heights. On the contrary, Sajedi et al. [18] considered a planing hull using numerical methods and determined the effects of a mounted transom wedge. Their numerical results indicated good agreement with their empirical measurements, which were already conducted in calm water.

### *1.3. Stepped hulls*

Planing hulls may exhibit undesirable behavior in terms of resistance under some particular conditions. For example, due to wetted chine at lower speeds, planing hulls may exhibit more significant resistance and lower lift-to-drag ratio than those of displacement vessels [19]. Among the adopted solutions suggested to overcome this challenge, creating a step at the bottom of the vessel is one of the most practical methods. Application of such cuts would lead to the division of the body into two segments called aft and fore body. Through separation of water from the fore body and its reattachment with the aft body [20], the wetted surface of the vessel was reduced, hence a decrease in the viscous friction. On the other hand, the higher pressure resulting from the reattachment of water with the aft body caused an increase in the lift-to-drag ratio. Meanwhile, according to Savitsky and Morabito [21], aft body can produce only 10% of the necessary lift and the remaining lift is generated by the fore body. However, since this 10% lift must be generated in a relatively small region, the downstream of the reattachment point, the shape, height, and step location are critically important [22]. Of note, these geometrical characteristics can change the performance of the stepped vessels by changing the way the spray root is attached to the fore body [23]. It should also be noted that the distribution of the longitudinal lift in stepped planing hulls increases its longitudinal stability since this lift is divided between two or three bodies (depending on the usage of one or two step(s)), and it is not concentrated in a specific region. Another noticeable point about the performance of these vessels is the fact that due to water separation from the body in the step location, a particular condition prevails in terms of air injection such that if recognized and used in an appropriate way, this capability of the step(s) may enhance the performance of the non-stepped planing

[24,25]. Since there are several influential parameters involved in prediction of the behavior of the stepped planing hulls, different researches were conducted to ascertain their effects. Clement and Koelbel [26] presented a summary of up-to-date research conducted on stepped planing hulls until 1993. Indeed, the findings specifically about non-stepped vessels were employed to demonstrate the behavior of stepped planing hulls. Based on the method proposed by Savitsky [27], different mathematical models were presented to predict the behavior of the single-stepped vessels under different conditions [28,29].

### 1.4. Experimental studies on stepped hulls

Given the importance of empirical data in hydrodynamics, several experimental studies have been carried out on stepped planing hulls. For instance, Najafi et al. [30] evaluated the performance of single-step planing hulls in terms of the drag, trim angle, and rise-up and measured the wetted surface areas behind the vessel. Sajedi et al. [31] compared a single-step model with a non-step one at Froud numbers up to 3.87. They found that a step could eliminate instability at high speeds. Recently, a stepped planing hull was also compared with wedge mounted hulls by Sajedi and Ghadimi [32] in calm water in the presence of irregular waves. Their measurements showed that both step and wedge could have benefits in some conditions. More recently, Sajedi et al. [33] evaluated the effects of simultaneous transverse step and transom wedge on planing hulls. They reported that combined configuration could yield the least trim angles. Najafi et al. [34] carried out a study on the wetted surface area of the stepped hulls as one of the primary factors affecting the total resistance of planing hulls. They determined the wetted surface of the fore and aft bodies of the stepped hulls and compared them with the total wetted surface of the same hull without transverse step. Najafi et al. [35] also extended their study to two-step hulls and determined the effects of the fore and aft step geometric features on the reattachment lengths as well as the wetted surface area of the hull.

### 1.5. Numerical studies on stepped planing hulls

De Marco et al. [36] employed CFD techniques to study planing hulls and demonstrated the flow pattern beyond the transverse step for the first time. In addition, Najafi and Nowruzi [37] compared five step shapes and analyzed the hydrodynamic performance of Fridsma planing hull in terms of resistance, trim angle, rise-up, and lift-to-drag ratio. Given the degrees of freedom in the simulation of the planing hull, the moving hull posed a challenge to griding the computational domain. In this regard, Doustdar and Kazemi [38] compared the reliability of both fixed and moving meshes in a stepped planing hull simulation. Sajedi and Ghadimi [39] found the optimum location of the transverse step by carrying out some tests in a towing tank and then simulated different step positions using CFD methods. Afriantoni et al. [40] numerically studied the angle variation of the stepped hull and calculated the most proper angle based on stability analysis. As a result, it can be concluded that with a capability of considering the nonlinear motions of the vessels and complex nature of the environment, numerical methods may challenge the development of analytical methods usually composed of considerable linearization of the flow. However, validation criterion for any CFD analysis provides a possibility to make a comparison between its results and available corresponding experimental data.

### 1.6. Specific studies on two-stepped hulls

Despite the potential advantages of two-step vessels such as proper longitudinal stability caused by the distribution of pressure on the bottom along the three hulls, sporadic research has been conducted on these vessels. For instance, Taunton et al. [41,42] conducted extensive experiments on different models of planing hulls including single- and two-step models. In these experiments, the performance of the models under study was examined at different speeds in calm water in terms of resistance, dynamic sinkage, dynamic trim, and wetted surface area. Vitiello et al. [43] also examined the performance of two-step planing hulls in terms of the effective ship power, total resistance, and trim angle. Moreover, Lee et al. [44] conducted an experiment on a two-step vessel in stationary water under seven different arrangements of fore and aft steps as well as three types of displacement at different speeds. Then, they compared their results with non-step high-speed vessels. They concluded that the resistance of the stepped vessels is less than that of non-stepped hulls. Nourghassemi et al. [45] employed Reynolds Average Navier-Stokes (RANS) solver and simulated a two-step planing hull. They reported different findings about the resistance, trim, rise-up, and pressure distribution along the hull. Ghadimi and Panahi [46] studied two-step planing hulls and defined the hydrodynamic forces and moments at different yaw angles and beam Froude numbers in calm water. On the contrary, Esfandiari et al. [47] compared the behavior of a double-step hull with that of a non-stepped one in rough water using numerical methods. In order to efficiently exploit the advantages of two-step hulls and enhance their behaviors, Zou et al. [48] investigated the roll of stern flap on the performance of two-step planing hulls. More recently, Sajedi and Ghadimi [49] compared the stability and resistance of two- and non-step hulls in a towing tank and reported greater longitudinal stability and less trim angle for the two-step hull. On the contrary, Ma et al. [50] attempted to investigate the planing trimaran in multi-hull vessels under four conditions of no, single, two, and three steps. Kazemi et al. [51] studied the cougar model in three configurations of non-, single-, and two-step to determine the dependance of the resistance of the vessel on the weight ratio. They also managed to extensively investigate different parameters using artificial neural networks.

It is particularly evident that there is no sufficient experimental data about some new fields of interest related to planing crafts such as two-step hulls. For example, Danielson and Stromquist [22] stated in their study on two-step vessels that due to lack of experimental data, the seakeeping analysis of the considered vessel was not feasible; therefore, they could only study the impact of variations in the geometrical characteristics of step(s) namely the longitudinal position, height, and required power. On the contrary, application of planing hulls at high speeds would bring about advantages in terms of costs and design. Despite the extensive researches in this field, the behavior of these vessels at high speeds cannot be easily predictable.

A meticulous review of the presented literature revealed that the conducted research on the high-speed planing hulls did not provide thorough understanding of their dynamic behavior and that the advantages and restrictions of the application of two-stepped vessels, compared to single- and non-step vessels in each study, depended on the type of the vessel and other experimental conditions. In addition, not all of the influential parameters affecting the behavior of these vessels have not been completely recognized or understood. Therefore, under current circumstances, it is imperative that researchers initially conduct different experimental tests on the considered vessel to establish the necessary confidence before adopting any of the two methods, namely analytical or numerical, to evaluate the behavior of high-speed planing hulls. Followed by comparing the obtained results with the reported data of other studies, possible influential parameters were identified and a good foundation was established for extensive future studies in the field of stepped vessels such as those conducted on non-step planing hulls. One of the notable features of this study is its application of a model equipped with a chine that can be used at speeds above 10 m/s. Accordingly, the current research studied a particular model of planing hull experimentally and numerically under two different conditions of single and two steps. Different physical parameters such as bow rise-up, transom and CG, trim, and resistance of the considered model were also measured. The measured parameters were then compared and analyzed at speeds of 7.5, 8.025, 8.5, and 9.5 m/s to examine the impact of each of the considered geometries and physical parameters. Numerical simulations were performed using STAR-CCM+ software, and the two-phase flow was solved using FVM and Volume Of Fluid (VOF) techniques at the speeds of 10 m/s and 12 m/s to further analyze the position of steps and hydrodynamic performance of the examined hulls. In order to find the suitable test cases in the numerical modeling, Taguchi test design method was employed, and the interaction of the three parameters of the first and second step lengths and speeds at two levels was investigated. The obtained data revealed how a hard-chine planing hull could take advantage of one and two steps at the Froude number of 4.09. Consideration of the experimental database regarding the performance of single- and two-step hard-chine vessels in calm water as well as the application of a validated numerical method to predict the behavior of the vessel with different step shapes could provide an appropriate basis for future studies on this type of vessel.

## 2. Physical description of the model

### *2.1. Problem statement*

In this research, the vessel was set to be a planing monohull. A hard-chine vessel is characterized by a V-shaped body, deadrise angle of $\beta$, and beam of $B$ (illustrated in Figure 1). Its mass $M$ (kg) is turned into a non-dimensional form as:

$$C_M = \frac{M}{\rho B^3}, \tag{1}$$

where $\rho$ is the fluid density. The boat is supposed to reach the planing speed that can be characterized by Froude number:

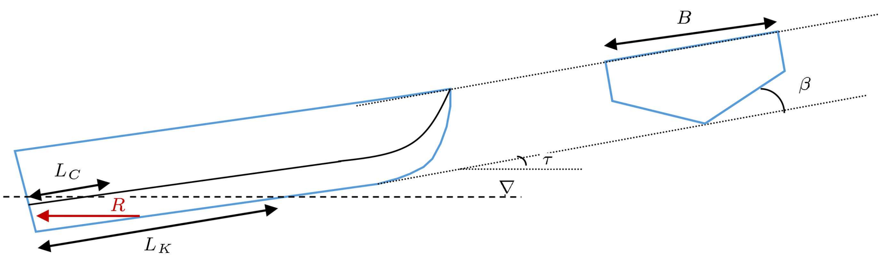


**Figure 1.** A planing hull that moves forward under a steady condition.

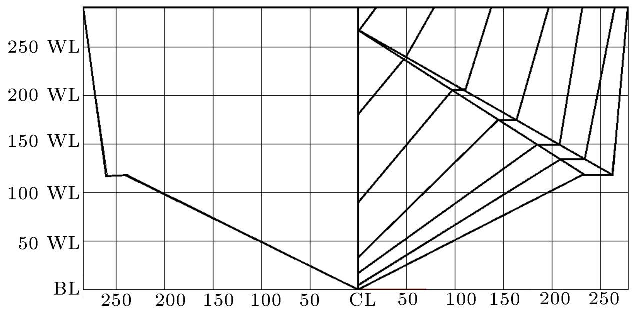


**Figure 2.** Bodyline of a vessel without a step.

**Table 1.** Principal characteristics of the investigated vessel [31].

| Parameter | Value (m) |
|---|---|
| L | 2.64 |
| LCG | 0.79 |
| VCG | 0.19 |
| B | 0.563 |

$$\text{Fr} = \frac{u}{\sqrt{gL}}, \tag{2}$$

where $u$ is the advanced moving of the boat. The Froude numbers smaller than 0.4 are considered as the displacement regime; those between 0.4 to 1.0 are representative of the semi-planing condition; and those beyond 1.0 are recognized as the planing regime. The considered vessel is a 1:5 scale of the main vessel called cougar. This vessel has a constant deadrise of 24 degrees which is made of fiberglass. Its length-to-width ratio and weight are 4.7 and 86 kg, respectively. This hull is selected mainly because it has a constant deadrise angle, thus experiencing longitudinal instability. In order to avoid the incurring instability, a model test was constructed and examined with and without step(s). The main characteristics of the vessel are presented in Table 1, and the bodyline of the tested model without step is illustrated in Figure 2. Model A is a non-step hull, Mode B is a single-step hull, and Model C is a two-stepped hull.

## 3. Experimental set up

Experimental tests were conducted by towing the vessel in the towing tank based on the recommended guidelines of International Towing Tank Conference (ITTC) related to the targeted tests on the resistance of high-speed vessels. These tests were done in National Iranian Marine Laboratory (NIMALA) of 400 m in length, 6 m in width, and 4 m in depth. National Iranian Marine Laboratory was established in 2012 with the main objective of performing all designing-engineering tests for surface ship and submarines [31]. The maximum speed achieved in this towing tank was in the range of 19 m/s. The tested model was then towed at the intersection of the CG with the direction of propulsion system whose angle from the base line was 6 degrees. This model is free at two degrees of freedom, i.e., heave and pitch, and other motion components are assumed to be fixed. The measured parameters include the drag and trim. A photograph of the model test in tank is illustrated in Figure 3.

## 4. Tests conditions

Three different models were considered in the conducted tests. Two types of these models possess step, one with a single step and the other with two steps. Step location is selected differently based on the intended model test and full-scale vessels. Figure 4 shows the ratio of the length of the forward and after steps to the beam of several scaled and full-scale vessels. The length-to-beam ratio of the selected vessels is about 5.

As shown in Figure 4, the average ratio of the forward step length to the beam is between 1 and 1.5, and the ratio of the after-step length to the beam is between 0.5 and 1. Accordingly, the distance of the step of a single-step vessel from the transom is 770 mm where the ratio of the step length to beam is 1.5 (30% of the length of the vessel). Of note, in the case of the two-step planing hull, the distances of the forward and after steps from the transom are 15% and 30% of the length of the vessel, respectively. In addition, the ratios of the length of the after and forward steps to the beam are 0.75 and 1.5, respectively. The step height for both of the stepped hulls was 4% of the beam, i.e., 0.55 m.

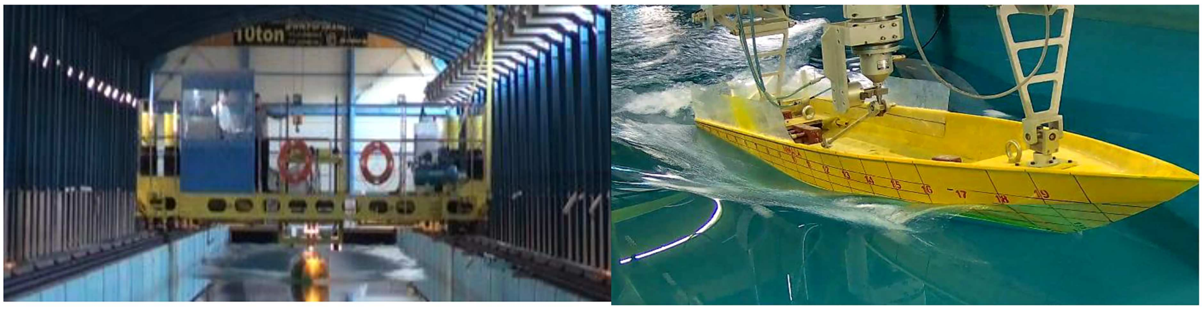


**Figure 3.** A photograph of the model test at National Persian Gulf Towing Tank.

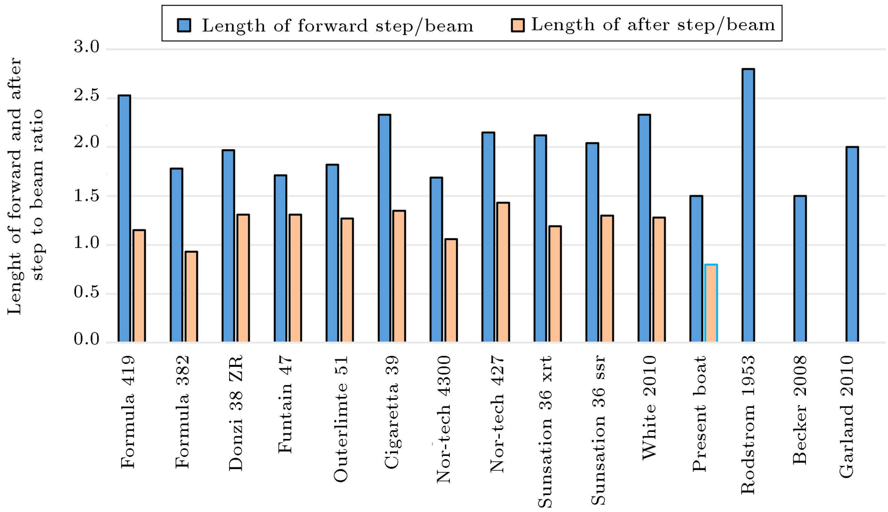


**Figure 4.** Ratio of the length of the forward and after step to the beam of several models.

### *4.1. Tests results and discussion*

Table 2 presents the registered parameters for the single-step hull according to which the single-step model remains stable at these speeds. These tests were conducted at speeds of 7.5, 8.025, 8.5, and 9.5 m/s. The model trim decreased, while its rise-up increased. Figure 5 shows the movement of the single-step model at a speed of 8.025 m/s.

Table 3 presents the results of the last series of tests done on the two-step hull. The obtained results in this table indicate that upon adding the second step to the vessel, the longitudinal stability would be enhanced, thus avoiding proposing. These tests were conducted at speeds of 7.5, 8.025, 8.5, and 9.5 m/s.

**Table 2.** Result of the model with single step.

| $U$ (m/s) | $Fr_B$ | $Z_1$ (m) | $\tau$ (deg) | $R_T/\Delta$ |
|---|---|---|---|---|
| 7.5 | 3.22 | 0.058 | 4.9 | 0.162 |
| 8.025 | 3.45 | 0.0625 | 4.1 | 0.167 |
| 8.5 | 3.65 | 0.068 | 3.7 | 0.177 |
| 9.5 | 4.09 | 0.078 | 2.8 | 0.2 |

**Table 3.** Result of the double stepped vessel.

| $U$ (m/s) | $Fr_B$ | $Z_1$ (m) | $\tau$ (deg) | $R_T/\Delta$ |
|---|---|---|---|---|
| 7.5 | 3.22 | 0.05 | 2.84 | 0.179 |
| 8.025 | 3.45 | 0.056 | 2.93 | 0.18 |
| 8.5 | 3.65 | 0.059 | 2.84 | 0.186 |
| 9.5 | 4.09 | 0.066 | 2.63 | 0.21 |

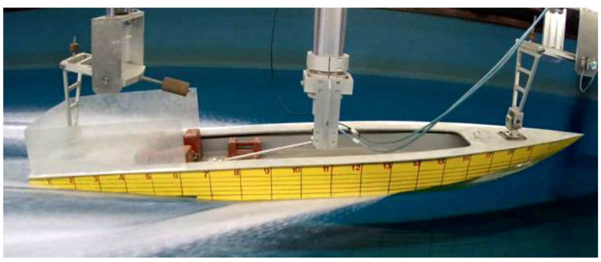

**Figure 5.** Motion of a single-step vessel at 8.025 m/s.

### *4.2. Comparison of the results of different models*

This section makes a comparison of the results obtained from a series of these conducted tests. The obtained results show the impacts of the location and number of steps. The steps are located at 30% and 15% of the transom distance from the length of the vessel. A comparison of trim angles and rise-up for different models is made and presented in Figures 6 and 7.

As observed in Figure 6, upon adding a step to the vessel, its trim would decrease. The obtained results indicated that such trim reduction for the two-step hull was more than that of a single-step vessel. For this reason, the transom lift would increase and consequently, the trim would decrease. Figure 7 shows the computed rise-up at the center of the bow for the

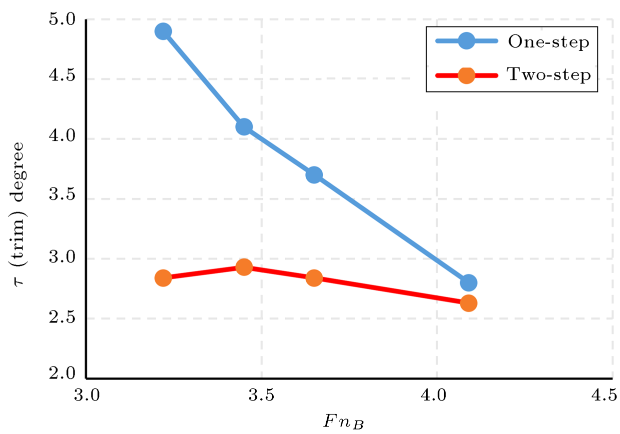


**Figure 6.** Comparison of the trims of different models.

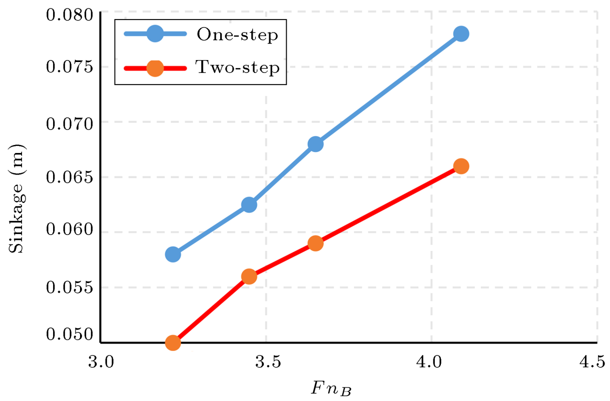


**Figure 7.** Comparison of the sinkage of different models.

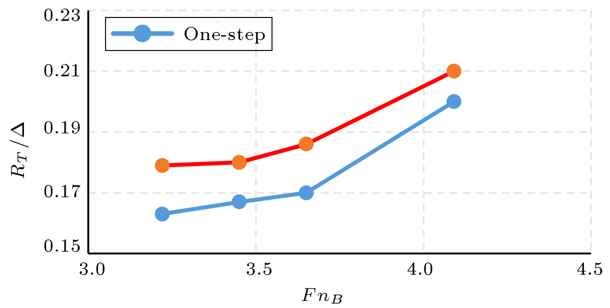


**Figure 8.** Comparison of the resistance of different models.

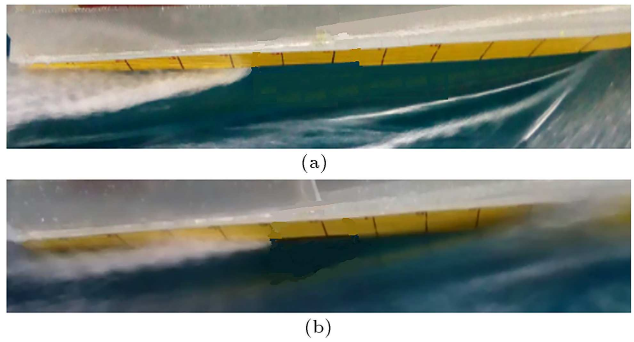


**Figure 9.** Flow (water) separation in the single-step vessel at: (a) 9.5 m/s and (b) 8.025 m/s.

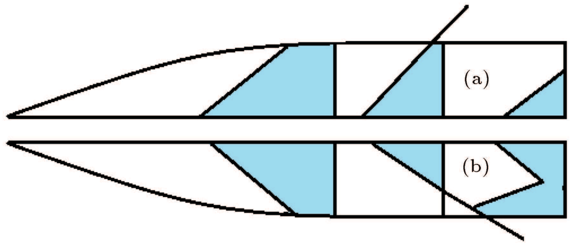


**Figure 10.** Flow (water) separation in the two-step vessel at: (a) low speed and (b) a higher speed.

tested. From these plots, one may conclude that the rise-up of the vessel would decrease by adding a step. This conclusion makes sense since step addition would cause trim reduction. As a result, rise-up was reduced. Figure 8 shows the computed resistance of different models.

While the single-step vessel has the least resistance in the planing regime, the double-step planing hull exhibits maximum resistance mainly due to trim reduction which leads to an increase in the wetted surface and resistance. The most important characteristics of a single-step vessel include its resistance reduction in the planing regime and its increasing stability. Ventilation also occurs in a double-step hull, implying the existence of the pressure pick point in the second body which accompanies the longitudinal stability of the vessel. One of the most important factors in choosing a step is to get the water to the chin line, as observed well in the first step. To better understand this, see Figure 9.

As shown in Figure 9, the flow separation becomes more apparent at 9.5 m/s; yet, the vessel trim decreases. As a result, the vessel bow penetrates into water and the surface becomes wetter than before. In addition, while the flow separation occurs at 8.025 m/s (Figure 9(b)), its separation length is less than that of the former case, hence earlier pressure pick point. Consequently, the vessel trim increases more than that of the vessel at 9 m/s and the flow separation in double-step planing hull is given in Figure 10.

With an increase in the velocity, the vessel trim will be reduced until when appropriate ventilation occurs for the first step. This, in turn, will cause a reduction in the pressure resistance; however, the frictional resistance would increase due to the reduction in the trim. In case the velocity increases over a particular limit, separation from the chine does not occur and water separates from the step. This is accompanied by an increase in the wetted surface area, and the third body becomes even wetter at this speed than the previous speed. Upon increasing the velocity, no proper ventilation occurs while the resistance increases. A comparison was made for eight experimental works at the volume Froude number of 4.75, as depicted in Table 4.

The least amount of drag is related to Garland's work followed by the study done in this paper. Figure 11 makes a comparison between the findings.

### *4.3. Uncertainty*

According to ITTC recommendation, the levels of uncertainty should be kept to a minimum. Drag uncertainty is calculated based on the total drag coefficient. The levels of uncertainty for trim and resistance were determined based on the relations corresponding to the hydrodynamic aspect of the vessel. To determine the levels of uncertainty, it is imperative to act on the governing relations recommended by ITTC. These levels were calculated based on the trim results at the speed of 7.5, 8.5, and 9.5 m/s for one- and two-

**Table 4.** The characteristics of steps investigated in experimental studies.

| Name | Δ (kg) | Length (m) | Number of step |
|---|---|---|---|
| Taunton et al. [41]. | 24 | 2 | 1 |
| De Marco et al. [36]. | 30 | 0.9 | 1 |
| Khazaee and Salari [13] | – | 8 | 1 |
| Kazemi et al. [51] | 84 | 2.64 | 1 |
| Tork Chooran et al. [53] | 1 | 7 | 1 |
| Najafi et al. [30] | 2.5 | 48 | 1 |
| Garland et al. [54] | 1.5 | 25.8 | 1 |

**Table 5.** The calculated drag and trim uncertainties (stepped model).

| | One step | | Two step | |
|---|---|---|---|---|
| *V* (m/s) | Drag (%) | Trim (%) | Drag (%) | Trim (%) |
| 7.5 | 0.629 | 2.4 | 0.88 | 3.3 |
| 8.5 | 1.4 | 3.7 | 1.8 | 4.3 |
| 9.5 | 0.406 | 2.12 | 0.03 | 2.1 |

**Table 6.** Determination of trim uncertainty.

| Definition | Governing equations |
|---|---|
| Total trim uncertainty | $(U_\tau)^2 = (B_\tau)^2 + (P_\tau)^2$ |
| Total bias limit for trim % of $(U\tau)^2$ | $(B_\tau)^2 = (\theta_V)^2 + (\theta_{\Delta FP} B_{\Delta FP})^2 + (\theta_{\Delta AP} B_{\Delta AP})^2$ |
| Total bias of ΔFP % of ΔFP | $B^2_{\Delta FP} = B^2_{\Delta FP1} + B^2_{\Delta FP2}$ |
| Calibration bias of ΔFP% of (BΔFP)2 | $B_{\Delta FP1} = \sqrt{Z_i nc^2}$ |
| Potentiometer misalignment bias of ΔFP% of (BΔFP)2 | $B_{\Delta FP2} = \Delta FP - \cos(\theta_M) \times \Delta FP$ |
| Total bias of ΔAP% of ΔAP | $B^2_{\Delta AP} = B^2_{\Delta AP1} + B^2_{\Delta AP2}$ |
| Sensitivity coefficient for speed *V* for trim | $\theta_V = -4 \times g \times \frac{\Delta AP - \Delta FP}{V^3}$ |

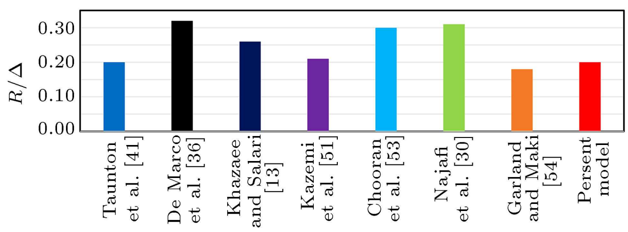


**Figure 11.** Comparison of the experimental works.

step models (Table 5). The results of the uncertainty calculations were given based on the trim percentage. As shown in Table 6, the relations and levels of uncertainty depend on four parameters namely the trim, sinkage, speed, and number of conducted tests.

As observed in Table 6, the highest level of uncertainty is attributed to the trim measurement.

## 5. Numerical studies

### *5.1. Governing equations*

The unsteady Navier-Stokes equations for a three-dimensional unsteady flow based on the RANS method include continuity and momentum equations, which are introduced in Eqs. (3) and (4), respectively:

$$\frac{\partial U_i}{\partial x_i} = 0, \tag{3}$$

$$\frac{\partial U_i}{\partial t} + \frac{\partial (U_i U_j)}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\nu\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right)\right] - \frac{\partial \overline{u'_i u'_j}}{\partial x_j}, \tag{4}$$

where $U_i$ is the averaged velocity, $x_i$ the spatial coordinate, $t$ the time, $u'_i$ the oscillating velocity, $\rho$ the fluid density, $p$ the average pressure, and $\nu$ the kinematic viscosity. The Reynolds stress tensor $(\overline{u'_i u'_j})$ can be defined according to Boussinesq approximation as follows:

$$\overline{u'_i u'_j} = \nu_t \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) + \frac{2}{3}\delta_{ij} k, \tag{5}$$

where $\nu_t$ is the vortical viscosity. To perform fluid flow simulations, the $k-\omega$ Shear Stress Transport

(SST) turbulence model which is widely used in solving external flow problems was employed. This model took into account the features of two models, i.e., $k-e$ and $k$–$w$. In addition, this model predicts the free shear flow rate; therefore, it can be regarded as a suitable model for free shear currents. The SST model is a model based on the equations of turbulent kinetic energy transfer $k$ and turbulence frequency $\omega$. The kinetic energy of the turbulent, $k$, and frequency, $\omega$, were obtained through the following transfer equations:

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)=\frac{\partial}{\partial x_j}\left(\Gamma_k\frac{\partial k}{\partial x_j}\right)+\tilde{G}_k -Y_k+S_k, \quad (6)$$

$$\frac{\partial}{\partial t}(\rho \omega)+\frac{\partial}{\partial x_i}(\rho \omega u_i)=\frac{\partial}{\partial x_j}\left(\Gamma_\omega\frac{\partial \omega}{\partial x_j}\right)+G_\omega-Y_\omega +D_\omega+S_\omega. \quad (7)$$

### 5.2. Free surface capturing

Free surface capturing, as one of the most challenging issues of multiphase problems, requires some specific assumptions and calculations. VOF model assumes both phases as homogenous, thus solving the governing equations only once and presenting the amounts of pressure and velocity. However, the application of a volume fraction for the phases is indicative of each phase which can provide an accurate scheme of the free surface form.

### 5.3. Methods in CFD simulation

Numerical simulations were performed to extend the results after experimental modeling. Numerical results were then extracted at two speeds of 10 and 12 m/s. To properly estimate all unknown hydrodynamic parameters at each time step, RANS equations were solved in an implicit, unsteady, and iterative manner. The pressure-velocity coupling was accomplished based on the SIMPLE method, and the selected turbulence model was SST-K $\omega$. In the simulations, two degrees of freedom for heave and pitch were taken into consideration. Dynamic Fluid-Body Interaction (DFBI) model was also employed to consider these degrees of freedom, and overset dynamic mesh technique was used to discretize the domain. The two-phase current was solved using the VOF model functioning based on tracking the free surface boundary. To reduce the computational cost, simulate only half of the model body, as shown in Figure 11. The reference coordinate axis is located at the CG of the model. The positive direction of the $x$-axis is in the opposite direction of the water inlet velocity. The cubic computational domain dimensions are selected as $-7L < X < 1L$, $-2.5L \leq Y \leq 0$ and $-2L \leq Z \leq 1L$, assuming that

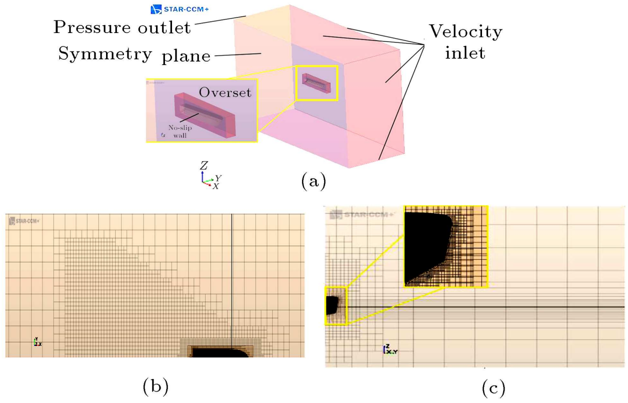


**Figure 12.** (a) Boundary conditions, stationary, and moving computational domain, (b) and (c) the top and side views of the grid, respectively, including the boundary layer around the model.

$L$ is the length of the model. Figure 12 shows the computational domain with mesh around the model.

Another point to note is the choice of time step ($\Delta t$) according to Eq. (8), which is expressed as a function of length ($l$) and velocity ($V$) based on the ITTC recommendation of 2011 [52]. Here, this length is assumed to be equal to the wetted length of the keel ($L_k$) of the model. Of note, Courant number (CFL) remains below 1 as a function of the time step, speed, and minimum element length in the direction of fluid flow. Eq. (9) defines the Courant number:

$$\Delta t = 0.01 \sim 0.005\frac{l}{V}, \quad (8)$$

$$c=\frac{v-\Delta t}{\Delta x}\leq c_{\max}, \quad (9)$$

where $\Delta x$ is the distance of the first cell, the smallest cell, from the body surface. Of course, the Courant number changes with a change in the Froud number.

An important criterion to be considered in the mesh production within the boundary layer is Y+ which refers to the dimensionless distance of the first node from the surface. According to ITTC recommendations, the value of Y+ can be up to 300. The average value of Y+ is about 40 at a speed of 9 m/s. Figure 13 shows the value of Y+ on the floor of the single- and double-step models at 9 m/s.

### 5.4. Mesh study and uncertainty of grid and validation

Table 7 shows the computed total resistance of the single-step models versus the number of cells at a speed of 9.5 m/s. As observed in this table, upon increasing the number of cells to more than 1,400,000, the resistance change would be negligible. Hence, 1,400,000 cells were selected to conduct the intended simulations.

**Table 7.** The accuracy of the drag based on a different mesh.

| Grid accumulation | Num. mesh $\times 10^6$ | Numerical drag ($R/\Delta$) |
|---|---|---|
| Coarse | 1 | 0.180 |
| Medium | 14 | 0.195 |
| Fine | 20 | 0.197 |
| Difference percentage | Coarse to medium | 8.3% |
| | Medium to fine | 1% |

**Table 8.** Comparison of the experimental measurements and numerical data for single-step models.

| | | Drag ($R/\Delta$) | | | Trim (degree) | | |
|---|---|---|---|---|---|---|---|
| Model | Velocity (m/s) | Exp | Num | Error (%) | Exp | Num | Error (%) |
| Single step | 8.5 | 0.17 | 0.175 | 2.9 | 3.7 | 4 | 8.1 |
| Single step | 9.5 | 0.2 | 0.195 | 2.5 | 2.8 | 3.2 | 14 |
| Two step | 8.5 | 0.186 | 0.18 | 3.2 | 2.84 | 3.3 | 16 |
| Two step | 9.5 | 0.21 | 0.201 | 4.5 | 2.63 | 2.9 | 10 |

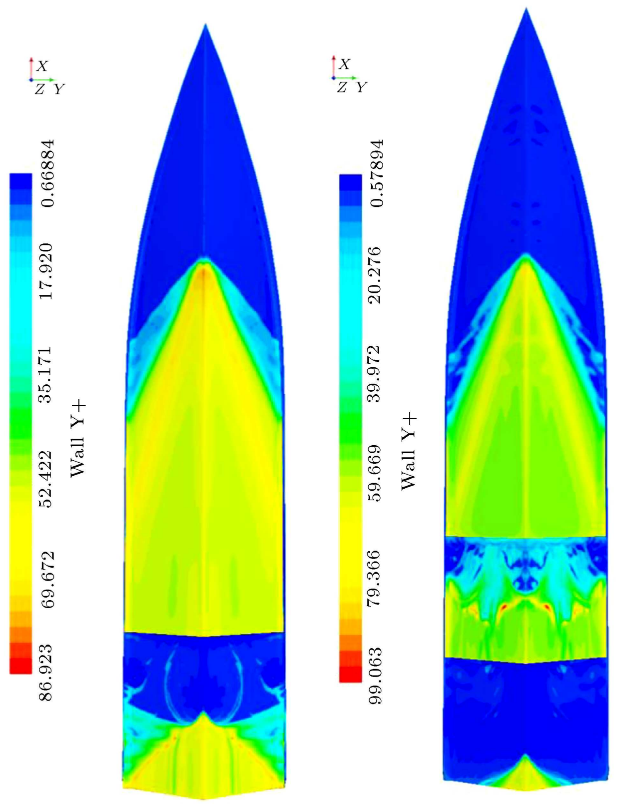


**Figure 13.** The amount of Y+ in single- and two-step models at 9 m/s speed.

Among different levels of uncertainty of CFD, grid uncertainty is the most influential. Here, Grid Convergence Index (GCI) is calculated for three different meshes, as shown in Table 7. In the present study, $R_K = \varepsilon_{21K}/\varepsilon_{32}K$ is in the range of $0 < R_K < 1$, and the mesh modifying factors are $r_{21} = \sqrt{2}$ and $r_{32} = \sqrt{2}$. The value of GCI for single-step floating resistance at a speed of 9 m/s and different meshes in Table 6 is equal to 6.1%. Based on Table 8, validation is conducted against the experimental model. A comparison was made between the experimental measurements and numerical results for single-step models in Table 8, and the results were in good agreement.

### 5.5. Design of experimental (Taguchi technique)

To extend the results, the number of required simulations was extracted using the Taguchi test design method. Three factors given in Table 9 namely the speed as well as the locations of the first and second steps at two levels were selected to design the test. The locations of the first and second steps were determined based on the percentage of the distance of the steps from the transom to the model length. The results of the trim, rise-up, and resistance are shown in Table 10.

Figure 14 shows the effect of each parameter. As observed in this figure, upon increasing both distance of the second step from the transom and speed, the resistance would increase. However, the trim decreased upon increasing the speed. As the longitudinal distance of the second step from the transom increased, the trim decreased and the wet surface was extended.

The contour in Figure 15(a) shows that the length of the first step has a negligible effect on the resistance and that the lines are almost vertical. However, according to Figure 15(b), the resistance increased as the length of the second step increased.

**Table 9.** Variables and their levels of change.

| Speed (m/s) | L1 (%) | L2 (%) |
|---|---|---|
| 10 | 20 | 30 |
| 12 | 30 | 40 |

**Table 10.** Simulation results.

| Case | Speed | L1-step | L2-step | Drag (N) | Trim (degree) | Rise-up (m) |
|---|---|---|---|---|---|---|
| 1 | 10 | 20 | 30 | 142 | 4.5 | 80 |
| 2 | 10 | 30 | 40 | 151 | 4.1 | 77 |
| 3 | 12 | 20 | 40 | 185 | 1.1 | 70 |
| 4 | 12 | 30 | 30 | 177 | 2 | 68 |

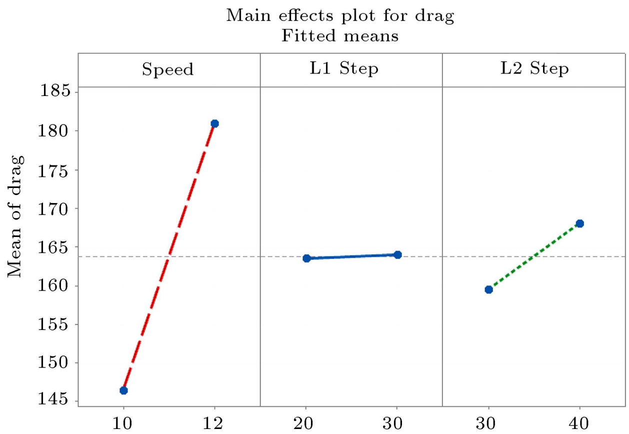


**Figure 14.** The effect of each parameter on the resistance.

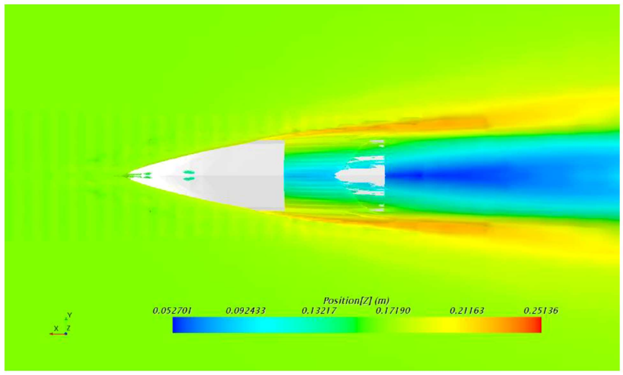


**Figure 16.** The wetted surface area of the single-step model at 12 m/s speed.

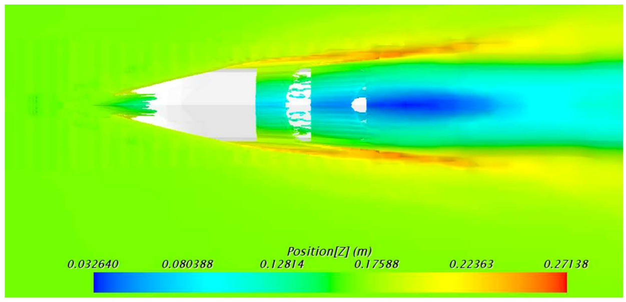


**Figure 17.** The trim and the wetted surface area of the two-step model at 12 m/s speed.

Figures 16 and 17 depict the wetted surface area of the two single- and double-step vessels at a speed of 12 m/s.

It is observed that the two-step model trim is less than the single-step model. However, the two-step model experiences greater resistance. Table 11 summarizes the results of the wetted surface of two single- and double-step models. The wetted surface of the second body decreases upon increasing the speed. The amount of wetted surface can be calculated using geometric relations. The highest wetting level was attributed to the double-step model.

According to Figure 18, based on the underwater camera, the current separation starts at the speeds higher than 4 m/s.

Figure 19 shows the flow separation for four numerical models. As evident in this figure, the separation keeps the middle body dry in Models 1 and 2. The separation length in models 1 and 2 is about 20% of the model length, and in models 3 and 4 about 10% of the model length.

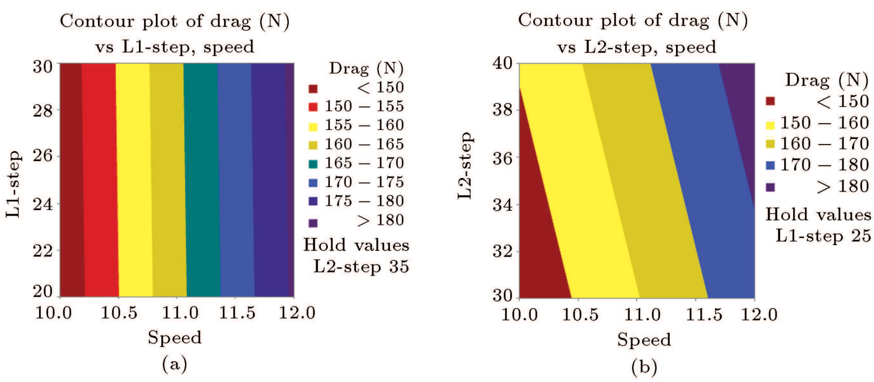


**Figure 15.** The effect of length of the first and second steps on the resistance.

**Table 11.** Wetted surface of models.

| Number of models | Fore body (m$^2$) | Aft body1(m$^2$) | Aft body 2 (m$^2$) |
|---|---|---|---|
| 1 | 0.59 | 0.0 | 0.15 |
| 2 | 0.6 | 0.0 | 0.1 |
| 3 | 0.62 | 0.1 | 0.1 |
| 4 | 0.66 | 0.19 | – |

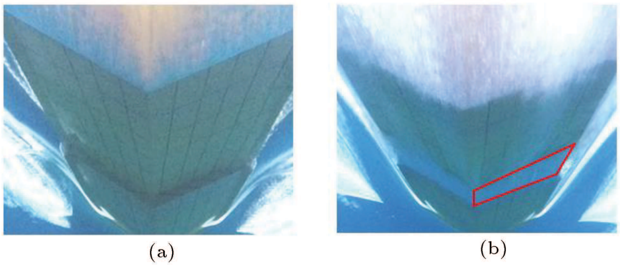


**Figure 18.** Flow separation at: (a) 4 m/s and (b) 6 m/s speed.

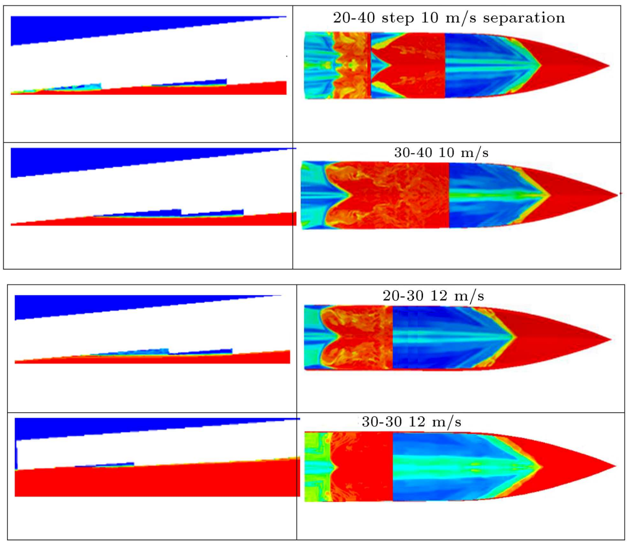


**Figure 19.** Flow separation in four numerical models.

Figure 20 shows the velocity and pressure counters for two single- and double-step models.

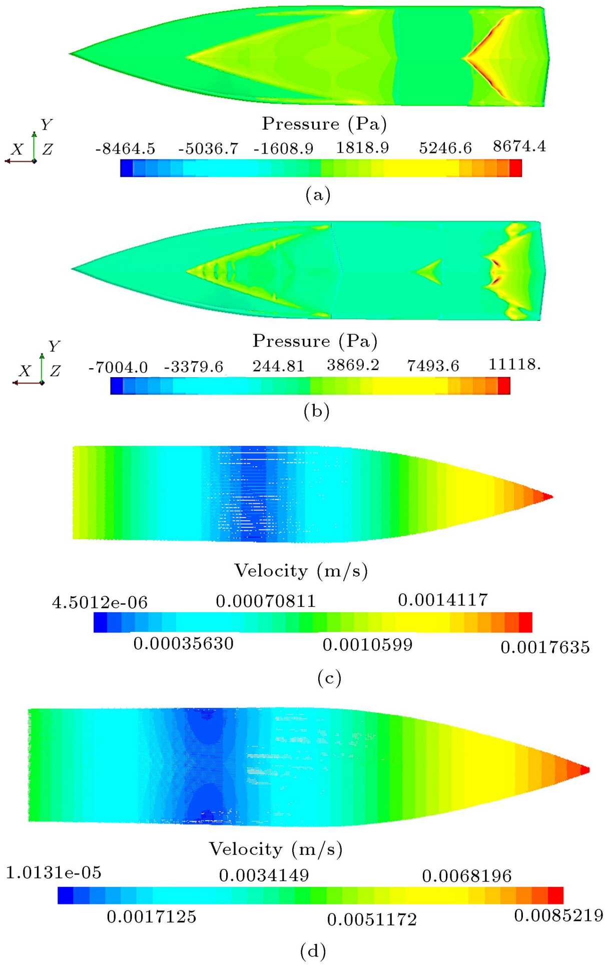


**Figure 20.** (a) Single-step model pressure contour. (b) Two-step model pressure contour. (c) Single-step model velocity contour. (d) Two-step model velocity contour.

## 6. Conclusions

In the current study, two different planing vessels of single- and double-step hulls were experimentally and numerically investigated. The main objective of assessing these models with similar hulls was to examine their longitudinal stability and performance. The tested models differed only in their number of steps. The targeted simulations were performed in STAR-CCM+ software, and the two-phase flow was analyzed using finite volume technique as well as volume of fluid scheme. The moving mesh with the overset technique was used for discretization purposes. The appropriate number of tests was determined based on the Taguchi method. The measured parameters at speeds of 7.5, 8.025, 8.5, and 9.5 m/s in the conducted tests included the bow rise-up, vessel trim, and resistance. As observed, adding the step(s) to the planing vessel would increase the lift at the transom, mainly due to the increase in the pressure on the second hull. This in turn would yield a reduction in the trim angle and an increase in the vessel stability. Overall, based on the presented results, the following remarks can be made:

1. Among the stepped planing vessels, the model with two steps had a lower trim angle than the others;

2. In case the planing vessel was equipped by single and double steps, porpoising phenomenon would be averted, hence its higher stability;
3. According to the numerical studies at speeds of 10 m/s and 12 m/s, as the second step moved away from the transom, the resistance increased, while the trim decreased. It was also observed that both single- and double-step models were stable at speeds up to 12 m/s;
4. The middle bodies of both Models 1 and 2 remained dry due to current separation, which made them less resistant; however, it caused instability in these models at higher speeds;
5. One of the main reasons for an increase in the pressure in the middle and end bodies was the current separation that occurred at a speed of 4 m/s.

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## Nomenclature

| | |
|---|---|
| $B$ | Beam (m) |
| $L$ | Length (m) |
| LCG | Longitudinal Center of Gravity |
| $m$ | Mass (kg) |
| $\beta$ | Deadrise angle (deg) |
| $\Delta$ | Weight (N) |
| $Fr_B$ | Beam Froude number |
| $\tau_S$ | Static trim angle (deg) |
| $Z$ | Rise-up |
| $R_T$ | Total resistance |
| $CG$ | Center of Gravity |
| $LOA$ | Overall length of the vessel |
| $L_s$ | Distance from the step to the transom stern |
| $C_\delta$ | Weight factor |
| $C_L$ | Lift coefficient |
| $v$ | Speed of models |
| $Cv$ | Speed coefficient |
| $Lc$ | Wetted Chine |
| $Lk$ | Wetted keel |

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