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Abstract: Transverse steps in modern high-speed craft can increase the longitudinal stability in addition to reducing frictional resistance. The porpoising instability can also be avoided by selecting the appropriate location and height of the transverse step. In the current paper, a non-step and a double-step model are investigated. The primary purpose of the present study is to examine the impact of second step on the stability and performance of the craft. Both models are generally identical. They are prismatic with a deadrise angle of 24 degrees, made of fiberglass, and are 2.64 meters long and 0.55 meters wide. The only difference between the two models is the bottom shape. One has two transverse steps, and the other has no step. These models are tested in a towing tank within a range of beam Froude numbers of 0.43 to 3.87. Measured parameters include rise-up of the bow and aft as well as center of gravity, trim, and resistance of the models. The obtained results indicate that through creating the second step, the longitudinal stability of the model increases, and the trim decreases. On the other hand, the double-step model has lower resistance in the pre-planing state.

Keywords: modern high-speed craft; porpoising; second transverse step; resistance; experiments

ABOUT THE AUTHOR

Professor Parviz Ghadimi received his Ph.D. in Mechanical Engineering in 1994 from Duke University, USA. He served one year as a Research Assistant Professor in Mech. Eng. Dept. and six years as a Visiting Assistant Professor in Mathematics Dept. at Duke. He then joined Dept. of Maritime Engineering at Amirkabir University of Technology, Iran, in Fall 2005. He is currently a Full Professor of Hydromechanics at that department. His main research interests include hydrodynamics, hydro-acoustics, thermo-hydrodynamics, and CFD, and he has authored over one hundred scientific papers as well as six books in these fields. The current topic is the result of an effort in his hydrodynamic group which focuses on the hydrodynamic performance of high-speed planing crafts.

PUBLIC INTEREST STATEMENT

High-speed planing vessels are widely used as recreational boats and improvement of their hydrodynamic stability is an important issue. Transverse steps in modern high-speed craft can increase the longitudinal stability in addition to reducing frictional resistance. Accordingly, the porpoising instability can be eliminated by selecting the appropriate location of the transverse step. In the current paper, a non-step and a double-step model are experimentally investigated. The primary purpose of the present study is to examine the impact of second step on the stability and performance of the craft. The measured parameters include rise-up of the bow and aft and center of gravity, trim, and resistance of the models. The obtained results indicate that by providing the second step, the longitudinal stability of the model increases, and the trim decreases. On the other hand, the double-step model has lower resistance in the pre-planing state.
1. Introduction

In recent years, planing hulls have been considered alternatives to displacement vessels due to their ability to move at high speeds. Planing hulls have resistance-velocity diagrams different from those related to displacement vessels, thus facilitating the achievement of higher speeds. In addition to planing hulls, other vessels such as hydrofoils, are also improving in parallel. However, planing hulls have much better flexibility for sport, military, and recreational applications. However, the use of these vessels in each of the mentioned applications requires knowledge of the effects of different parameters on the performance of the boats. Research in this field is divided into three categories: analytical, empirical, and numerical and all these approaches are still expanding. The range of parameters affecting the performance of these vessels is so wide that none of these approaches can be ignored. For example, investigating the water entry of different sections such as wedges and cylinders is just one of the lateral branches to identify the behavior of planing hulls and extensive research has been conducted in this area.

Arai and Matsunaga (1989), using empirical and numerical methods, investigated the bow flare slamming of a typical container ship. E-L-M. Yettou et al. (2006) conducted an experimental investigation to find pressure distribution around a free-falling wedge upon entering water. Hasheminasab et al. (2019) also used a drop test model to examine the effects of deadrise angle, drop heights, and space between two single wedges on the water entry of twin wedges. Arai and Tasoki (1987) studied flow around a two-dimensional wedge entering the water surface at constant vertical velocity. Judge et al. (2004) employed a two-dimensional vortex distribution method to examine the initial asymmetric impact of wedge with water, with horizontal as well as vertical velocity. Sun and Faltinsen (2007) developed a 2D boundary element method (BEM) to study the vertical water entry of a bow-flare ship section with a constant roll angle into initially calm water surface. Ghadimi et al. (2012) presented an analytical method as well as a numerical solution to study the water entry problem of a circular section.

Smoothed Particle Hydrodynamics method (SPH) is also one of the most efficient ways to study water entry. Farsi and Ghadimi (2014a) employed this method to determine the pressure distribution around different sections of the two catamaran models and presented the fluid-solid interaction in a free surface flow for different cases of symmetry and asymmetry wedges (Farsi & Ghadimi, 2015). They also conducted a simulation of the wedge water entry with a wide range of deadrise angles including 10 degrees, 20 degrees, 30 degrees, 45 degrees, 60 degrees and 81 degrees, with extreme deadrise angles of 10 degrees, 60 degrees, and 81 degrees and validated the obtained results of SPH method (Farsi & Ghadimi, 2014b). Feizi Chekab et al. (2016) used weakly compressible smoothed particles hydrodynamics (WCSPH) method to investigate the water entry of prismatic wedges, circular cylinders, and spherical bodies. On the other hand, to provide a database for the designers of the planing hulls, Ghadimi, Feizi Chekab et al. (2014) used Finite Volume Method to study the water entry of some arbitrary bow sections. Finite volume method has also been used in other papers to study the water entry of wedges with laminar and turbulent assumptions (Shademani & Ghadimi, 2017a), water entry of twin wedges with different deadrises (Shademani & Ghadimi, 2017b), calculating the forces, spray parameters and secondary impact of fixed width wedges at extreme angles (Shademani & Ghadimi, 2017c) and simulation of the water entry of planing catamaran hulls (Shademani & Ghadimi, 2017d). Recently, Zheng and Zhao (2020) also used the modified host-cell immersed boundary method to investigate the water entry problem.

In addition to experimental and numerical studies, extensive theoretical research has been conducted on water entry problem. E. Yettou et al. (2007) determined impact pressure as well as the overall force acting on the two-dimensional wedge. Qin et al. (2011) employed a modified Logvinovich model to investigate the water entry of an asymmetric wedge with roll motion. Ghadimi et al. (2013) determined the water impact on a dropping wedge with a constant velocity by using the Schwartz–Christoffel conformal mapping. Based on added mass theory and momentum variation, Ghadimi, Tavakoli, Dashtimanesh, Toghiaghani et al. (2017a) provided a mathematical model to simulate the coupled roll and heave motions of the asymmetric impact of a two-dimensional wedge body.
However, despite much research through experimental, numerical, and analytical approach regarding water entry problem, there remain many dark corners in this field. On the other hand, considering the six degrees of freedom of movement of vessels, a careful study of their motion requires simultaneous consideration of all these degrees of freedom. This can only be done using a numerical and experimental approach. However, the high cost of these methods, and even the inability to use them in some cases, makes the development of analytical methods unavoidable. Another reason to enhance analytical methods is that under different circumstances, it may not be important to consider the effect of other motions for examining a particular motion. Savitsky (1964) was among the first to obtain parameters such as lift, drag, and wetted surface area as a function of velocity, trim angle, deadrise angle, and loading using semi-empirical methods. After that, Zarnick (1978) investigated movements of these vessels without linearization, considering several assumptions as well as using a modified low-aspect-ratio or strip theory.

In this context, roll motion, as one of the most critical motions of vessels, has been repeatedly investigated, individually. Judge and Judge (2013) investigated various modeling assumptions associated with transverse plane dynamics in roll and hydrodynamic forces in the planing regime. Tavakoli et al. (2015) using 2.5D theory and attempted to mathematically model forced roll mechanism to determine hydrodynamic roll coefficients. Ghadimi, Tavakoli, Dashtimanesh et al. (2016a) presented a mathematical model which is derived by applying an analytical model of the water entry to predict the roll motion. Morabito (2015) in 2015 examined the force on the boat’s body under yaw motion. One of the achievements in providing relationships for discrete motions is to make it possible to obtain relationships for the coupled motions. So far, some relationships have been provided by researchers to consider coupled heave and pitch motions (Ghadimi, Tavakoli, Dashtimanesh et al., 2016b) as well as coupled heave, pitch, and roll motions (Tavakoli et al., 2017). However, these investigations may be conducted in calm water or in the presence of waves, depending on the purpose of the researcher. For example, Zarnick (1978) considered waves. Similar studies have also been done to consider the movements of the vessel in the presence of different waves, both in terms of the nature of the wave and its direction of movement relative to the vessel. Deyzen (2008) formulated a nonlinear mathematical model to simulate motions of a planing monohull in head seas. Taunton et al. (2011) designed a new series of high-speed hard chine planing hulls to study their performance in both calm water and waves. Haase et al. (2015) used 2D + t theory along with the BEM method to investigate a prismatic planning hull in head seas. In this study, they considered nonlinearity, such as breaking waves. Sebastiani et al. (2008) also provided a method for considering heave, pitch, and roll motions in the presence of waves. On the other hand, it is also important to examine different motions of the vessel in calm water as it makes it possible to identify and eliminate instabilities. Ghadimi et al. (2015) developed a new mathematical model based on pressure distribution to predict the stability of prismatic planing hulls in calm water. A mathematical model was also proposed by Ghadimi, Tavakoli, Dashtimanesh, Zamanian et al. (2017b) to predict the running attitude of warped planing hulls fixed in a heel angle and free to trim and sinkage. Ghadimi, Tavakoli, Dashtimanesh et al. (2016c) also presented another mathematical model based on 2D+T theory to predict the performance of hard-chine boats in both semi-planing and planing regimes.

Another advantage of understanding these motions in calm water as well as in the presence of waves is the possibility of designing and using appendages such as trimtabs, interceptors, and wedges or modifying the hull form, such as providing steps. In this regard, lifting surfaces such as wedge or interceptor are used both at the aft (for trim adjustment) and at the sides (to improve maneuverability) of the hull (Widmark & Marine, 2001). Numerous studies have been conducted on the effect of the interceptor flap and wedge to predict the trim angle and drag of the vessel and to model their behavior. Tsai et al. (2003) studied the compound effects of interceptor and stern flap for two high-speed craft with a transom stern. Karafiath and Fisher (1987) investigated the effect of a stern wedge on the annual fuel consumption of the destroyer and frigate size ships. Ghadimi, Loni et al. (2014) used empirical equations to investigate the usage of trimtab, mathematically. They examined the effects of span length on the resistance and dynamic trim angle of planing hulls. Karimi et al. (2013) tested two models of planing hulls with and without interceptors to find the effects of this appendage on high-speed craft performance.
Creating transverse steps on the bottom of planing hulls is another solution to improve the performance of these vessels. Creating steps will reduce the wetted surface area of the vessel. By creating transverse steps, the vessel is divided into two or more separated bodies. As a result, the flow of water separates at the location of each step and again attaches to the aft body. Hence, in general, the resistance of stepped vessels is less than that of non-step vessels (Faltinsen, 2005). This decrease in resistance results in lower fuel consumption of these vessels. Therefore, this advantage, despite the complexities of the design and construction of these vessels, makes their use in different applications more appropriate, and researchers are investigating their performance under different conditions. Splitting the planing hull into several sections using transverse steps causes the hydrodynamic lift to be distributed along the vessel. This is because the pressure caused by the reattachment of water to the aft body results in a hydrodynamic lift. Hence, increasing the longitudinal stability of stepped vessels is expected. According to Clement's research in 2003 (Faltinsen, 2005), 90% of hydrodynamic lift occurs in the forebody and 10% in the aft body. So, the position and height of the steps on stepped vessels are effective in the spray root attached to the aft body (Faltinsen, 2005) and ultimately strongly affect their performance (Clement, 2003).

Research on stepped vessels continued through empirical, numerical, and analytical approaches. Clement and Pope (1961) presented a database by which the resistance and trim of stepped planing hulls could be predicted. Savitsky and Morabito (2010) conducted a series of extensive experiments in 2010 to determine the profiles of the longitudinal surface wake of prismatic hulls. These experiments were carried out on vessels with 10, 20, and 30 degrees deadrise angles. Finally, empirical equations were obtained to determine the acceleration profiles that can be used to estimate the performance of stepped vessels. Meanwhile, Lotfi et al. (2015) compared calculated results obtained via numerical methods with experimental measurements. Bakhhtiari et al. (2016) computed the values of drag, pressure distribution, water spray, wake profile, wetted surface, and wave generated by a stepped planing hull using ANSYS-CFX commercial code. With the proven effectiveness of numerical results in studying stepped hulls, some researchers tried to find the best mesh generation methods. In this context, Doustdar and Kazemi (2019) examined the accuracy of the results obtained through fixed and dynamic mesh. Sajedi et al. (2019) studied the stability and rooster tail phenomenon of mono-hull planing craft with a constant deadrise angle, experimentally and numerically. Recently, Afriantoni et al. (2020) examined the stability of high-speed craft with step hull angle variations at a speed using a different meshing strategy in a numerical work.

Garland and Maki (2012) investigated the performance of a stepped vessel using a two-dimensional numerical simulation. By investigating the free surface elevation and the exerted pressure on the surface, they modified the steps position and height. Najafi and Nowruzi (2019) analyzed the effects of five different types of transverse steps on lift to drag ratio, resistance, trim angle and sinkage of high-speed planing crafts. Ghadimi and Panahi (2019) investigated the effects of steps on the forces and moments exerted on the yawed planing hulls. The obtained results indicated that surge force coefficient of the stepped hull is larger, while its sway force and rolling moment are smaller. Svahn (2009), in 2009, proposed a method to estimate the resistance of stepped hulls. This method was largely based on the method proposed by Savitsky (1964). Loni et al. (2013) also in 2013, presented a model for predicting the performance of stepped vessels.

The proper performance of single-step vessels reinforced the idea that the use of more transverse steps may increase this improvement. In 2012, Danielson and Stromquist (2012), based on the work of Svahn (2009) and Savitsky (1964), developed a model for double-step vessels. Vitiello et al. (2012) in 2012, studied effective ship power of the stepped hulls, which was directly subjected to the resistance of the vessel. The general pattern of research and identification of the characteristics of double-step hulls is still like the studies carried out around single-step vessels. That is, the effect of the position and height of the steps (Lee et al., 2014) and other geometrical parameters affecting the performance of the double-step hull are examined according to criteria such as resistance, dynamic sinkage, and dynamic trim (Tauntom et al., 2010). Table 1 displays a summary of different studies conducted on the stepped planing hulls since 2019.
Table 1. Numerical studies conducted on stepped planing hulls since 2019

| Authors | General description | main Investigated topic | year |
|---------|---------------------|-------------------------|------|
| Afriantoni et al. (2020) | They examined the stability of high-speed craft with step hull angle variations at a speed using a different meshing strategy in a numerical work. | step hull angle | 2020 |
| Ghadimi and Panahi (2019) | They investigated the effects of steps on the forces and moments exerted on the yawed planing hulls. The obtained results indicated that surge force coefficient of the stepped hull is larger, while its sway force and rolling moment are smaller. | effects of steps on the forces and moments exerted on the yawed | 2019 |
| Dongmei et al. (2019) | They simulated the flow field around the stepped planing hulls based on the FVM (Finite Volume Method) numerical method in using the Taunton series. | air cavity | 2019 |
| Zou et al.(2019) | They examined the stern flap and double step as two general potential factors in resistance reduction. | flap and double step | 2019 |
| Ghadimi et al. (2019) | This paper investigated the performance and hydrodynamic Characteristics of a double-stepped planing hull and the effects of adding two steps to the bottom of a mono-hull. | double step | 2019 |
| Kazemi et al. (2019) | They study the effects of weight loading by simulating non-step and single-step planing hulls with free heave and pitch motions under different weight loadings. | weight loading | 2019 |
| Chooran et al. (2019) | This work addresses the numerical study of step height effect on the hydrodynamic performance of the planing hull. | step height | 2019 |

The present study is in line with an extensive research carried out by the authors. At this stage, it is only a matter of establishing an empirical database on the performance of the double-step hull and comparing them with the results of other types of planing hulls. This is due to the fact that any comprehensive survey of planing hulls requires extensive empirical information. For example, Danielson and Stromquist (2012) avoided the study of double-step vessels, simply because they did not have sufficient empirical information. The information obtained at this stage of the project will be used as a reference for future numerical parametric studies. In this study, the stability and performance of double-step hull and non-stepped hull are compared. Using the model test, the values of rise-up of the bow, aft, and center of gravity as well as trim and resistance of two-step and no-step boats are measured. A comparison of these parameters gives a good understanding of the performance of the steps in planing hulls.

2. Problem definition
The speed of the high-speed craft relative to its beam is defined as beam Froude number:

\[
Fr_B = \frac{U}{\sqrt{gB}}
\]  

(1)

where \( U \) and \( B \) are the speed and beam of the craft, respectively, and \( g \) is the acceleration of gravity. In the current paper, experiments are performed on two models, one of which is non-step,
and the other has two transverse steps. These two models are the same in terms of general shape, the center of gravity, length, and width. The distribution of the forces on the bottom of high-speed craft, changes as the Froude number increases. On the bottom of this kind of crafts, there are high-pressure points called stagnation points where the pressure is maximized. Creating transverse steps will increase the number of these points, thereby increasing the stability of the craft. This issue has been shown in Figure 1.

Figure 1 illustrates the pressure lines called stagnation lines. As observed, the number of these lines in Figure 1(b) is larger than Figure 1(a). This increases the longitudinal stability of model B and reduces the wetted surface area of the craft.

On the other hand, the porpoising phenomenon emerges due to the longitudinal imbalance of the gravity force and pressure force due to the water pressure on the bottom of the craft (hydrodynamic force), as shown in Figure 2. In this case, the trim of the craft is continuously changing, and the craft is unstable.

Figure 2 shows three different conditions of the craft. In condition “a”, the lift force of the aft increases and gradually drives the craft to condition b and eventually to condition c. As the lift of the bow increases, the “a” condition is repeated, and thus the bow oscillates.

3. Physical definition of the models
The boat model is designed to eliminate the instability of the Cougar boat and is tested in the towing tank. The length of the model is 20% of the length of the cougar boat. By performing resistance tests on the model, the exact speed and time at which the instability occurs are extracted. A two-stepped model is then used to solve this problem. Steps below the hull change the pressure distribution and eliminate the instability of the vessel. Based on beam Froude number, the models are tested at speeds of up to 9 m/s, which is the range of instability in the prototype vessel. Figure 3 displays a view of the cougar boat.
The length and width of these models are 2.64 and 0.55 meters, respectively. These models are prismatic and have a constant deadrise angle of 24 degrees and are made of fiberglass. Each of these models weighs 86 kg. Principal characteristics of the towed models are shown in Table 2. The prototype vessel is longitudinally unstable. By modeling the vessel, this problem is investigated, and a solution is provided. The trim of the bow is 2.3 degrees, and the center of gravity is 0.791 meters to the aft. The angle between direction of the main shaft and the horizon line is 6 degrees. The models are tested experimentally at beam Froude numbers of 0.34 to 3.87 which correspond to speeds of 1 to 9 m/s. The models’ characteristics are displayed in Figure 4.

4. Test procedure
The targeted experiments are conducted in the towing tank of National Persian Gulf Marine Laboratory in accordance with the ITTC recommendations for towing tank tests. This laboratory has a length of 400 m and a width of 6 m. These models are drawn at the point of contact of

| Parameter | Value            |
|-----------|------------------|
| L         | 2640 mm          |
| LCG       | 791 mm of transom|
| VCG       | 185 mm           |
| m         | 86 kg            |
| τₗ       | 2.3 deg          |
| B         | 551 mm           |
| Frₖ      | 0.43–3.87        |
| deadrise | 24°              |
the center of gravity and the thrust system, which is at 6 degrees from the base line. The model has two degrees of freedom for heave and pitch motions, while the rest of the movements are fixed. The measured parameters in the towing tank are drag and trim. The primary specifications of the towing tank are given in Table 3. The carriage in this laboratory is a passenger type with a capacity of 5. Its low-speed driving mode is 4.5 to 2 m/s and its high-speed driving mode is 2.8 to 2 m/s. Three sensors are installed on the model to determine the resistance, trim and rise-up. Tests are performed in two degrees of freedom. Dynamometer is mounted for determining the resistance of models. It is of two-component type and its maximum capacity is 100 Newton for displacement vessel and 600 Newton for planing hull. The dynamometer error is 2% of one Newton. Two potentiometers are installed to measure the heave and trim of the bow and aft body. Figure 5 shows a view of the installation of the sensors on the models. Finally, the intended parameters are measured by the potentiometers and converted to a trim angle using Equation 2. In the calculations, the dynamic trim angle is added to the static trim angle. Figure 5(a) shows an overview of the tests carried out.

Table 3. Characteristics of National Persian Gulf Towing Tank

| Parameter                          | Value     |
|------------------------------------|-----------|
| Length of canal                    | 400 m     |
| Width of canal                     | 6 m       |
| Depth of canal                     | 4 m       |
| Maximum Velocity of carrier        | 18 m/s    |
| Density of towing tank water      | 1002 kg/m³ |
| Kinematic viscosity of towing tank water | 9.75E-07 |
| Temperature of water              | 21°       |
| Distance of between potentiometer | 1901 mm   |
| Distance of between towing situation and transom | 791.49 |

Figure 5. a) Overview of the test of the non-step model at the speed of 9 m/s. b) location of the potentiometer and dynamometer on model.
The towing location of the vessel in the towing tank is the intersection of shaft direction and center of gravity. Therefore, the main vessel's shaft angle with horizontal axis must be calculated. The main vessel shaft over which this model is constructed forms a 6 degrees’ angle, as shown in Figure 5(b). The towing location is at 791 mm from the transom. In the conducted experiments, the model is towed. However, there is an alternative method called Down-Thrust in which the vessel is pushed. Pushing implies that towing force in the towing tank replaces the propeller thrust in the actual vessel. DT method does not consider the moment effects, which could cause an increase in τ angle on the craft. Through DT method, the direction of the thrust force is applied at the intersection of engine thrust direction and keel line at the bow (De Marco et al., 2017; Vitiello & Miranda, 2014). Both methods are common for towing tank tests and provide the same force and moment equilibriums in calm water due to the same force direction, which is in the direction of thrust or shaft. Besides, in both towing and pushing methods, the external force acts at the center of gravity, which leads to the same moment condition. The beginning of the longitudinal instability caused by a lack of force equilibriums is also the same in both methods. In the towing method, thanks to the use of magnetic potentiometers bow and aft of the vessel can move freely, without any disturbance, and consequently, the porpoising phenomenon can be well observed. In this series of experiments, the rise-up with respect to the calm condition is registered at every moment at two different points with the help of potentiometer and using Equation (2), it is transformed to trim and vessel's rise-up at the center of gravity (CG).

\[ \tau = \tan^{-1} \left( \frac{Z_2 - Z_1}{L_2 - L_1} \right) \]  

(2)

Z represents the position of the potentiometers. Figure 5(b) indicates the special position, while Figure 5(b) shows a view of how the potentiometers are installed on the vessel.

Table 4. The location of the steps of some of the double-stepped vessels in the world

| boat              | L/B  | forward step to stern/beam | aft step to stern/beam |
|-------------------|------|-----------------------------|------------------------|
| Formula 419       | 5.1  | 2.53                        | 1.15                   |
| Formula 382       | 4.6  | 1.78                        | 0.93                   |
| Donzi 38          | 4.5  | 1.97                        | 1.31                   |
| Fountain 47       | 5.3  | 1.71                        | 1.31                   |
| Outer limits      | 5.5  | 1.82                        | 1.27                   |
| Cigarette 39      | 4.8  | 2.33                        | 1.35                   |
| Nor-tech 4300     | 4.9  | 1.69                        | 1.06                   |
| Nor-tech 4227     | 5    | 2.15                        | 1.43                   |
| Sunsation 36 XRT  | 4.5  | 2.12                        | 1.19                   |
| Sunsation 36 SSR  | 4.5  | 2.04                        | 1.3                    |
| Present Model     | 5    | 1.43                        | 0.72                   |
5. Test conditions
Two different models have been tested in these experiments. The locations of the steps in double-step model are selected based on the available double-step vessels in the world. The location of the steps of some of these vessels is presented in Table 4.

Columns 1 and 2 of Table 3 provide the name of the boats, and their length-to-width ratio, respectively. On the other hand, the distance of the steps from the aft is divided by the width of the vessel to allow a better comparison between them. The results of these divisions are shown in columns 3 and 4 of Table 3. The total length of the model is 2640 mm. For the double-step model, the distance of the first and second steps from the aft is 30% and 15% of the length of the model, respectively. The height of the step of the model is 4% of the model’s width. The total width of the model is 551 mm. Test results are presented in the next section.

6. Results of the models and description
In this section, the results of the experiments are presented. The measured parameters include resistance, trim, and rise-up of the center of gravity. The tests are conducted at the speeds of 1 to 9 m/s. The list of the tests is presented in Table 5.

As evident in Table 4, in the planing regime, i.e., at beam Froude number of 1.72 onwards, the trim of the models starts decreasing after an increase and then become longitudinally unstable. Porpoising appears at a speed of 8 m/s. The center of gravity and the center of pressure are two determining factors in the occurrence of the propositional phenomenon. LCB is the center of the underwater volume, the location of this center is usually important in displacement and semi-displacement regimes. This range includes beam Froude numbers between 0 and 2.5. However, in the planing regime, the underwater volume is low, and the static buoyancy force reaches its minimum value. Therefore, LCB in beam Froude numbers above 2.5 does not play a major role in stability. The instability of this model occurs in the planing regime (Faltinsen, 2005). In this motion regime, the pressure center is the determining factor.

| Table 5. Measured parameters for the case of non-stepped hull |
|------------------|---|---|---|---|---|---|
| \( U \) (m/s) | \( F_{RB} \) | \( Z_{L1} \) (mm) | \( Z_{CG} \) (mm) | \( Z_{L2} \) (mm) | \( \tau \) (deg) | \( R_{T} \) (N) | \( R/\Delta \) |
| 1 | 0.43 | -3.1 | -1.78 | 1.27 | 0.13 | 7.8 | 0.009 |
| 2 | 0.86 | -22.7 | -8.67 | 23.59 | 1.39 | 52.9 | 0.062 |
| 3 | 1.29 | -34.59 | 4.03 | 92.8 | 3.83 | 113.3 | 0.134 |
| 4 | 1.72 | -17.9 | 26.71 | 129.25 | 4.43 | 128.02 | 0.151 |
| 5 | 2.15 | 1.64 | 92.61 | 169.75 | 5.05 | 136.75 | 0.162 |
| 6 | 2.58 | 27.00 | 70.26 | 169.70 | 4.29 | 133.9 | 0.158 |
| 7 | 3.01 | 46.60 | 81.54 | 161.86 | 3.47 | 135.37 | 0.160 |
| 8 | 3.44 | PORP. | PORP. | PORP. | PORP. | PORP. | PORP. |
| 9 | 3.87 | PORP. | PORP. | PORP. | PORP. | PORP. | PORP. |

Figure 7. Diagram of a) resistance b) trim c) rise up of the non-stepped model.
Notable in these tests is the study of the behavior of the models in all displacement, semi-planing, and planing regimes. It should be noted that the dynamic trim value of the models is added to their static trim value. The trim first increases and then decreases. Parameters cannot be accurately measured when porpoising occurs. Figure 7 shows the trim and resistance diagrams.

As shown in Figure 7, resistance increases as trim increases in displacement and semi-displacement regimes. In this situation which continues up to the speed of 4 m/s, the dominant resistance is the pressure resistance. According to Equation 3, as the trim increases, the pressure resistance increases, too.

\[
R_p = \Delta \times \tan \tau
\]

\[
R_F = \frac{1}{2} C_f A V^2
\]

Here, \( \Delta \) is the weight of the vessel, and \( \tau \) is the angle of trim. At the start of planning regime, resistance decreases somewhat due to the decrease in the wetted surface area and the angle of the trim. Then, with increasing speed and decreasing the trim angle and eventually increasing the wetted surface area, according to Equation 4, the total resistance increases until the vessel becomes unstable. In general, the pressure resistance in the displacement and semi-displacement regimes is greater than the frictional resistance. This is because, in these motion regimes, the trim angle of the model is higher. However, in planing regime, the friction resistance is greater than the pressure resistance.

Table 6 presents the results of the two-step model. The results show that by adding a second step to the model, the longitudinal stability is enhanced, and the porpoising is avoided. These tests are performed at speeds of 1 to 9 m/s. The maximum recorded resistance is equal to 160.7 Newton, and the angles are initially ascending, then descending. Figure 8 shows the diagram of the resistance and trim of the boat.

Figure 8 illustrates the resistance, trim and rise-up diagrams for the two-step model. Trim has an upward trend, then a downward trend, and finally, an upward trend. In the planing regime, the behavior of resistance and trim is opposite to each other, implying that with reduced trim, the resistance is increased and vice versa.

**7. Comparison between the tested models**

In this section, the effect of second step on the stability, resistance, rise-up, and trim of the two-step model are compared to the non-step model. The distance of the first and second steps to the aft of the

| Table 6. Results associated with the model with two-step model |
|---------------------------------------------------------------|
| **U m/s** | **Fr** | **Z_{L1} (mm)** | **Z_{CG} (mm)** | **Z_{L2} (mm)** | **\( \tau \) (deg)** | **R_{f} (N)** | **R/\Delta** |
|-----------|--------|-----------------|-----------------|-----------------|--------------------|---------------|--------------|
| 1         | 0.43   | -0.9            | -1.20           | -2.1            | -0.03              | 8.53          | 0.010        |
| 2         | 0.86   | -13             | -8.94           | 3               | 0.42               | 45.1          | 0.053        |
| 3         | 1.29   | -33             | -9.48           | 59.8            | 2.46               | 96.13         | 0.114        |
| 4         | 1.72   | -14.6           | 5.70            | 65.5            | 2.12               | 119.6         | 0.142        |
| 5         | 2.15   | 2.58            | 17.72           | 62.3            | 1.58               | 149.4         | 0.177        |
| 6         | 2.58   | 12.3            | 28.14           | 74.8            | 1.66               | 169.7         | 0.201        |
| 7         | 3.01   | 15.87           | 42.52           | 121             | 2.79               | 150.09        | 0.178        |
| 8         | 3.44   | 27.9            | 56.06           | 139             | 2.94               | 151.7         | 0.180        |
| 9         | 3.87   | 36.8            | 62.91           | 139.8           | 2.73               | 160.89        | 0.191        |
model is 791 and 340 mm, respectively. All tests are performed at speeds of 1 to 9 m/s. The trim angle diagram for the two modes is shown in Figure 9. The results show that the trim angle of the two-step model is generally less than that of the non-step model in all motion regimes. The initial trim values of the two-step model are less than the non-step model. The primary reason for this difference is the positive lift provided at the aft of the two-step model. By increasing the lift at the aft of the two-step model, its trim is reduced. Both models are stable in displacement and semi-displacement regimes. The stability of the models is due to the presence of a large underwater volume of the model. On the other hand, by increasing the pressure on the aft of the two-step model and providing a stagnation line, the model becomes more stable, and the porpoising disappears.

In Figure 10, the rise-up at the center of gravity of the models is compared. By creating steps on the model, the wetted surface area, and rise-up decreases. A special feature of the two-step model is the reduction of trim and rise-up along with the reduction of wetted surface. These factors stabilize the model and reduce the resistance. This difference increases with increasing velocity. Hence, at beam Froude numbers beyond 1.5, this difference is markedly increased.

Figure 11 compares the resistance between the two models. In the pre-planing regime, due to the reduced trim angle and reduced pressure resistance, the double-step model's resistance is lower. By decreasing the trim angle due to the increased lift on the aft of the double-step model, the stability of the model increases. However, in the second mode, i.e., from beam Froude number of 2 onwards, the resistance of the non-step model is reduced. It is obvious that since the required ventilation is not
achieved (due to an increase in trim angle), the pressure resistance increases sharply. But then, with an increase in lift at the aft, it increases somewhat. As such, ventilation occurs, and as a result, resistance decreases.

8. Conclusions

In this paper, two models of high-speed craft are studied and compared. The prototype vessel, which is about 13 meters long, is longitudinally unstable. One of the models is the same as the prototype, but the second model has two transverse steps. The purpose of testing these models, which have the same length and width, is to evaluate their longitudinal stability and performance. Measured parameters in these experiments include rise-up of the bow and aft and center of gravity as well as trim angle, and resistance of the models. The major results of these experiments can be summarized as follows:

(1) The trim angle of the two-stepped model is less than that of the non-step model. The main reason for this difference is the increase in the aft lift (near the transom) of the two-stepped model.
(2) Rise-up of the double-step model is less than that of the non-step model.
(3) The resistance of the vessel can be measured in two states: one is in the pre-planing regime, and the other is in planing regime. The resistance of the double-step model in the pre-planing and planing regimes is lower and higher than the non-step model, respectively.
(4) The presence of steps in the double-step model results in stability and elimination of the porpoising phenomenon.
This study is beneficial for understanding the performance of the step(s) on high-speed craft. Experimentally, different solutions are proposed to increase the longitudinal stability of these vessels. Some of these solutions are the addition of wedge or interceptor or a combination of step and wedge. In future studies, the researchers seek to increase stability by using the hybrid method and comparing it with the current one.

Nomenclature

| Symbol | Description                  |
|--------|------------------------------|
| B      | Beam (m)                     |
| L      | Length (m)                   |
| LCG    | Longitudinal center of gravity |
| m      | Mass (Kg)                    |
| VCG    | Vertical center of gravity (m) |
| β      | Deadrise angle (deg)         |
| Δ      | Weight (N)                   |
| Fr_B   | Beam Froude number           |
| τ_s    | Static trim angle (deg)      |
| SPH    | Smoothed Particle Hydrodynamics method |
| WCSPH  | weakly compressible smoothed particles hydrodynamics |
| Z      | Rise-up                      |
| R_T    | Total Resistance             |
| CG     | Center of gravity            |

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