Numerical Study on Resistance of Stepped Planing Hull

Fajri Ashfi Rayhan[1*], Andika Masrul[1], Arya Khairullah Akbar[1], and Bima Anugerah Putra[1]

[1]*Naval Architecture and Marine Engineering, Universitas Pembangunan Nasional Veteran Jakarta, 16514, Indonesia*
**Corresponding author: fajri.ar@upnvj.ac.id*

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ABSTRACT

A stepped planing hull, also known as a step hull, is a hull modification that reduces the wetted surface area. Although this type of hull has proven effective in several ships, it is still rarely used. The step hull possesses numerous advantages that make it ideal for activities involving small and fast boats. However, regrettably, its full potential remains untapped at present. The purpose of this study was to identify the effect of variations in the angle of the step hull on resistance or drag. The study utilized the CFD method, and three hull configuration models were used at each change in hull step angle of 180º, 210º, 240º, and 270º. Configurations 1 and 2 have similarities in terms of rear hull length (600 mm), hull height (20 mm for configuration 1 and 30 mm for configuration 2), and deadrise angle (15° for configuration 1 and 20° for configuration 2). Configuration 3 has similarities with an 800 mm rear hull, 20 mm hull height, and 15° deadrise angle. It was found that as the Froude number increases, the coefficient of total resistance decreases. Conversely, as the Froude number increases, the resulting resistance also increases. The configuration with the highest resistance value corresponds to the alteration from configuration 2 with a hull step of 180°, and that the alteration from configuration 2 with a hull step of 270° corresponds to the configuration with the lowest resistance value. This study concludes that deadrise angle and the height of the step hull are the main factors that require careful consideration when designing ships that use a step hull. Therefore, this research provides an understanding of the step hull and can serve as a basis for the development of the step hull.

Keywords: *CFD, resistance, ship, step angle, step hull*

I. Introduction

The fundamental aspect of shipping is a law discovered by a Greek scientist named Archimedes. His theory discussing displacement and buoyancy is the reason why a ship can float despite having a significant weight. The Archimedes principle, also known as the principle of buoyancy, is a guiding principle for ships to operate safely and efficiently at sea [1]. There are stages involved in building a ship, and the first and most fundamental stage is the design phase. There are various methods for designing a ship, and one of them is using the 3D modeling technique. There are three types of hull models for ships, namely those with displacement hulls, semi-planing hulls, and planing hulls [2]. The maritime industry can drive the development of a country in various aspects, such as tourism, military, economy, and others. Ship models are in high demand for various sectors such as state interests, military applications, transportation, exploration, tourism, recreation, and speed competition activities [3].

To achieve optimal speed, fast boats need to be designed from various aspects, such as safety and performance. In particular, hull planing is critical for speed optimization, as it

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plays a significant role in reducing resistance and increasing efficiency, which can save fuel consumption [4]. Speed is indeed highly sought after in ship design; it cannot be denied that safety and comfort are crucial considerations when designing a ship. It would be futile to have a ship with excellent speed if it carries a high risk of accidents and does not provide a comfortable experience for its users. The safety aspect is also essential to ensure the ship's stability and crew's comfort during navigation, especially to avoid capsizing, reduce ship movements, and prevent water from wetting the deck [5, 6].

The stepped planing hull, also known as a step hull, is a hull modification that involves a series of steps or longitudinal notches. These steps can either run straight across the hull or form a 'v' shape with apertures on the outboard side. This modification is designed to enhance a vessel's performance by reducing water surface area turbulence underneath the hull. This innovative design increases lifting force while simultaneously decreasing resistance, resulting in higher speeds that can be achieved with lower engine power requirements [7]. Experimental studies have demonstrated that ships equipped with stepped hulls exhibit lower overall resistance compared to those without this feature [8]. Furthermore, step hull ships benefit from a reduced trim angle, thereby enhancing stability during high-speed operation [3]. Vitiello et al. [9] developed eight types of step hulls, each featuring a transparent bottom with variations in the number of steps, longitudinal step position, and step height. This innovative design allows for the observation of the vortex phenomenon occurring beneath the step hull structure. These characteristics make stepped hulls particularly advantageous for high-performance vessels, such as speedboats, racing boats, and certain powerboats. However, increasing the angle of the step hull can have an impact on resistance. Conversely, the effects of both the step hull angle and its position have not been extensively studied. Therefore, this study aims to investigate the resistance in the hull area with step variations to prove the effect of step hull angles on reducing drag and choosing an optimal hull shape that responds well to ship movements.

II. Material and Methods

According to Rahman [10], mentioning the Froude number can significantly impact the characteristics of fast boats. One of the reasons why ships can reach high speeds is due to their large Froude number. The Froude number (Fn) can be defined in equation 1 as follows:

$$Fn = \frac{V}{\sqrt{g.L}} \qquad (1)$$

Where (Fn) is the Froude number, (V) is the ship's speed (m/s), g is the acceleration due to gravity (m/s^2) and L is the ship's length (m).

According to Zubaer et al. [11] a ship with a maximum operating speed above 30 knots is considered a fast ship. Considering the various types of ship hydrostatic behaviour using the Froude number (Fn), a ship with Fn above 0.4 or a submerged hull (submerged hull) is still considered a fast boat, such as monohulls in general and catamarans.

The Step Hull is a modification to the ship's hull aimed at reducing the amount of hull area exposed to water. Typically, this hull is shaped like a "V" and has a large opening on the outboard side to provide air for the purpose of pulling it down. The Step Hull is said to be more effective because the area submerged in water can be divided into several transverse components compared to the length of the ship. This results in a more efficient surface area and low friction with the flow. Therefore, the philosophy of Step Hull is to reduce the surface submerged in water. While many believe that this hull reduces the area exposed to water, it can also be said to minimize the hull area [12]. Figure 1 shows the components and dimensions of the Step Hull.

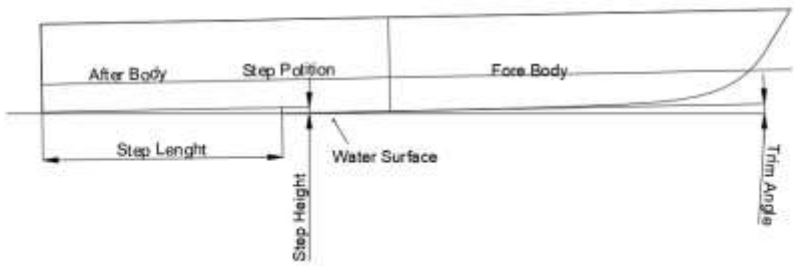

Fig. 1 Ship with step hull

According to Harnita's research [13], the ship's resistance at a certain speed is the fluid force that opposes the ship's speed or movement. The resistance of the ship is influenced by various factors, including the speed of the ship (V), the weight of the water displaced by the hull submerged in water (Δ), and the shape of the ship's hull.

Based on Birk [14], ship resistance is affected by the ship velocity, the weight of the water displaced by the submerged hull, and the ship hull shape. Ship resistance is denoted by RT, which stands for total resistance, with the equation 2:

$$RT = \frac{1}{2}\varepsilon \cdot \rho \cdot s \cdot V^2 \qquad (2)$$

RT is the total resistance (N), ε is the total resistance coefficient of the ship (-), ρ is the density of the fluid (kg/m^3), s is the wet surface area of the ship (m^2), V is the speed of the ship (m/s).

In addition to the total resistance, it is crucial to identify the types of fluid flow occurring around a ship's hull. The fluid flow can be mathematically explained by utilizing a dimensionless coefficient known as the Reynolds Number (equation 3), which distinguishes between laminar and turbulent flow regimes.

$$R_e = \frac{V \cdot L}{\vartheta} \qquad (3)$$

Re is Reynolds Number (-), Vs is ship velocity (m/s), L is the length of the ship (m), ϑ is kinematic viscosity (m^2/s).

In the study of hydrodynamics, the RANS equations, also known as the Reynolds-averaged Navier-Stokes equations, are mathematical equations that describe the motion of fluid flows over time. These equations are derived from the concept of Reynolds decomposition, where instantaneous fluid properties are separated into time-averaged quantities and their fluctuations. The main application of RANS equations is in describing turbulent flows. By incorporating knowledge about the turbulence properties of the flow, these equations provide an approximation of the time-averaged solution to the Navier-Stokes equation. In Cartesian coordinates, and using Einstein notation, this equation can be expressed for a stationary flow of an incompressible, Newtonian fluid. The formula is written (equation 4):

$$\rho\bar{u}_j\frac{\delta\bar{u}_i}{\delta x_j}=\rho\overline{f_i}+\frac{\delta}{\delta x_j}\left[-\bar{p}\delta_{ij}+\mu\left(\frac{\delta\bar{u}_i}{\delta x_j}+\frac{\delta\bar{u}_j}{\delta x_i}\right)-\rho\overline{u'_i u'_j}\right] \quad (4)$$

A ship that is above sea level will always experience external forces that cause it to move. This movement is primarily caused by waves. The ship's response to waves can be characterized by two types of motion: rotational motion, which includes rolling, pitching, and yawing, and linear motion, which is an irregular straight motion in accordance with its axis, including surging, swaying, and heaving.

The ship's response to regular waves is expressed in seakeeping, commonly referred to as the Transfer Function, which is a tool for transferring external loads (waves) in the form of a response to a structure. Seakeeping is the ratio between the amplitude of the ship's movement in the form of translation or rotation to the amplitude of the waves at a certain frequency. To carry out research, proper supporting data is essential as it significantly influences the process of completing the research. Collecting data on ship resistance and aspects that cause differences in ship resistance is necessary. The data collected should include the main dimensions of the ship, as shown in Table 1.

Table 1. Ship main dimension

Ship model	
Type	non-*step* hull *(Model Scale)*
Deadrise angle	15^o dan 20^o
Scale	1:8
Length (m)	2.5
Breath (m)	0.5
Height (m)	0.312
Ratio (L/B)	5
Displacement (Kg)	48

The modelling of the step hull was carried out using Maxsurf software. The modelling process involved creating an initial hull shape and then modifying it into a step hull. Several models were created with different variations of the step hull angle and deadrise angle.

There are three variations in the configuration based on differences in length of step hull, height of step hull, deadrise angle, and step angle. These configurations have an increasing hull step angle, which results in the data shown in Figure 2 and Table 2. Figure 3 shows the lines plan of hull model.

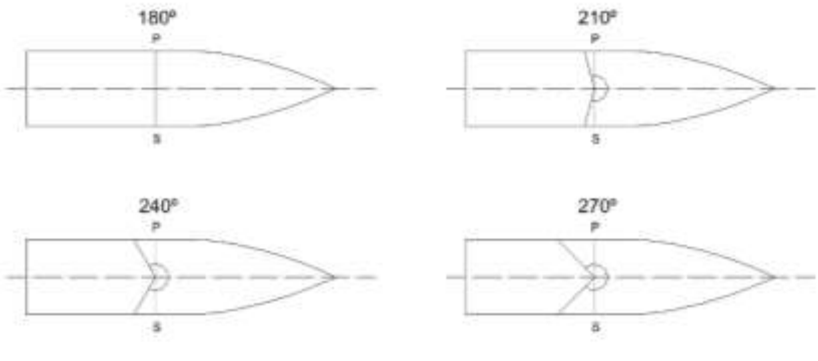

Fig. 2. Step angle configuration

Table 2. Variation and configuration

No.	Case	L_s (mm)	H (mm)	β (deg)	Step Angle (deg)
1	Wo/s-15	-	-	15	-
2	Wo/s-20	-	-	20	-
3	Configuration 1; Step Hull = 180º	600	20	15	180
4	Configuration 1; Step Hull = 210º	600	20	15	210
5	Configuration 1; Step Hull = 240º	600	20	15	240
6	Configuration 1; Step Hull = 270º	600	20	15	270
7	Configuration 2; Step Hull = 180º	600	30	20	180
8	Configuration 2; Step Hull = 210º	600	30	20	210
9	Configuration 2; Step Hull = 240º	600	30	20	240
10	Configuration 2; Step Hull = 270º	600	30	20	270
11	Configuration 3; Step Hull = 180º	800	20	15	180
12	Configuration 3; Step Hull = 210º	800	20	15	210
13	Configuration 3; Step Hull = 240º	800	20	15	240
14	Configuration 3; Step Hull = 270º	800	20	15	270

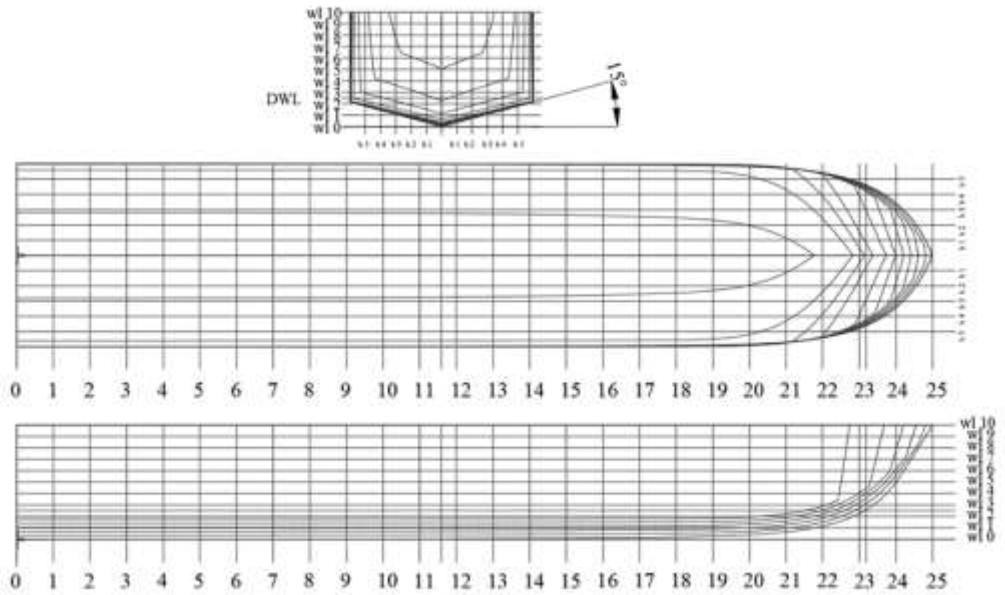

Fig. 3. Lines plan with 15° deadrise angle

After modelling the detailed ship components using Maxsurf Modeler Advanced software, the CFD approach will be simulated using ICEM CFD and Ansys CFX. The CFD simulation process consists of three stages: (i) modelling and meshing, (ii) set up, and (iii) simulations. Furthermore, the seakeeping analysis is conducted using Ansys Aqwa. The process of creating boundary conditions is carried out using Ansys ICEM, which aims to classify the analysis elements based on their intended location by creating field boundaries according to the ITTC (International Towing Tank Convention) rules. The boundary distance used in the process can be observed in Figure 4. The convergence is achieved when the force value of the meshing results reaches a size of 0.00625, as shown in Figure 5.

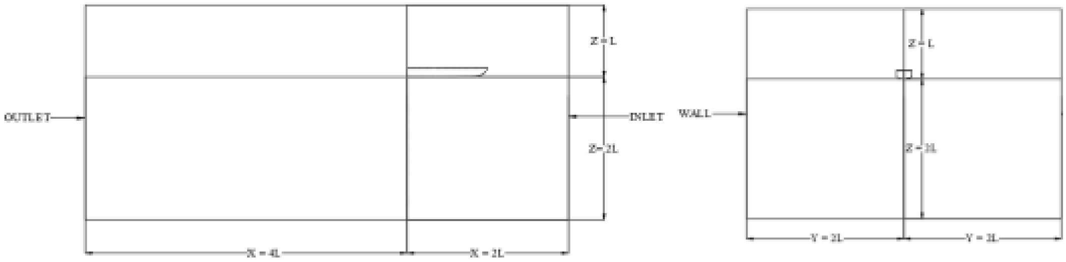

Fig. 4. Boundary condition based on hull length

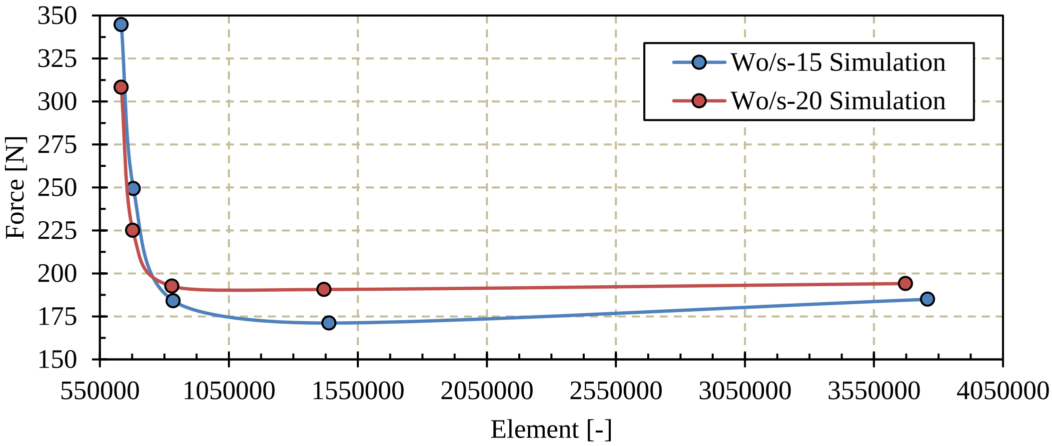

Fig. 5. The Convergence graph

In this study, secondary data validation was performed by referring to the journals [8] and [15]. Validation was carried out by comparing the results of total resistance values obtained from the Wo/s-15 and Wo/s-20 hull models under similar conditions using the CFD method, with the Wo/s-15-7 and Wo/s-20-7 hull models [8] using the experimental towing tank method. The simulated and experimental data were analyzed using the mean deviation equation, which calculates the average distance between data values and the average. The mean deviation or average deviation is used to determine the difference in data values that deviate from the average. To quantitatively determine the deviation between the simulated and experimental data, the mean deviation is calculated using the following equation:

$$MD = \frac{1}{N}\sum_{1}^{N}\left|(dpre - dexp).\frac{100}{dexp}\right| \quad \text{.....} \quad (5)$$

Where MD is the mean deviation [-], N is the sum of data [-], d predictions is the simulated data values, d experiments is the experimental data values.

III. Results and Discussions

Figure 6 displays the hull resistance measurements obtained from Wo/s-15 and Wo/s-20 setups. The findings revealed that the resistance value exceeded that predicted by the Wo/s-15 model. Notably, the two models exhibited an average deviation of 5.9% and 4.9%, respectively, suggesting a high degree of similarity between the CFD and experimental data.

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Therefore, the CFD simulations seem to have accurately predicted the hull resistance of the ship.

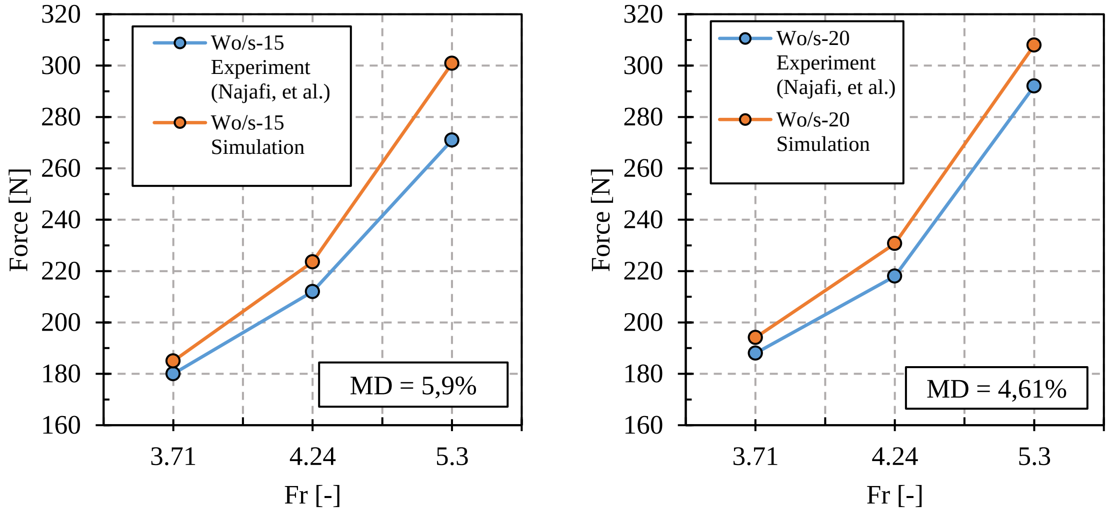

Fig. 6. Mean deviation of experimental and simulation data: (a) Wo/s-15 set up, and (b) Wo/s-20 set up.

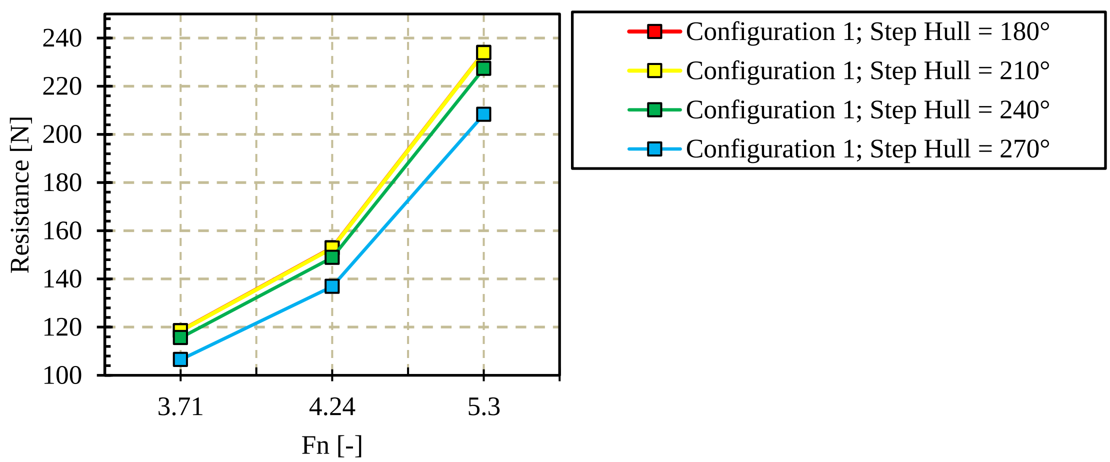

Fig. 7. Resistance vs. Froude number of Configuration 1

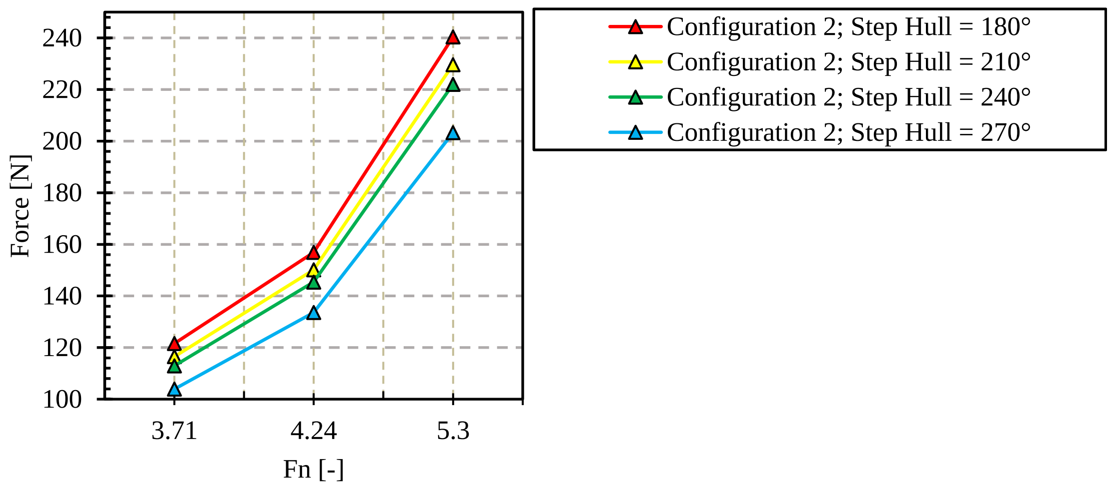

Fig. 8. Resistance vs. Froude number of Configuration 2

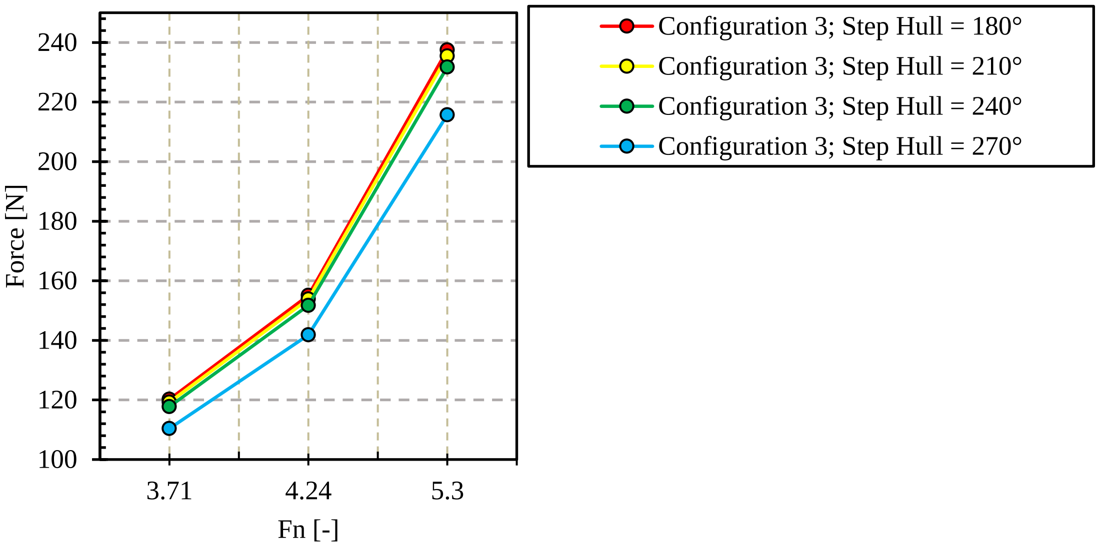

Fig. 9. Resistance vs. Froude number of Configuration 3

Figure 7, 8, and 9 clearly illustrate that as the Froude number increases, the resulting resistance also increases. Undoubtedly, the potential flow theory provides reasonably precise estimations for practical applications across a wide range of Froude numbers. These estimations encompass the wave drag, hydrodynamic lift, pitch moment, sinkage, trim, and wave profile along a ship's hull [16-25]. This correlation was confirmed by Figure 7, 8, and 9, as none of them displayed a higher Froude number while experiencing decreased resistance. The color variation in the images indicates the differences in the step hull angle of the hull of the ship model. Figure 7, 8, and 9 serve as evidence that as the Froude number increases, the step hull angle increases, leading to a decrease in resistance. In Figure 7, configuration 1 with a step hull angle of 180° is represented by a red square-shaped symbol, indicating that it exhibits the same resistance as configuration 1 with a 210° step hull angle. This suggests that altering the hull step angle from 180° to 210° does not affect the resistance. Therefore, this finding can serve as a reference for avoiding design variations in the step hull angle between 180° and 210°.

In this study, there were a total of 12 variations divided into three configurations. Configurations 1 and 2 share similarities in terms of the rear hull length (600 mm), hull height (20 mm for configuration 1 and 30 mm for configuration 2), and deadrise angle (15° for configuration 1 and 20° for configuration 2). Configuration 3, on the other hand, shares similarities with the rear hull length of 800 mm, hull height of 20 mm, and deadrise angle of 15°. The variable difference between the three configurations lies in the step hull angle, with each configuration featuring four different step hull angles starting at 180°, 210°, 240°, and 270°. The Froude number, which represents the effect of waves on the ship model, influences the increase in the resistance. A higher Froude number indicated a more intense wave impact. As the waves become more forceful, the ship model experiences greater resistance, which impedes forward movement. Among several environmental factors, the impact of waves on a ship is a significant cause of reduced speed and operational efficiency, posing a major challenge [26].

The resistance of a ship in configuration 1, with hull step angles of 180 and 210, yields similar data, as depicted in Figure 7. Consequently, the resistance data for configuration 1, with step hull angles of 180 and 210, exhibits overlapping results. This occurrence can be attributed to the significant influence of the deadrise angle and step hull height. For instance, when the deadrise angle is set at 15 and the step hull height is 20, similar resistance values are observed, despite the variation in step hull angle within the range of 180 to 210 and the step hull length falling between 600 and 800 mm. As a comparison to a different step hull, Najafi reported that the deadrise angle and longitudinal distance of the step from the transom have a significant impact on the total resistance of planing hulls [8]. Increasing the deadrise angle increases resistance, while reducing the longitudinal distance of the step from the transom decreases resistance. Stepped hulls have lower resistance compared to without step hulls due to the difference in bottom wetted area.

In contrast to the trend data from Figure 7, the trend data from Figure 8 displays all the lines, revealing distinct variations for each hull step. The trend data from Figure 9 is somewhat similar to Figure 7. However, the spacing between the trend data is wider, creating a more-clear arrangement. Through Figure 7, 8, and 9, it becomes apparent that the configuration with the highest resistance value corresponds to the variation from configuration 2 with a hull step of 180°, while the variation from configuration 2 with a hull step of 270° exhibits the lowest resistance. It was discovered that a larger deadrise angle and a step hull height of 20 and 30 mm, respectively, resulted in the highest and lowest resistance data across all step hull variations. Consequently, the deadrise angle and step hull height emerge as the dominant factors that require careful consideration in the design of ships utilizing a step hull. For this reason, the total resistance, trim angle, reattachment lengths, and forebody and aftbody wetted areas are measured at various deadrise angles, longitudinal distances of the step from the transom, and hull speeds [8].

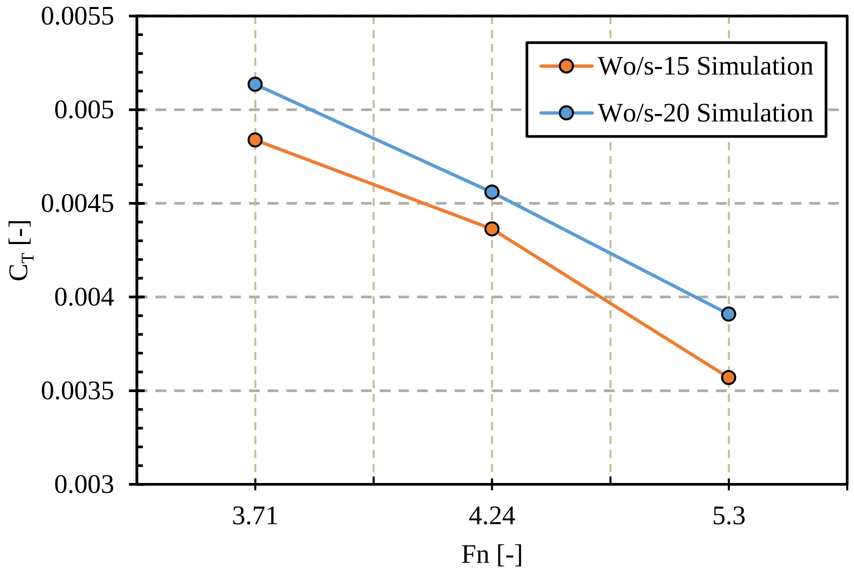

Fig. 10. Coefficient of total resistance (CT) vs. Froude number of Wo/s

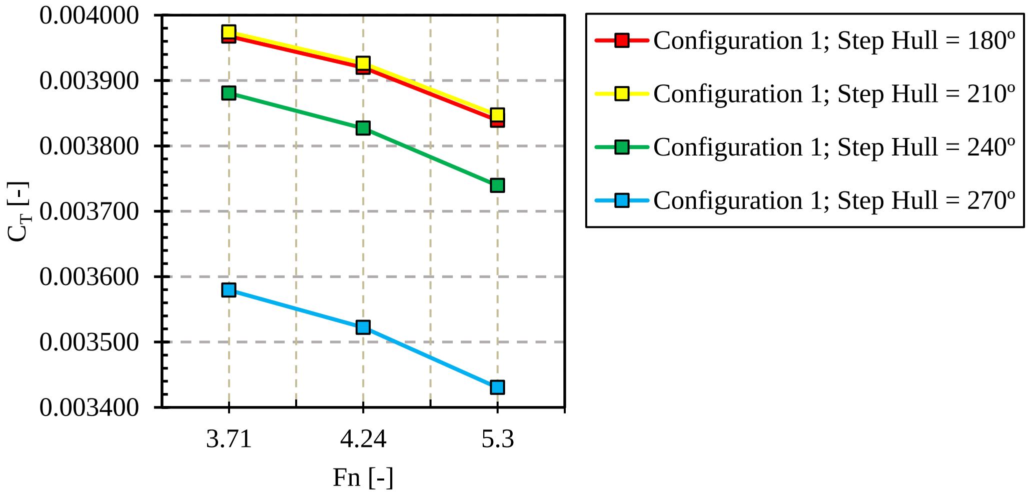

Fig. 11. Coefficient of total resistance (CT) vs. Froude number of configuration 1

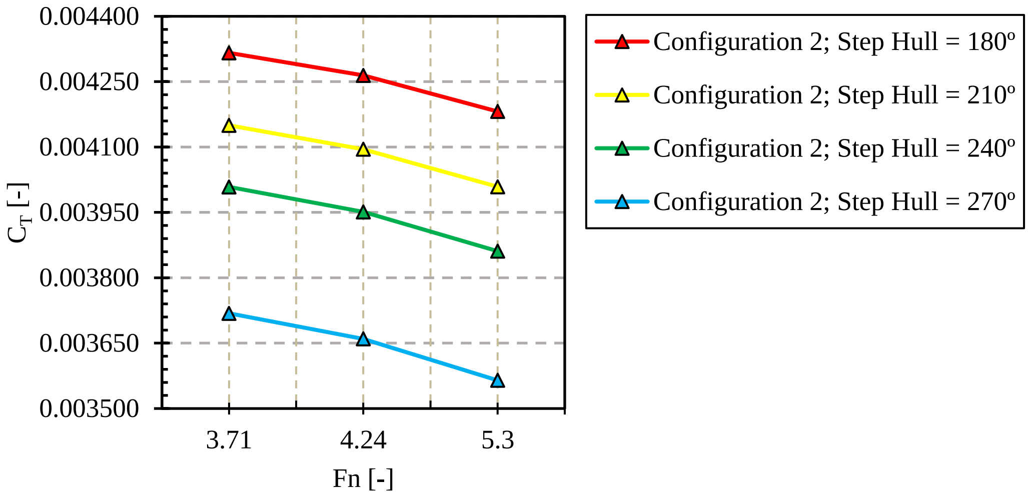

Fig. 12. Coefficient of total resistance (CT) vs. Froude number of Configuration 2

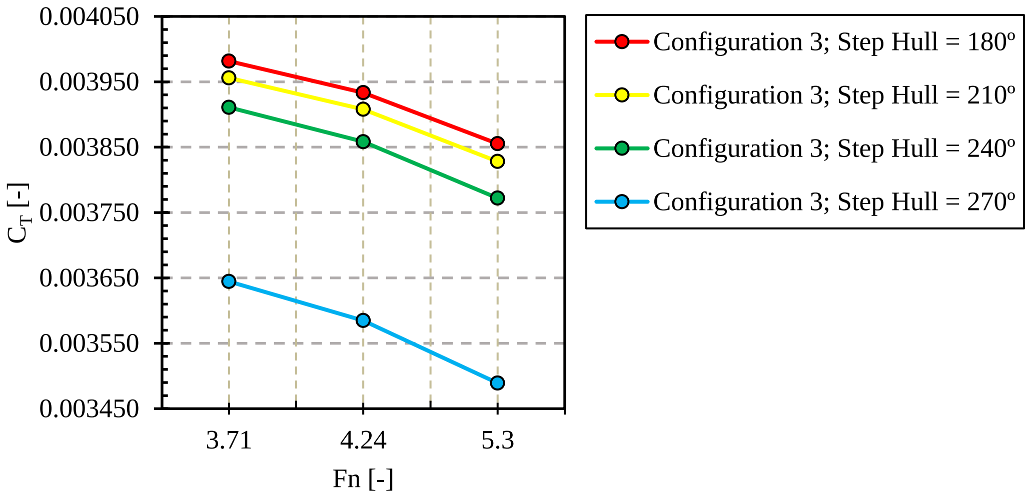

Fig. 13. Coefficient of total resistance (CT) vs. Froude number of configuration 3

Based on Figures 10-13, it can be deduced that the coefficient of total resistance decreases as the Froude number increases. These findings align with a previous study that compared the resistance of a planing hull without a step hull to one with a step hull, confirming that an increase in the Froude number leads to a reduction in the coefficient of total resistance [27].

Figures 11-13 also indicate that larger step angles result in lower coefficients of total resistance. However, in configuration 1, a step angle of 180° demonstrates a lower total resistance coefficient than a step angle 210°. The variations in the CT curve's rise and fall can be attributed to wave system interference, highlighting the significance of a well-designed hull that enables optimal operation at desired speeds [28].

Analyzing Figures 11-13 shows that the configuration exhibiting the highest coefficient of total resistance value corresponds to the variation from configuration 2 with a hull step of 180°. In contrast, the variation from configuration 2 with a hull step of 270° displays the lowest coefficient of total resistance. A greater step hull height of 30 mm generates the highest and lowest resistance data among all step hull variations, according to the research. As a direct consequence of this, the height of the step hull is the primary factor that determines the total resistance coefficient. Previous studies have demonstrated a general increase in the total hull resistance coefficient with decreasing water depths [29].

IV. Conclusions

The highlight of this research is to study the resistance and total resistance coefficient of fast boats with variations in deadrise angle, angle, height, and step hull length. It can be concluded that as the Froude number increases, the coefficient of total resistance decreases. Conversely, as the Froude number increases, the resulting resistance also increases. It can be inferred that the configuration with the greatest resistance value corresponds to the alteration from configuration 2 with a hull step of 180°, whereas the alteration from configuration 2 with a hull step of 270° demonstrates the lowest resistance. As a result, the angles of deadrise and the height of the step hull are the primary factors that demand meticulous attention when designing ships that employ a step hull.

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