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Effect of the Addition of Hydrofoil on Lift Force and Resistance in 60 M High-Speed Vessel

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Abstract

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The development of sea transportation technology is needed to meet the demand for ships that can carry heavier loads and operate at high speeds. Modifications in the form of additional hydrofoil variations were conducted to produce higher lift and reduce the resistance generated by the ship so that the ship can go more efficiently at high speed. This study aims to obtain the effect of adding hydrofoil to ships with variations in the type and shape of foil and find out which types and shapes can reduce resistance on the ship. This research was conducted with several model analysis tests using Computational Fluid Dynamic (CFD) based software, namely Tdyn, at several different speeds. The results of this study show that of the six variation models analyzed, rectangular fully submerged foil models can reduce the total resistance value of the ship by 17.822% from the original ship on Froude Number (Fr) 0.670. The type and shape of the foil is very influential on the lift and resistance produced by the ship.

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1. Introduction

Sea transportation is a mode that is important in the movement of goods and people, especially in the river, lake, and islands. Sea transportation has a better cost efficiency than air transportation and could reach a remote area. Sea transportation has a weakness, which usually has a longer travel time than other modes of transportation. To overcome these weaknesses, researchers have developed high-speed craft. Innovations in the development of high-speed craft are needed to overcome the requirement of efficient and reliable transportation.

High-speed craft is a unique vessel that can run at high speed. These vessels have an excellent dynamic performance to achieve high speeds. There are several types of high-speed craft, such as planing craft and hydrofoil craft, which are related to this study. A planing or semi-planing craft is a watercraft that uses hydrodynamic pressure distribution on its hull during a high-speed forward movement that supports most of its weight and lift a large portion of the hull out of the water [1]. Planing craft is the most common type of high-speed craft due to the more simple design. In calm water, this type of vessel can travel smoothly but have a poor seakeeping performance and could potentially lose significant speed due to pounding and slamming in waves [2].

A hydrofoil is a particular vessel that has foils under its hull. The foil on the vessel is intended so that when the vessel is moving at high speed, the hull of the ship can be lifted upward, thereby reducing some section of the hull immersed in water. The reduction of WSA (Wetted Surface Area) of the vessel can reduce resistances that occur on the vessel [3].

Currently, researches and developments on the application of hydrofoil on ships have been much advanced, although it's not as popular as its golden age back in the 60s. The development of the hydrofoil had been quite slow in recent decades, there have been no significant innovations on hydrofoils, and the commercial usage of hydrofoil was still limited, especially in Indonesia. It is quite unfortunate, consider hydrofoils could produce 50% less resistance than that of a conventional vessel of the same weight and could have inherent stability that generates a high level of comfort [4].

The addition of hydrofoil on short-distance commercial ferries can reduce travel time by up to 33% [5]. The addition of a single hydrofoil to a gliding hydrofoil craft also improves the seakeeping performance, decreases the resistance at high speed, and give a more constant speed compared to a planing hull craft [2].

A numerical computation study on the effect of the position of the placement of hydrofoil on ship resistance in towing tanks found that positioning the main foil closer to the LCG generates smaller resistances [6]. The shape and angle of attack

of hydrofoil also affect the lift-drag coefficient and the form factor [7]. However, the high demand for ships that can carry heavier loads and can operate at high speeds encourages the development of hydrofoil vessels that have larger load capacities at high speeds and have better seakeeping performance [8].

Computational Fluid Dynamics is one of the analytic systems that involve fluid flows, heat transfer, and other phenomena using computer-based simulation [9]. Numerical methods based on CFD have deemed a better option as experimental tests in the towing tank are financially much more expensive [10]. A numerical based CFD simulation shows that CFD simulation could predict the force experienced on a hydrofoil with a consistent 10-15% variance from the experimental data [11]. The project by Besana also proved the feasibility of utilizing CFD for an approach to hydrodynamics analysis of hydrofoil [12].

Based on the literature review, it can be concluded that some researchers have done some researches on the application of hydrofoil. But research on hydrofoil still needs to be conducted to improve its hydrodynamics performances. In this research, the application of foil on the 60-meter ship will be applied to be used as a hydrofoil ferry and analyzed using a numerical based CFD method. The 60-meter ship was chosen because of its larger size than the hydrofoil vessels in general, so it can carry more loads. However, due to its larger size, the ship becomes heavier and requires a greater lifting force.

The main objective of this study is to determine the effect of hydrofoil types and shapes on the lift and resistance of ships and to obtain the best configuration and shape of the hydrofoil, which has the greatest lifting force and the smallest resistance. In this research, hydrofoil will be applied using fully submerged foil and surface piercing foil types in the form of rectangular, tapered, and swept foil. Each model will be varied with the ship's speed and analyzed using the CFD (Computational Fluid Dynamic) method to get the most optimal lift to drag ratio.

2. Methods

2.1. Research Object

The object of this study is the modification of a 60 m high-speed vessel model with additional hydrofoils. The 60 m high-speed vessel model is a remodeled test subject of Indonesia Hydrodynamic Laboratory. The type of hydrofoil used is the type of fully submerged foil and surface piercing foil with rectangular, tapered, and swept shapes. The main dimension of the model used in this study is shown in Table 1. Ship models and hydrofoil variations used in this study were designed using 3D software. The model of the ship is shown in Figure 1.

Table 1. Main Dimension of Model

Dimension	Value
Length Over All	3.986 m
Length of Waterline	3.600 m
Length of Perpendicular	3.563 m
Breadth	0.532 m
Draft	0.172 m
Depth	0.333 m
Displacement	0.131 ton
Wetted Surface Area	1.452 m ²

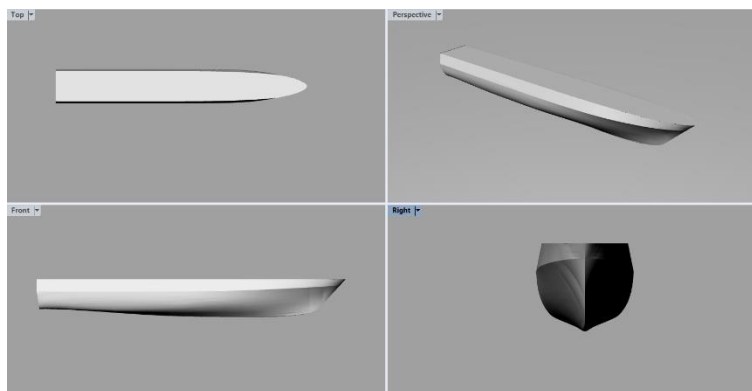


Figure 1. Ship 3D Model

2.2. Foil Type and Dimension

The foil used in this study is based on foil developed by NACA. Tests by NACA are very systematic with dividing the effect of curvature and thickness distribution and are carried out at higher Reynold numbers [13]. The design and testing of NACA foils that have been carried out in the past 80 years have provided valuable information to aerodynamics and hydrodynamic experts [14]. The foil used for the hydrofoil in this study is NACA 63(2)-615 series, shown in Figure 2, with a max thickness of 15% at 34.8% chord and max chamber 3.3% at 50% chord. The dimension of the foil used in this study is shown in Table 2. The foil used for the strut in this study is NACA 642-015 series, shown in Figure 3, with max thickness 15% at 35% chord and max chamber 0% at 0% chord. The dimension of the strut used in this study is shown in Table 3. The original model of the ship (Figure 1), was modified by adding variations of foil, shown in Figure 4.

Table 2. Foil Dimension

Dimension	Value
Main Chord	0.4 m – 0.5 m
Span	0.6 m
Angle of Attack	5°
Area	0.24 m (fully submerged)

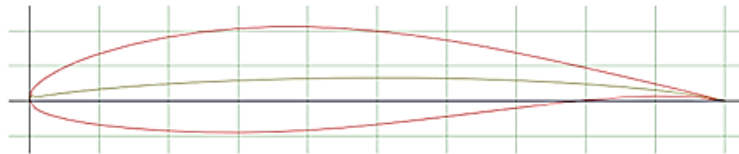


Figure 2. Foil NACA 63(2) – 615

Table 3. Strut Dimension

Dimension	Value
Main Chord	0.24 m
Fore Strut Length	0.21 m
Aft Strut Length	0.27 m

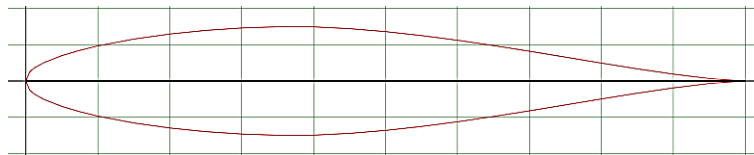


Figure 3. Foil NACA 64 – 015

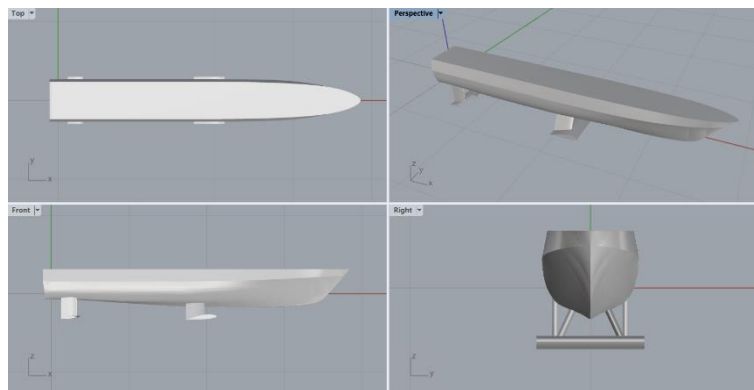


Figure 4. Model with Hydrofoil

2.3. Foil Types and Dimensions

In this study, a modification was carried out by adding a hydrofoil with two types of foil, namely fully submerged and surface piercing with varying shapes for each foil. The foils of each variation are shown in Figure 5a - 5f.

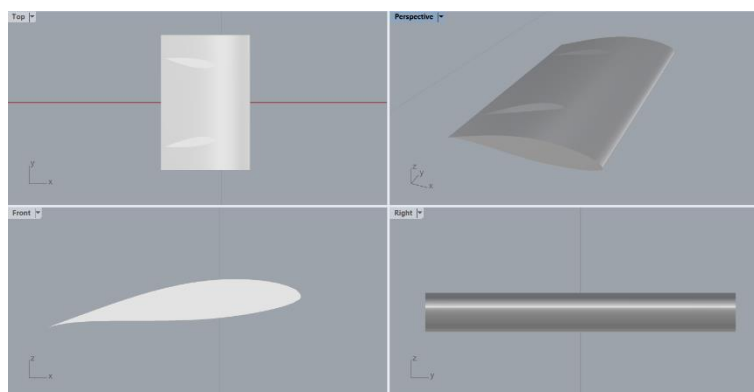


Figure 5a. Rectangular Fully Submerged Hydrofoil

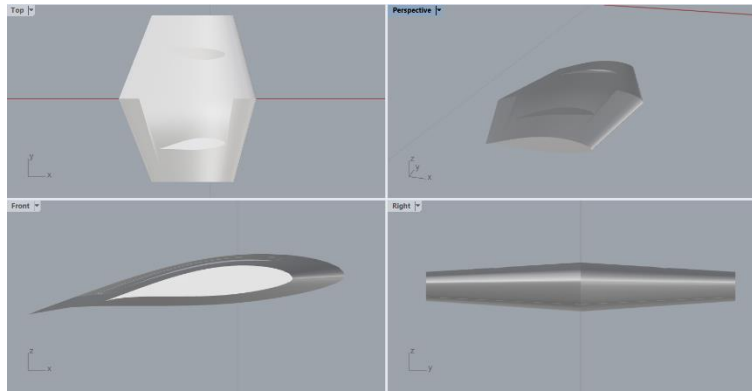


Figure 5b. Tapered Fully Submerged Hydrofoil

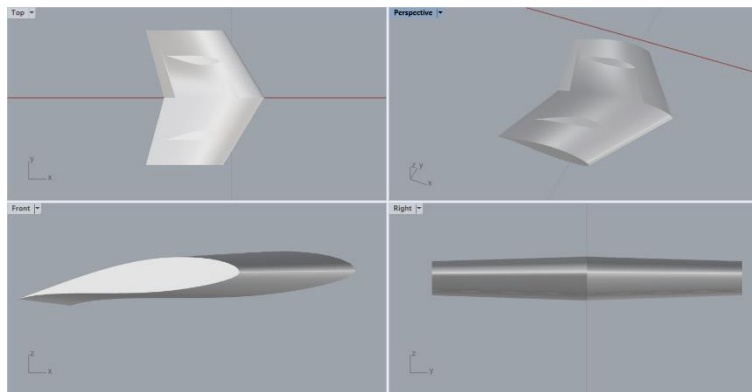


Figure 5c. Swept Fully Submerged Hydrofoil

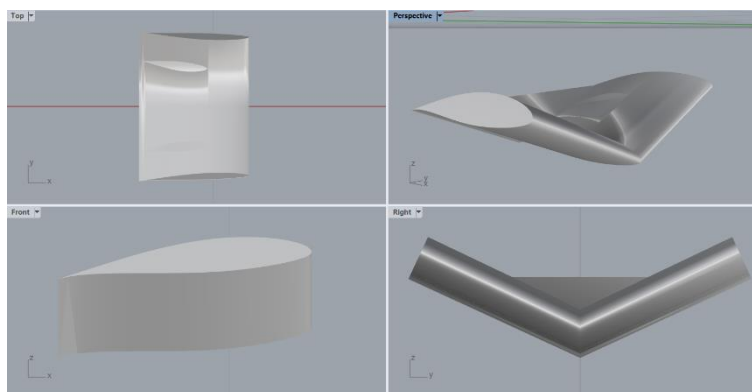


Figure 5d. Rectangular Surface Piercing Hydrofoil

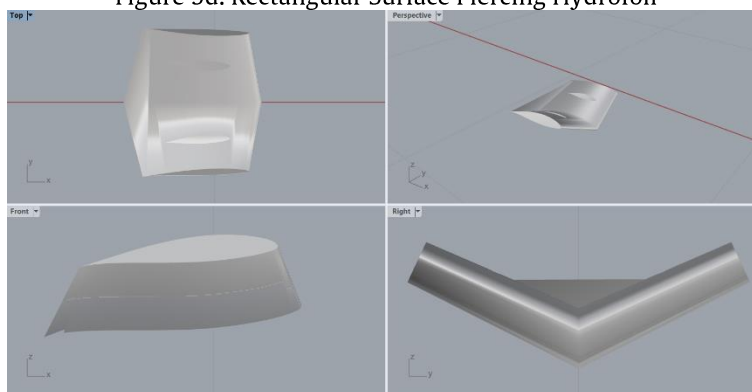


Figure 5e. Tapered Surface Piercing Hydrofoil

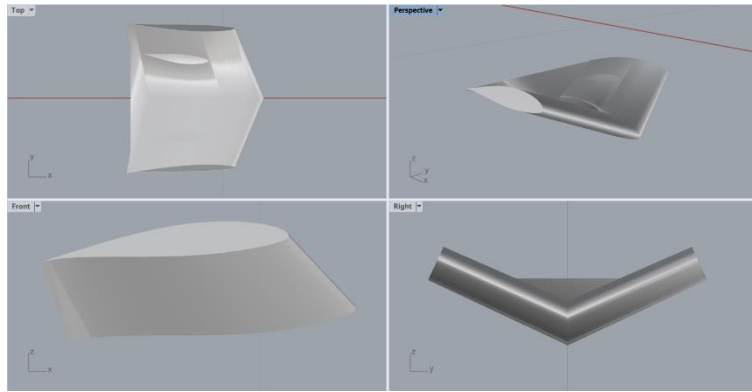


Figure 5f. Swept Surface Piercing Hydrofoil

2.4. Heave and Pitch Correction

The heave correction for hydrofoils use the following Equation 1, as described in [15].

$$\Delta z = \frac{Fz}{\rho g A_{wp}} \quad (1)$$

Where Δz for heave correction, Fz for lift force, ρ for density, g for gravity, and A_{wp} for Water Plane Area. The trim correction for hydrofoils use the following Equation 2, as described in [15].

$$\Delta \alpha = \frac{My}{\rho g I_y} \quad (2)$$

Where $\Delta \alpha$ for trim correction, My for the moment of trim, ρ for density, g for gravity dan I_y for y-axis moment of inertia (pitching). The moment of inertia pitching is calculated by the following Equation 3, as described in [16].

$$I_{yy} = \frac{1}{g} \sum [w_i (x_i^2 + z_i^2)] \quad (3)$$

Where g is the acceleration due to gravity, w_i is the weight of each fraction, x_i is the horizontal distance from CG of each fraction to the ship's CG, and z_i is the vertical distance from CG of each fraction to the ship's CG. In this study, the lift force and resistance are analyzed at three different speeds, shown in Table 4, from 10 to 30 knots or from Froude number 0.223 to 0.67.

Fr	V(m/s)	V(knot)
0.223	5.144	10
0.447	10.288	20
0.670	15.433	30

3. Results and Discussion

3.1. Lift Forces and Trim Moments

There were two stages of running CFD software to get the value of lift and resistance in this study. The first stage is to get the value of lift and trim produced by each hydrofoil, and the second stage is to process the ship models that have been lifted according to their new equilibrium at the designated speed. This process aims to get the value of the ship's resistance after the ship lifted due to hydrofoils.

Table 5 and Table 6 show the lift forces and trim moments in several models. Based on Table 5, the highest lift value produced by hydrofoils occur at the froude number 0.670 for all models. The highest lift force is 1,391 N in models with rectangular fully submerged foil types. As for the smallest lift value was the model with swept fully submerged foil type at froude number 0.223 with a value of 998.33 N.

In the term of trim moments, Tapered model has the highest value at Fr 0.67 on Fully Submerged Foil, while Rectangular model reaches the highest value at Fr 0.67 on Surface Piercing Foil. The type and shape of hydrofoil have an impact on the lift forces and trim moments produced by hydrofoil.

By using Equation 1 and Equation 2, the lift forces and trim moments are processed to get the heave and trim values of each model based on the Froude number, as shown in Table 7 and Table 8. Heave and trim were used to obtain the equilibrium condition of the ship at a certain speed. The new WSA of the ship at equilibrium condition, as shown in Table 9, was obtained based on the heave and trim values. The equilibrium condition of each variation is shown in Figure 6 – Figure 12.

Table 5. Lift Forces (N)

Fr	Fully Submerged Foil			Surface Piercing Foil		
	Rectangular	Tapered	Swept	Rectangular	Tapered	Swept
0.223	1,058.80	1,003.80	998.33	1,056.90	1,056.70	1,052.50
0.447	1,227.00	1,191.00	1,150.30	1,166.20	1,182.90	1,213.30
0.670	1,391.00	1,350.70	1,378.90	1,315.10	1,315.90	1,326.40

Table 6. Trim Moments (Nm)

Fr	Fully Submerged Foil			Surface Piercing Foil		
	Rectangular	Tapered	Swept	Rectangular	Tapered	Swept
0.223	1,570.20	1,550.50	1536.1	1,649.90	1,650.00	1,625.90
0.447	1,970.00	1,910.50	1,855.40	1,994.70	1,925.00	2,015.70
0.670	2,250.00	2,327.40	1,973.30	2,358.00	1,984.30	2,067.10

Table 7. Heave (m)

Fr	Fully Submerged Foil			Surface Piercing Foil		
	Rectangular	Tapered	Swept	Rectangular	Tapered	Swept
0.223	0.061	0.048	0.063	0.060	0.050	0.055
0.447	0.069	0.056	0.069	0.065	0.056	0.063
0.670	0.199	0.187	0.203	0.195	0.185	0.191

Table 8. Trim (°)

Fr	Fully Submerged Foil			Surface Piercing Foil		
	Rectangular	Tapered	Swept	Rectangular	Tapered	Swept
0.223	0.820	0.810	0.802	0.862	0.862	0.849
0.447	1.029	0.998	0.969	1.042	1.006	1.053
0.670	1.175	1.216	1.031	1.232	1.037	1.080

Table 9. Wetted Surface Area (m²)

Fr	Fully Submerged Foil			Surface Piercing Foil		
	Rectangular	Tapered	Swept	Rectangular	Tapered	Swept
0.223	2.457	2.566	2.432	2.432	2.481	2.430
0.447	2.373	2.480	2.365	2.310	2.423	2.354
0.670	0.982	0.927	0.956	0.708	0.794	0.773

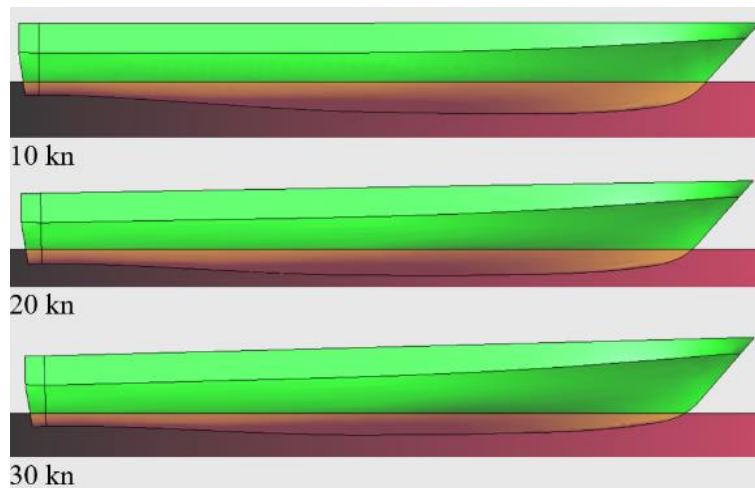


Figure 6. CFD Simulation Condition on Original Model

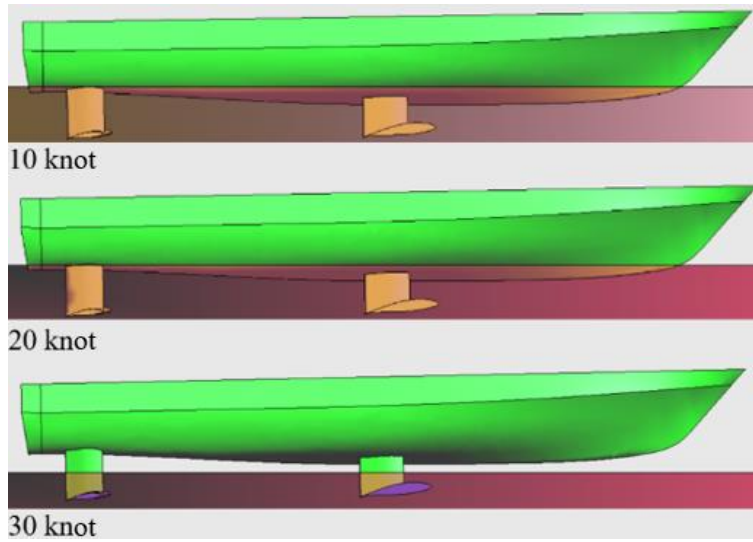


Figure 7. CFD Simulation Condition on Rectangular Fully Submerged Foil Model

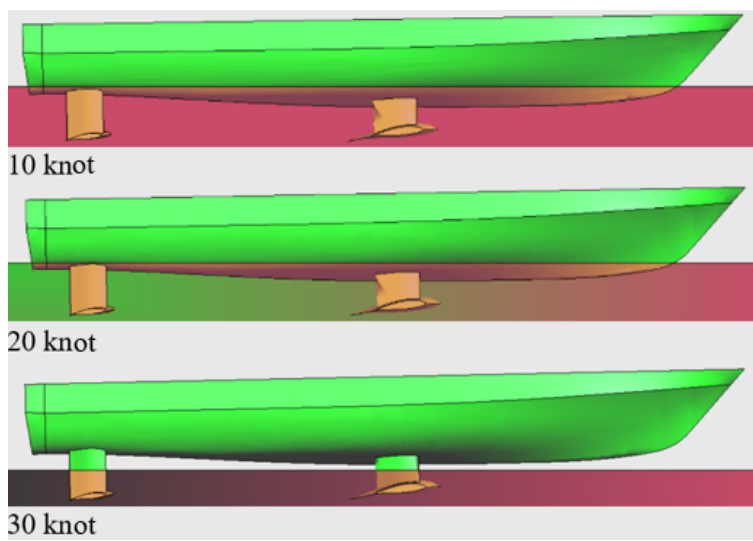


Figure 8. CFD Simulation Condition on Tapered Fully Submerged Foil Model

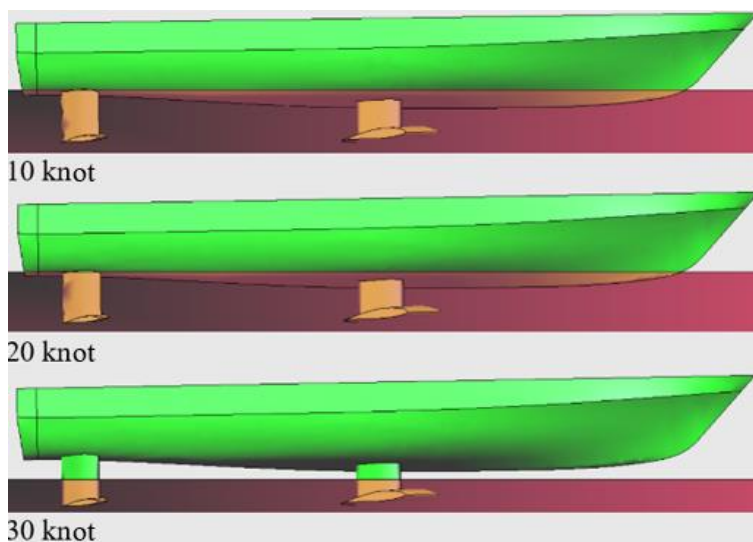


Figure 9. CFD Simulation Condition on Swept Fully Submerged Foil Model

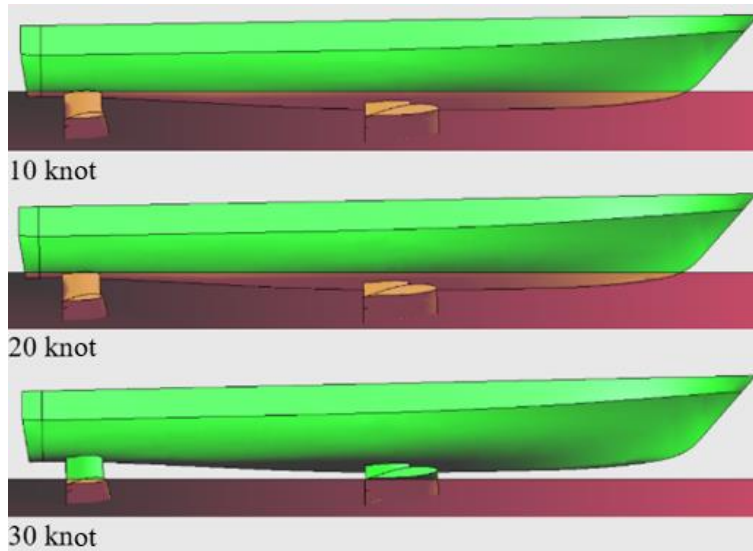


Figure 10. CFD Simulation Condition on Rectangular Surface Piercing Foil Model

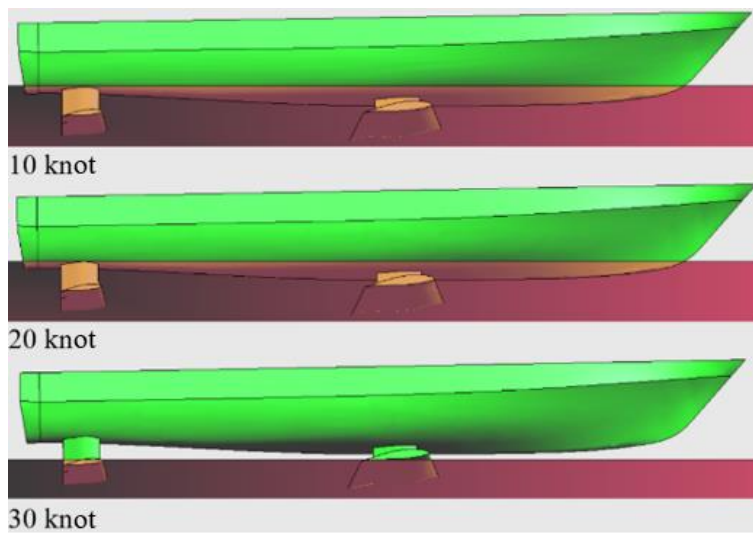


Figure 11. CFD Simulation Condition on Tapered Surface Piercing Foil Model

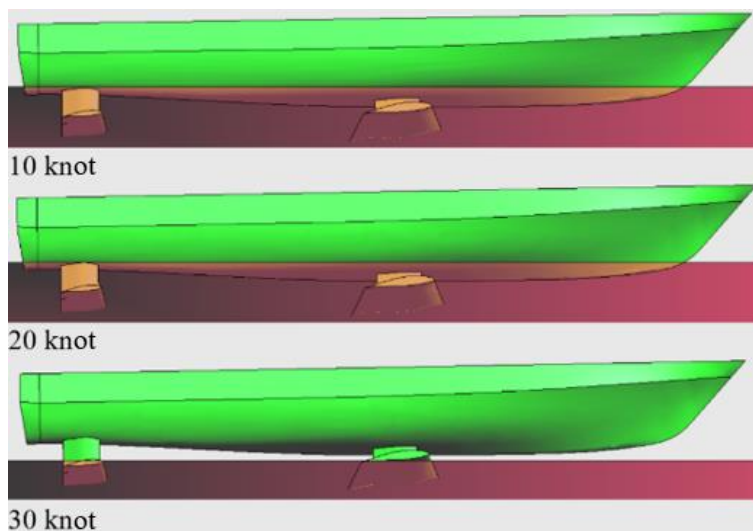


Figure 12. CFD Simulation Condition on Swept Surface Piercing Foil Model

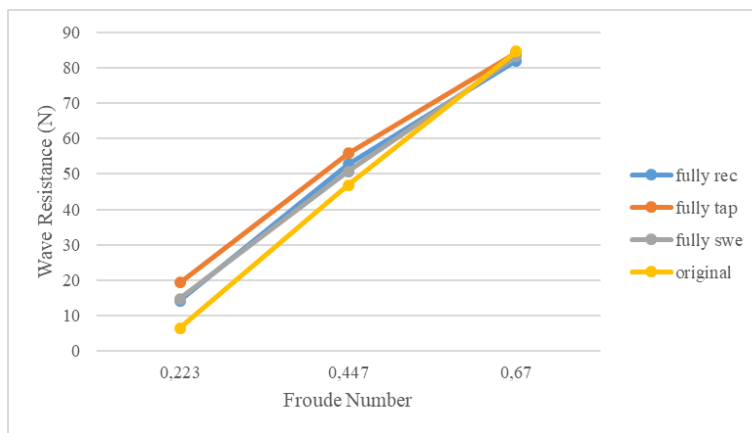
3.2. Wave Resistance

Based on Table 10 and Figure 13, the value of hydrofoil model wave resistance at low-speed froude numbers 0.223 and 0.447 is higher than the original model resistance because at low speed, not all the hulls are lifted so that the resulting wave effect comes from the hull and hydrofoil. But at froude number 0.67, the fully submerged type hydrofoil has a lower resistance than the original model.

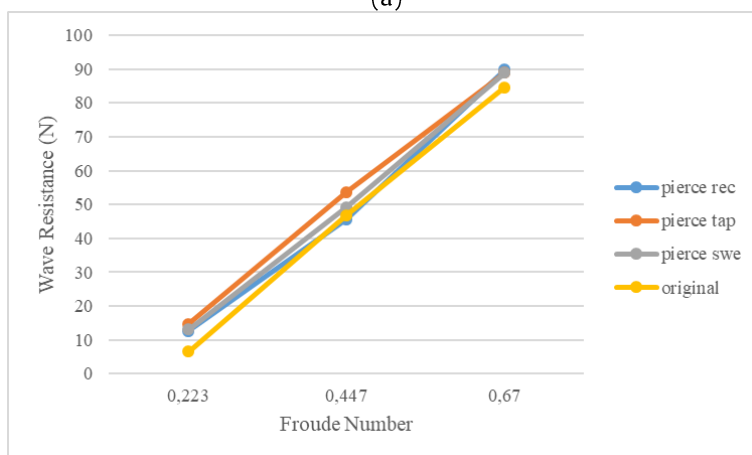
On the other hand, the wave resistance in the fully submerged foil type is lower than the surface piercing foil type. This can occur because, in the fully submerged type, the distance between the foil and the surface of the water is not as close as the surface piercing type. According to research from Silverleaf and Cook in 1970 [17], and Schultz in 1971 [18], this situation resulted in smaller waves and can also reduce seasickness and discomfort to passengers.

Table 10. Wave Resistance (N)

Fr	Original	Fully Submerged Foil			Surface Piercing Foil		
		Rectangular	Tapered	Swept	Rectangular	Tapered	Swept
0.223	6.47	14.160	19.390	12.660	12.660	14.760	13.060
0.447	46.62	52.780	55.800	50.670	45.710	53.650	49.240
0.670	84.66	81.900	84.220	83.230	89.880	88.960	88.900



(a)



(b)

Figure 13. Wave Resistance on Fully Submerged Foil Models (a) and Surface Piercing Foil Models (b)

3.3. Viscous Resistance

At Fr 0.223 to 0.447, the Viscous resistance of all hydrofoil models is greater than the original one, as shown in Table 11 and Figure 14. However, in Fr 0.67, all hydrofoil configurations experienced a significant decrease in viscous resistance so that the value was smaller than the original model.

The viscous resistance of hydrofoil models decreases as the speed increased. Based on Table 9, the higher the model's speed, the greater the lift produced by hydrofoil so that the wetted surface area of the ship will be smaller and the friction between the fluid and the ship's portion will be smaller as well. The smallest value of viscous resistance occurs in a model that has the most significant lift force with a surface piercing foil type at Fr 0.67.

Table 11. Viscous Resistance (N)

Fr	Original	Fully Submerged Foil			Surface Piercing Foil		
		Rectangular	Tapered	Swept	Rectangular	Tapered	Swept
0.223	2.86	3.400	3.570	3.110	3.360	3.480	3.160
0.447	10.21	10.810	11.520	10.850	10.980	13.340	10.750
0.670	23.90	7.310	6.740	6.760	3.490	4.860	4.230

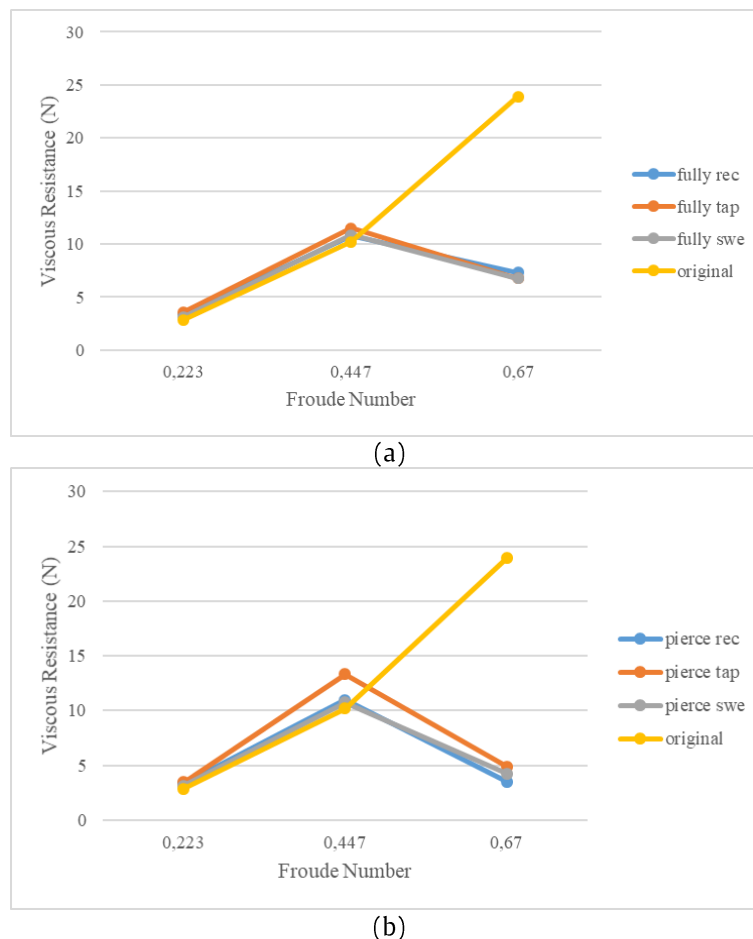


Figure 14. Viscous Resistance on Fully Submerged Foil (a) and Surface Piercing Foil (b)

3.4. Total Resistance

The total resistance is the sum of wave and viscous resistances. In Table 12 and Figure 15, the hydrofoil model's total resistance is smaller than the original at Fr 0.670. This condition occurs because hydrofoil vessels have a greater lift force. The lift force produced by the hydrofoil causes the ship's WSA reduced so that the friction between the hull and water was reduced as well.

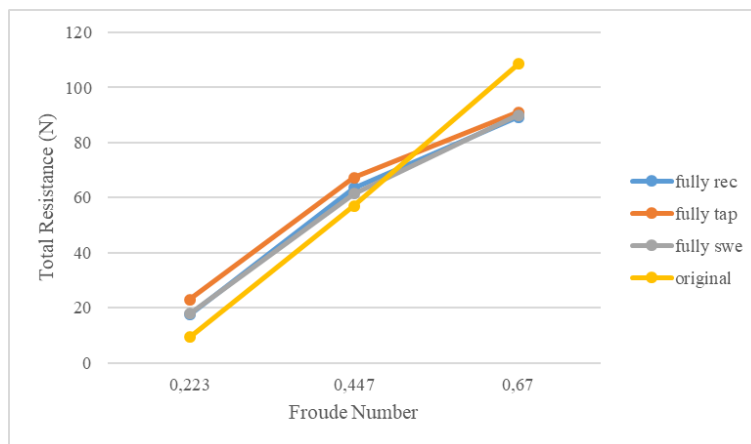
Models that experienced a significant total resistance decrease occurred in the hydrofoil models with a fully submerged foil configuration. The decrease in the three hydrofoil models' total resistance is more than 16% of the total resistance of the original model at Fr 0.670. In contrast, the surface piercing configuration experienced a smaller decrease in the total resistance value of 13% of the original ship's total resistance.

Based on Table 12 and Figure 15, the total resistance, which has additional hydrofoil, always decreased. These results show that the addition of hydrofoil can reduce the value of resistance on a ship. The foil works more effectively at high speeds. Both total resistances of surface piercing foil at Fr 0.223 and 0.447 are lower than that of fully submerged foil. However, at Fr 0.67, there is a decreased performance on the surface piercing foil so that the total resistance is higher than the fully submerged foil. Based on AJ Acosta's research, the surface piercing foil has a faster L/D ratio decrease than the fully submerged foil, which has a slighter L/D ratio decrease [19].

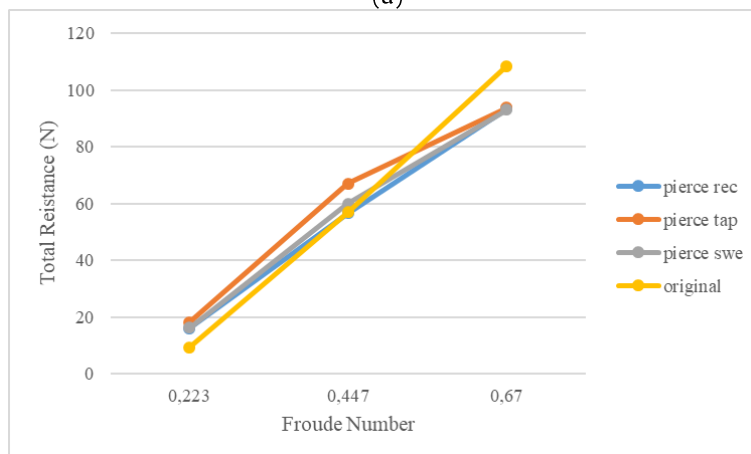
The addition of hydrofoil had different effects on ship resistance, but most of it experienced a significant decrease in total resistance. Some researchers researched the effect of the position of supporting hydrofoil on ship resistance using towing tanks. The results showed that ship resistance with a fully submerged rectangular hydrofoil increased by 5.21% to 45.05% than the original ship resistance [6]. Other studies on the effect of foil position on lift and resistance carried showed that ship resistance with a rectangular fully submerged hydrofoil decreased by 19.14% to 37.56% than the original ship resistance [20]. Research on the change in the angle of swept fully submerged foil to lift and resistance indicated that the fully submerged swept hydrofoil could reduce drag by up to 50.8% from the original [21]. Other research about lift and resistance on dihedral surface-piercing hydrofoil showed that rectangular surface-piercing hydrofoil could reduce drag by 25% to 60% from the original [22].

Table 12. Total Resistance (N)

Fr	Original	Fully Submerged Foil			Surface Piercing Foil		
		Rectangular	Tapered	Swept	Rectangular	Tapered	Swept
0.223	9.33	17.560	22.950	17.900	16.020	18.240	16.220
0.447	57.03	63.590	67.320	61.520	56.690	66.990	59.990
0.670	108.56	89.210	90.960	89.990	93.370	93.820	93.130



(a)



(b)

Figure 15. Total Resistance on Fully Submerged Foil (a) and Surface Piercing Foil (b)

4. Conclusion

From the six models analyzed with CFD software, the most significant lift force was generated by rectangular fully submerged foil at Fr 0.670, which is 1391 N. While for the lowest lift, it is generated by the swept fully submerged foil model at Fr 0.223, which is 998.33 N. The lowest total resistance value is generated by fully submerged hydrofoil types with rectangular fully submerged, tapered fully submerged, and swept fully submerged types at Fr 0.670, which are 89.21 N, 89.99 N, and 90.96 N. The total resistances were reduced by more than 16% of the total resistance of the original ship.

The type and shape of hydrofoil affect the lift and resistance generated by hydrofoil. This study shows that the model that produced a large lift force and effectively reduced resistance value was the rectangular, fully submerged model. The type of hydrofoil variable has more effect on lift and resistance than the shape of the hydrofoil. Hydrofoil with fully submerged type results in a higher lift and lower resistance than surface piercing types.

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