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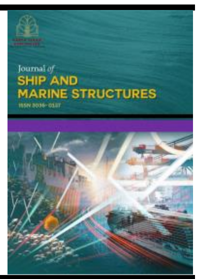

Experimental Study on the Effect of Hydrofoil Aspect Ratio on Fishing Boat Speed

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ABSTRACT

Fishing boats operate at specific velocities on the water's surface, where the water's density creates friction between the boat's hull and the water, resulting in resistance that hinders forward motion. This resistance leads to a decrease in boat velocity, making time usage inefficient. This research aims to investigate a device in the form of a hydrofoil that can enhance fishing boat velocity while reducing fuel consumption. The hydrofoil approach to increase the boat velocity is by decreasing the hull's wetted surface area, thereby reducing the frictional resistance with the water. Applying hydrofoils to generate lift on the hull has been shown to reduce boat resistance. This study was conducted in calm water, exploring the effect of varying hydrofoil aspect ratios on boat velocity. The results indicate that a hydrofoil with an aspect ratio of 9 produced a boat velocity of 10.5 knots, while an aspect ratio of 3.25 resulted in 9.9 knots. A higher hydrofoil aspect ratio reduces the pressure on the bottom surface and increases velocity on the top surface, leading to improved performance. Therefore, Hydrofoil 2, with a higher aspect ratio, outperformed Hydrofoil 1, which had a lower aspect ratio.

1. Introduction

As is widely known, fishing boats sail at specific speeds across the water's surface. The water's viscosity generates friction between the boat's hull and the water, resulting in a forward drag force, often referred to as the boat's resistance. Increased resistance reduces the boat’s speed, leading to inefficient time usage and higher fuel consumption during the voyage [1]. Ship resistance is the study of fluid reactions caused by a ship's movement through the fluid [2]. In naval hydrodynamics, resistance (also referred to as drag) is the magnitude of the fluid force acting on the ship in such a way that it opposes the ship's motion [3,4]. This resistance is equal to the component of force acting parallel to the axis of the ship's velocity [5].

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The high cost of fuel presents a significant challenge for fishermen. Technological solutions can be implemented without modifying the existing components of the boat or increasing operational costs [6]. This research explores a technological device, such as a hydrofoil installed below the ship's hull, that can enhance fishing boat speed, ultimately reducing fuel consumption.

Boat speed can be improved by reducing the hull's wetted surface area, thereby decreasing drag [7]. Hydrofoils to generate lift on the hull is one such approach that can effectively reduce resistance [8]. The speed of a ship is generally estimated by the shipyard based on experience in constructing similar vessels, supported by several other factors such as principal dimensions, draft, form coefficients, and engine power. When sailing at a certain speed, the ship encounters resistance that must be minimized to improve efficiency, including frictional resistance, wave resistance generated by the ship's movement, and hydrodynamic factors related to hull design. Therefore, to achieve optimal hydrodynamic characteristics, ship hull designs are classified into *displacement hulls* and *planing hulls* [9].

A hydrofoil installed beneath the ship's hull functions to generate dynamic lift, raising the hull above the water surface [10,11]. The primary reason for using a hydrofoil is that as the hull lifts out of the water, the ship's weight is supported by the hydrofoil, reducing the wetted surface area and thereby minimizing drag caused by friction between the submerged hull and the water. The hydrofoil enhances lift as speed increases. Once the hull is fully lifted to its maximum limit, the required lift force remains constant. A hydrofoil on a ship is weight-sensitive and must operate at relatively high speeds to generate the necessary dynamic lift to support the vessel's weight with an appropriately sized foil [8].

Therefore, this study will evaluate the optimization of hydrofoil specification with varying the hydrofoil aspect ratios to determine the optimal speed for fishing boats. The analysis of boat speed will be conducted using experimental research methods.

2. Research Methodology

This research was conducted at the Bili-Bili Dam, Gowa Regency, over approximately 6 months. The experimental method (field test) is used, which involves manipulating variables to observe the resulting changes. This study aims to establish cause-and-effect relationships and analyze the effects of variable changes.

2.1 Research Object

The research object was the fishing boat RV. SBL 01 with the following specifications: length of 7.93 m, breadth of 1.37 m, and height of 0.80 m. The boat utilizes a planing hull design and is made of fiberglass. The hydrofoils installed on the boat consist of two types: Hydrofoil 1 with an aspect ratio (AR) of 3.2 and Hydrofoil 2 with an AR of 9. Both hydrofoils are tested to determine which is more efficient. Hydrofoil 1 has a chord of 40 cm, a span of 130 cm, and a thickness of 5 cm, while Hydrofoil 2 has a chord of 20 cm, a span of 180 cm, and a thickness of 2 cm.

The boat used for testing is the RV. SBL 01, with the design and appearance shown in Figures 1,2 and 3.

Fig. 1. Side view of the testing boat

Fig. 2. Bow design of the boat

Fig. 3. Rudder and propulsion system design of the boat

The hydrofoil shape and profile used in the tests are also shown in Figures 4 and 5 for Hydrofoils 1 and 2, respectively.

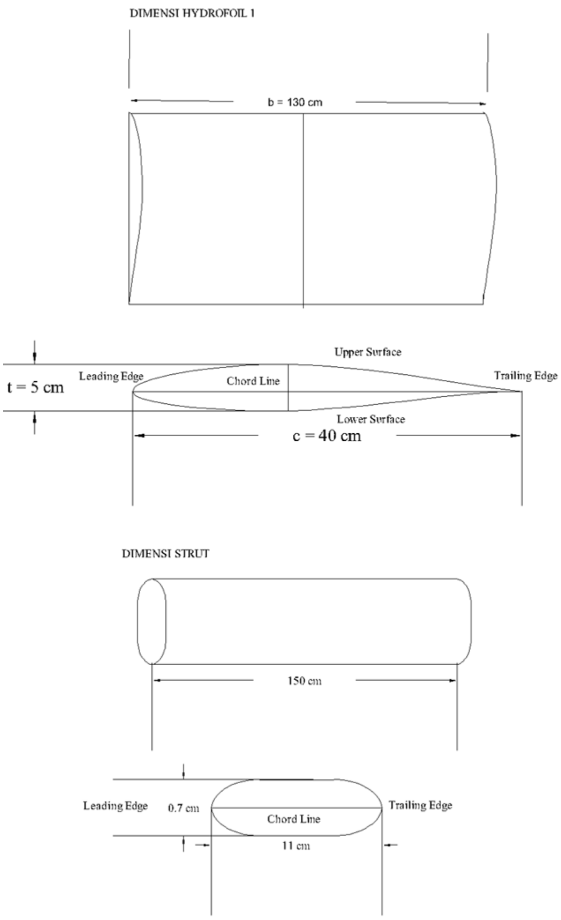

Fig. 4. Design and dimensions of Hydrofoil 1 and the strut

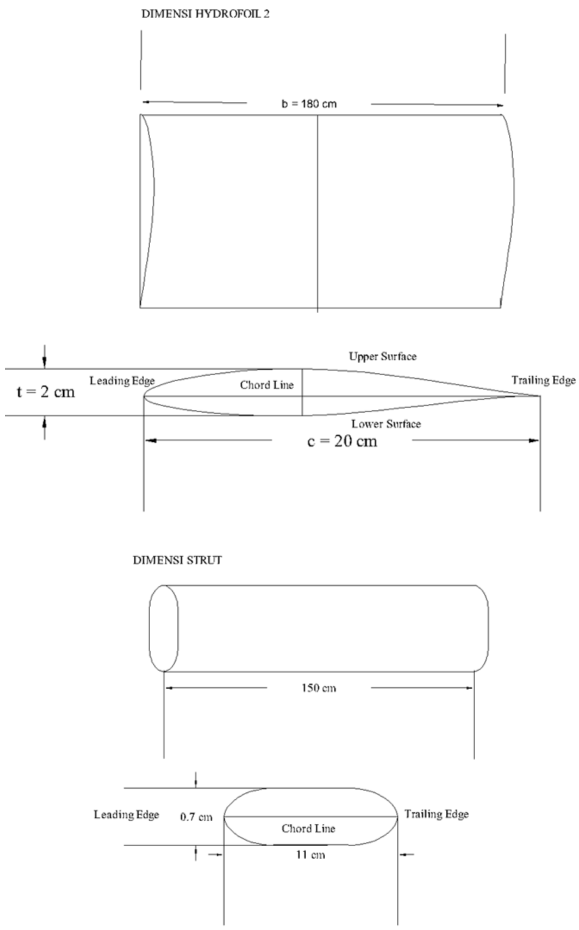

Fig. 5. Design and dimensions of Hydrofoil 2 and the strut

Figure 6 shows the manufactured hydrofoils. The foils were made from wood covered by aluminum sheet to reduce the friction resistance on the surface of the hydrofoil [12].

Figure 7 shows the front view of the Hydrofoils 1 and 2 foil installation. Figure 8 shows the side of the hydrofoil installation for several different angles tested in the present study. The aspect ratio is defined as the ratio of the square of the span length to the foil's cross-sectional area. A foil with a higher aspect ratio is more slender compared to one with a lower aspect ratio [13].

(a) (b)

Fig. 6. (a) Hydrofoil 1, (b) Hydrofoil 2

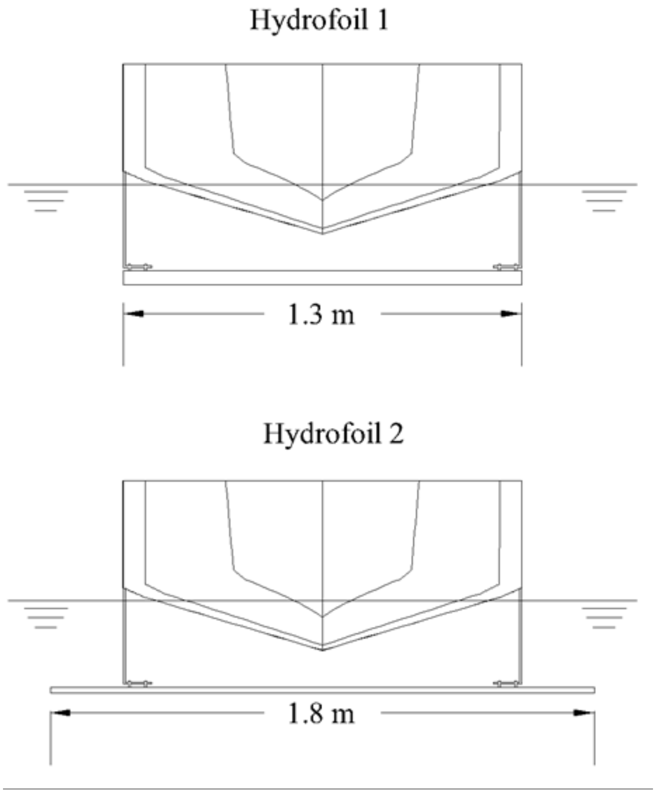

Fig. 7. Front view showing the position and placement of the hydrofoil and strut

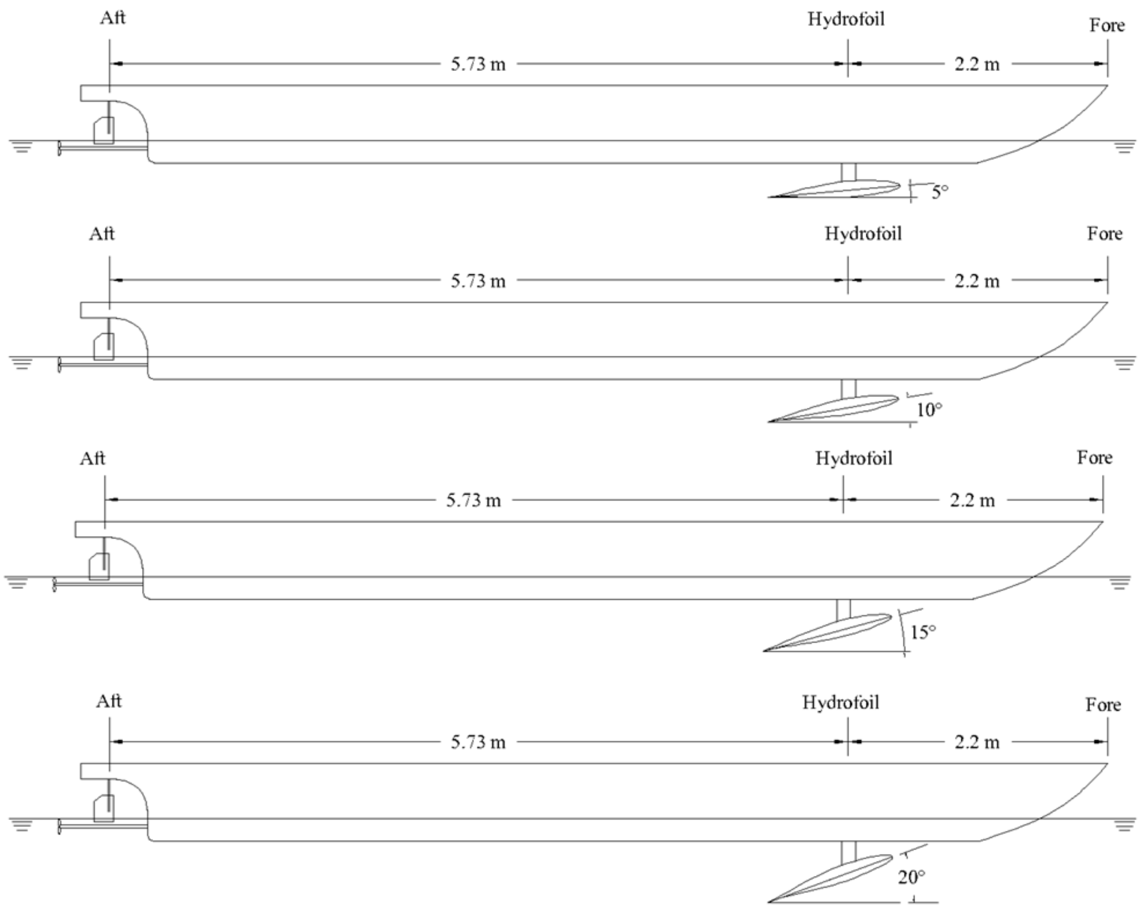

Fig. 8. Side view showing the placement of the hydrofoil and variations in the angle of attack

2.2 Engine Specifications

The boat was equipped with a 4-stroke engine, model GX420. This engine produces 15 HP, 29.3 N·m of torque, and a fuel tank capacity of 6.5 liters. The engine operates at 3600 rpm with a fuel consumption of 260 gr/HP-hour. Figure 9 shows the engine used in this research.

Fig. 9. Jian Dong GX420 Engine

2.3 Equipment and Materials

The equipment used in this study includes a stopwatch for measuring time, a protractor for measuring the angle of attack, a GPS for measuring the boat's speed, a measuring tape for assessing the dimensions of the hydrofoil and strut, and an inclinometer sensor for measuring the boat's trim angle.

2.4 Testing Procedure

The testing procedure involves running the boat on the water's surface at maximum speed. In the tests without hydrofoils, varying trim conditions were applied to gather the desired data. Afterwards, the boat was fitted with either Hydrofoil 1 or Hydrofoil 2, and testing was conducted by varying the hydrofoil angle at 5°, 10°, 15°, and 20°. Data was collected by measuring the boat's speed over 60 seconds for each test condition.

3. Results

3.1 Testing the Boat without Hydrofoil

The testing was conducted using a fishing boat with a planing hull type, the dimensions of which are shown in Table 1. The hydrofoil system used was a completely submerged foil type, specifically the NACA 64(1)-212, where the chord length is the same as the span length of the hydrofoil. The impact of different aspect ratios and variations in the hydrofoil angle on boat speed was analyzed through sailing tests conducted in calm water. The results of these tests provided the boat’s speed, the final trim angle of the boat, and the characteristics of each aspect ratio of the hydrofoil.

The tests were carried out under calm water conditions with maximum engine power for 60 seconds. To further analyze the hydrodynamic conditions and parameters of the RV. SBL 01, variations in the initial trim angle of the boat were also considered. The variations in the initial trim angle included stern trim (+) to reduce the wetted surface area of the bow section of the hull.

Three initial trim conditions were tested: no initial trim (trim = 0°), initial trim condition 1 (trim = +0.3°), and initial trim condition 2 (trim = +0.5°). Subsequently, tests were conducted under these three different trim conditions. The results of the average boat speed can be seen in Table 1.

Table 1
Results of the average speed test of the boat without a hydrofoil

Initial trim condition (°)	Velocity (m/s)
No initial trim (0°)	5.864
Initial trim 1 (+0.3°)	5.915
Initial trim 2 (+0.5°)	6.172

Table 1 shows that with the three variations of the boat’s initial conditions, the maximum boat speed without the hydrofoil is 6.172 m/s, which occurs under the initial trim condition 2. This indicates that the boat’s speed increases with the addition of the stern trim angle.

It is important to note that the RV. SBL 01 has a straight shaft and relatively low loading, so the propeller blades are positioned at a shallow depth when the boat is in a neutral trim condition (even keel). As a result, the surface area of water being pushed by the propeller is not maximized. By adding stern trim, the water area being pushed by the propeller is increased, thus generating greater thrust.

3.2 Testing the Boat with Hydrofoil
3.2.1 Relationship between boat speed and hydrofoil angle of attack

The next set of tests was carried out by installing a hydrofoil on the boat's hull. The tests were conducted under the same testing conditions and measurement parameters as the tests without the hydrofoil. The objective of these tests was to assess the changes in boat speed resulting from variations in the hydrofoil's aspect ratio under different initial trim conditions and angles of attack.

The variation in the angle of attack of the hydrofoil was aimed to evaluate the characteristics and speed at each of the specified angles. Four different angles of attack were tested: 5°, 10°, 15°, and 20°. The hydrofoils used in the tests were categorized into two types: Hydrofoil 1, with a low aspect ratio (AR) of 3.25, and Hydrofoil 2, with a high aspect ratio (AR) of 9. Hydrofoil 1 has a shorter span and a wider chord, while Hydrofoil 2 features a longer span and a narrower chord.

The tests were then conducted under three different initial trim conditions for each angle of attack on both hydrofoils. The results of these tests are presented in Table 2.

Table 2
Results of the average speed test of the boat without a hydrofoil

Angle (◦)	Velocity (m/s)					
	Hydrofoil 1			Hydrofoil 2		
	No initial trim	Initial trim 1	Initial trim 2	No initial trim	Initial trim 1	Initial trim 2
5	5.592	5.283	5.129	5.901	5.438	5.438
10	5.541	5.232	5.078	5.592	5.388	5.232
15	4.769	4.872	4.566	5.283	5.283	5.162
20	5.026	4.306	4.409	5.386	4.820	4.666

After obtaining the average speed for each condition, a comparison was conducted between the speeds without a hydrofoil and those with Hydrofoil 1 and Hydrofoil 2. These results are illustrated in Figures 10, 11, and 12.

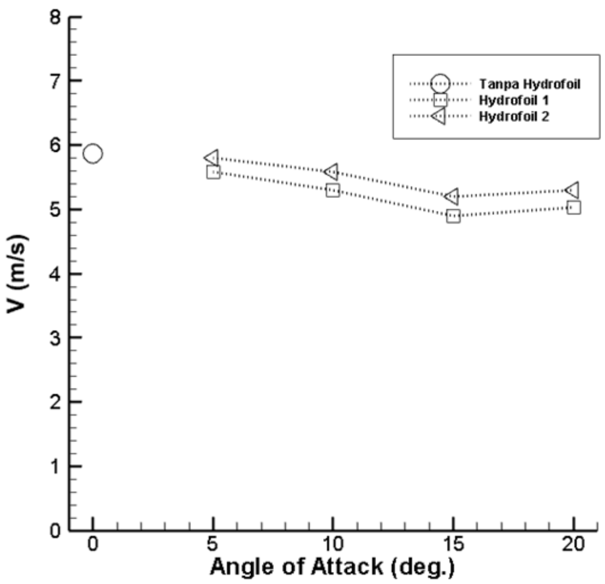

Fig. 10. Relationship between ship speed and angle of attack without initial trim

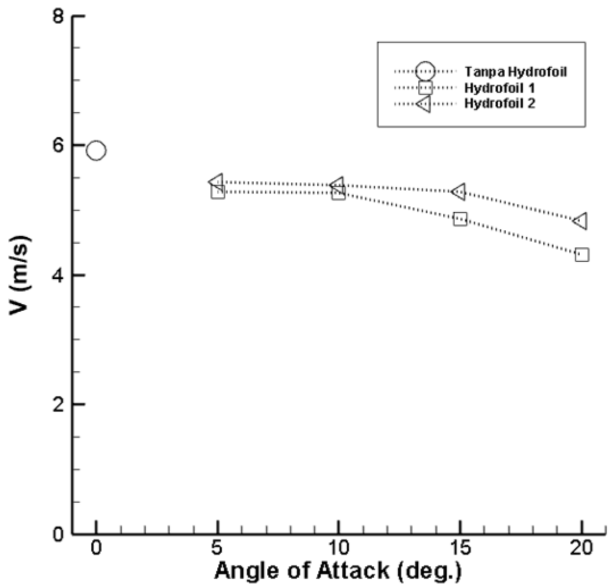

Fig. 11. Relationship between ship speed and angle of attack with initial trim 1

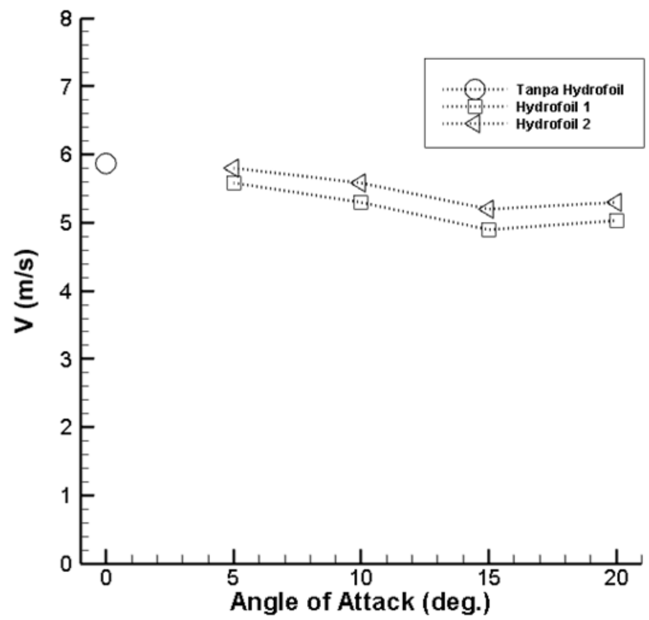

Fig. 12. Relationship between ship speed and angle of attack with initial trim 2

Figures 10, 11, and 12 indicate that the average ship speed decreases with the addition of hydrofoils, both Hydrofoil 1 and Hydrofoil 2, compared to the bare hull (no hydrofoil) (Table 3). Furthermore, Hydrofoil 2 consistently demonstrates higher average speeds than Hydrofoil 1 at all angles of attack, primarily due to its longer span.

Table 3
Percentage decrease in average boat speed (%) with hydrofoil

Angle (◦)	Hydrofoil 1			Hydrofoil 2		
	No initial trim	Initial trim 1	Initial trim 2	No initial trim	Initial trim 1	Initial trim 2
5	13.156	19.122	24.990	7.892	16.513	19.990
10	14.033	19.992	25.824	13.156	17.383	23.323
15	27.191	26.079	32.491	18.419	19.122	24.990
20	22.805	35.646	36.658	16.664	26.949	32.491

Compared to the bare hull, Hydrofoil 1 exhibits a maximum speed reduction of 13.15%, while Hydrofoil 2 shows a smaller reduction of 7.89%.

In the condition without initial trim, the LCG is located 2.546 m from the aft perpendicular (AP), as determined using Maxsurf software (details in Appendix). With initial trim 1, the LCG shifts to 2.467 m from the AP, moving further aft. For initial trim 2, the LCG shifts further to 2.425 m from the AP.

The angle of attack of 5° is identified as the most optimal for this hydrofoil system, as it produces higher speeds compared to other angles. However, field tests reveal that the addition of hydrofoils does not enhance operational speed. This is attributed to the dimensions and materials of the struts, which increase the ship's resistance.

For future designs, the strut chord dimension should be minimized to reduce added resistance while maintaining sufficient structural integrity. Additionally, the hydrofoil system requires a higher initial speed, as it is designed for high-speed boats.

Figures 10, 11, and 12 demonstrate that increasing the angle of attack raises pressure beneath the hydrofoil, resulting in reduced speed. Hydrofoil 2, with a longer span, generates higher lift forces than Hydrofoil 1, which spans only the ship's width. Hydrofoil 1's wider chord increases pressure without significantly enhancing lift, while Hydrofoil 2's extended span supports greater lift by exceeding the ship's width. The lift generated primarily around the trailing edge is more effective with a longer span, as it provides additional lift points beyond the ship's width, better supporting the boat's weight.

Hydrofoil 2's higher aspect ratio allows for reduced chord length while still producing greater lift. This contributes to an increase in the ship's trim and overall efficiency in lift generation.

3.2.2 Relationship between hydrofoil angle and boat trim angle

The results of the average trim angle measurements for the use of Hydrofoil 1 and 2 under each test condition are shown in Figures 13, 14 and 15.

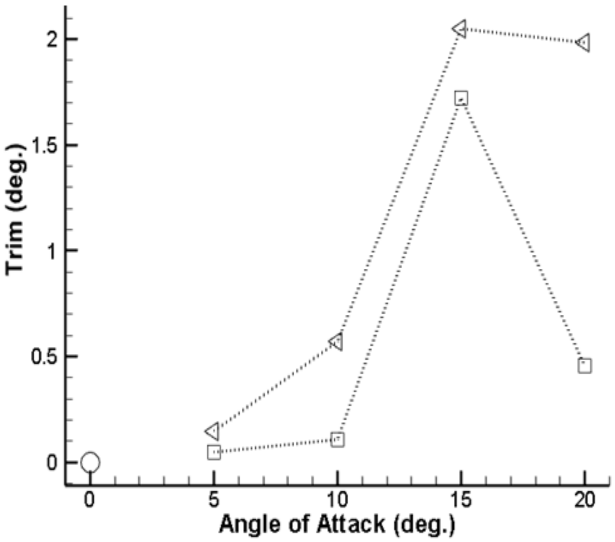

Fig. 13. Change in the average final trim angle without initial trim

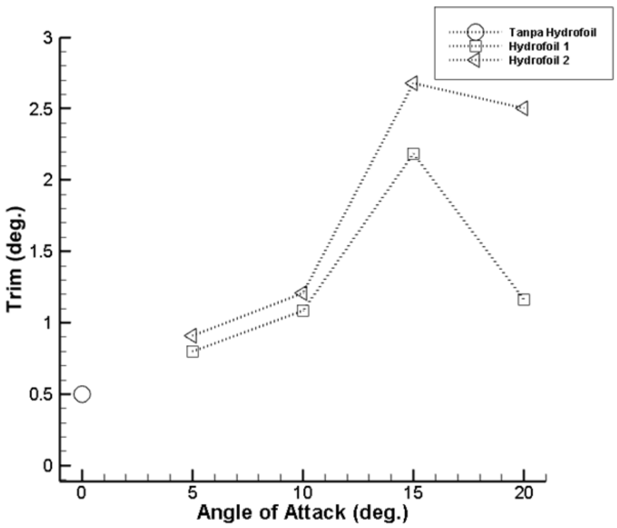

Fig. 14. Change in the average final trim angle with initial trim 1

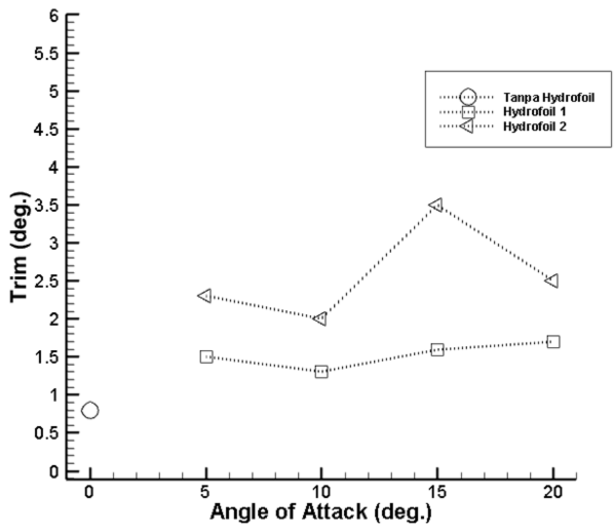

Fig. 15. Change in the average final trim angle with initial trim 2

As shown in the figures above, the use of Hydrofoil 2 results in a higher final trim angle compared to Hydrofoil 1. Hydrofoil 2 improves propulsion performance by reducing the weight and wetted surface area at the bow of the boat. While both hydrofoils have different aspect ratios, they both cause the ship's trim to reach the same maximum value, occurring at an angle of attack of 15°, as indicated by Abbott [14].

As illustrated in Figure 10, the highest ship speed occurs at an angle of attack of 5°, followed by 10°, 20°, and 15°. On the other hand, Figure 13 shows that the lowest stern trim occurs at an angle of attack of 5°, followed by 10°, 20°, and 15°. Comparing Figure 10 and Figure 13, it can be observed that as the angle of attack increases from 5° to 15°, the stern trim increases while the ship's speed decreases. This is due to the increased wetted surface area at the stern, which creates additional resistance and reduces speed.

3.2.3 Calculation of lift and drag forces on hydrofoil

To calculate the lift force on a hydrofoil, the following Equation (1) was used.

$$L = \frac{1}{2}\rho v^2 C_L A_p \tag{1}$$

Where,
$C_L 5°$ = 0.9
$C_L 10°$ = 1.2
$C_L 15°$ = 1.5
$C_L 20°$ = 1.1
ρ = 1000kg/m^3
v = 5.09 m/s
A_{p1} = 0.52 m^2
A_{p2} = 0.36 m^2

The calculation results from the equation above for each angle, along with the changes in C_L, A_P, and v, are presented in Table 4.

Table 4
Percentage decrease in average boat speed (%) with hydrofoil

Angle (◦)	Hydrofoil 1			Hydrofoil 2		
	No initial trim	Initial trim 1	Initial trim 2	No initial trim	Initial trim 1	Initial trim 2
5	1054.160	990.271	958.327	874.994	799.994	799.994
10	1391.349	1306.164	1263.572	1099.993	1055.549	1022.216
15	1472.984	1508.478	1437.491	1291.658	1291.658	1249.992
20	1145.260	963.059	989.088	967.586	855.550	824.994

To calculate the drag force produced by the hydrofoil, the following Equation (2) was used.

$$D = \frac{1}{2}\rho v^2 C_D A_p \tag{2}$$

Where,
$C_D 5°$ = 0.011
$C_D 10°$ = 0.017

$C_D 15°$ = 0.035
$C_D 20°$ = 0.020
ρ = 1000kg/m^3
v = 5.09 m/s
A_{p1} = 0.52 m^2
A_{p2} = 0.36 m^2

The results of the drag calculations for Hydrofoils 1 and 2 are presented in Table 5.

Table 5
Drag of hydrofoil (N)

Angle (◦)	Hydrofoil 1			Hydrofoil 2		
	No initial trim	Initial trim 1	Initial trim 2	No initial trim	Initial trim 1	Initial trim 2
5	74.171	65.453	61.298	57.762	48.284	48.284
10	112.325	98.991	92.641	79.358	73.075	68.532
15	165.882	173.972	157.984	144.181	144.181	135.029
20	106.554	75.347	79.475	85.970	67.214	62.499

The drag force increases compared to the condition without a hydrofoil due to the hydrofoil's position not being at the ship's center of gravity (CG). According to [6], the optimal placement of the hydrofoil is at the ship's CG, as it is the point where the ship's load is the greatest.

After obtaining the lift and drag forces for both hydrofoils with varying angles of attack, the lift-to-drag ratio (L/D) at each final speed achieved by the ship with the use of both hydrofoils was calculated, as shown in Table 6.

Table 6
L/D ratio of hydrofoils

Angle (◦)	Hydrofoil 1			Hydrofoil 2		
	No initial trim	Initial trim 1	Initial trim 2	No initial trim	Initial trim 1	Initial trim 2
5	14.212	15.129	15.633	15.148	16.568	16.568
10	12.386	13.194	13.639	13.861	14.444	14.915
15	8.879	8.670	9.098	8.958	8.958	9.257
20	10.748	12.781	12.445	11.254	12.728	13.200

The L/D ratios for Hydrofoil 1 and 2 can be seen in Figures 16, 17 and 18.

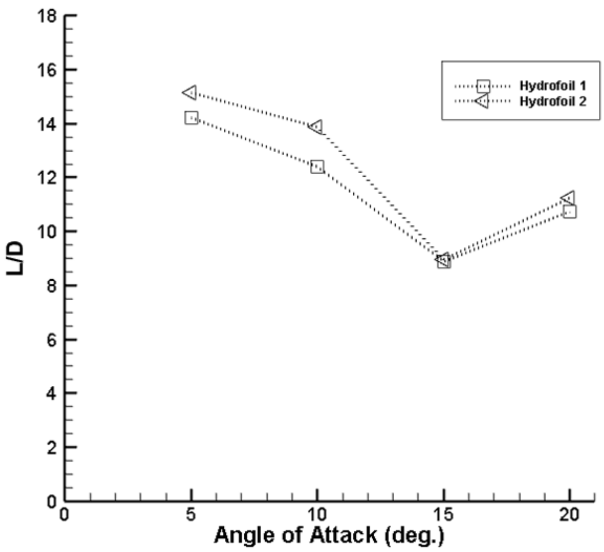

Fig. 16. Relationship between L/D and angle of attack in the condition without trim

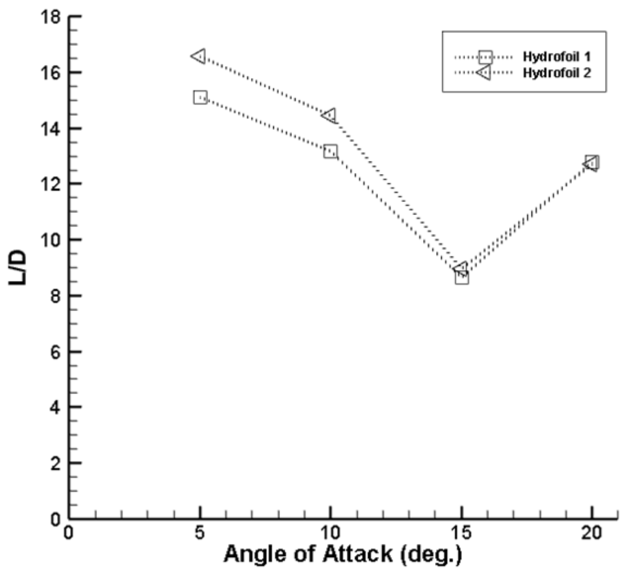

Fig. 17. Relationship between L/D and angle of attack in the condition with initial trim 1

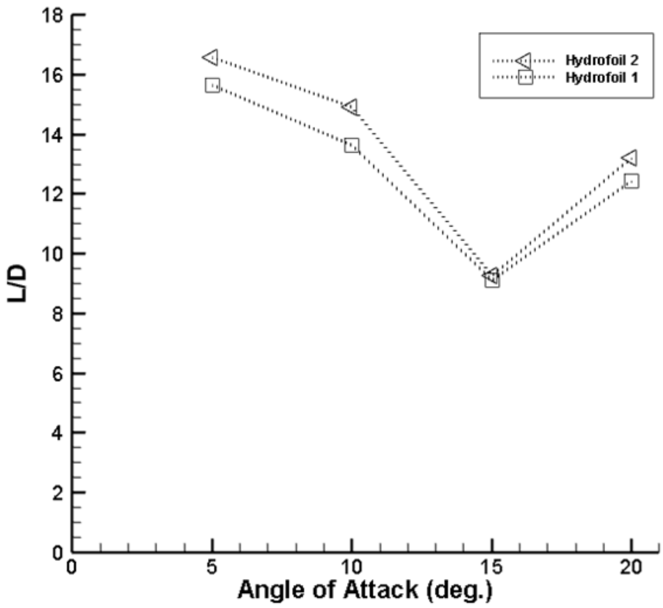

Fig. 18. Relationship between L/D and angle of attack in the condition with initial trim 2

From Figures 16, 17 and 18, it can be seen that the L/D ratio generated by Hydrofoil 2 is higher than that of Hydrofoil 1. This indicates that a higher aspect ratio can improve the L/D ratio at each increase in speed, making the use of Hydrofoil 2 more advantageous than Hydrofoil 1.

In Figure 10, the highest ship speed is achieved at an angle of attack of 5°, followed by 10°, 20°, and 15°. Meanwhile, Figure 18 shows that the highest L/D ratio is achieved at an angle of attack of 5°, followed by 10°, 20°, and 15°. Comparing Figure 10 with Figure 18, it is evident that from an angle of attack of 5° to 15°, the L/D ratio decreases, and the ship's speed also decreases due to the increased drag force on the hydrofoil.

3.2.4 Relationship between boat drag coefficient and Froude number

The total drag coefficient can be calculated as follows

$$C_T = \frac{R_T}{\frac{1}{2}\rho V^2 S} \tag{3}$$

In this equation, R_T represents the total drag force on the ship in each condition (N), which is derived from Maxsurf simulations along with additional hydrofoil drag calculations based on Equation (2). The density of water, ρ, is typically taken as 1000 kg/m^3. The speed of the ship, V, is given in meters per second (m/s) and can be found in the relevant tables (e.g., Table 1 or Table 2). The wetted surface area of the ship, S, is expressed in square meters (m²) and is obtained from Maxsurf simulations, including the dimensions of the hydrofoil. This formula helps calculate the drag coefficient, a dimensionless number that indicates the resistance encountered by the ship as it moves through the water.

For the condition without initial trim and without a hydrofoil, the total drag can be calculated as

R_T = 1036 N, obtained from Maxsurf simulations.
ρ = 1000kg/m^3
V = 5.86m/s (ship speed without initial trim, as seen in Table 1.
S = 9.784m^2, obtained from Maxsurf simulations.

$$C_T = \frac{1036\ N}{\frac{1}{2}1000kg/m^3(5.86\ m/s)^2\ 9.784m^2}$$

$$C_T = \ 0.009567\ N$$

For the condition without initial trim with Hydrofoil 1 at an angle of attack of 5°, the total drag can be calculated as follows:

R_T = 1278 N, obtained from Maxsurf simulations.
ρ = 1000 kg/m^3
V = 5.592 m/s (ship speed without initial trim, as seen in Table 1).
S = 9.983 m^2, obtained from Maxsurf simulations.

$$C_T = \frac{1278\ N}{\frac{1}{2}1000kg/m^3(5.592\ m/s)^2\ 9.983m^2}$$

$$C_T = \ 0.01198\ N$$

The same calculation method applies to other conditions with changes in R_T, S, and V. The results for the total drag coefficient (C_T) of the ship without a hydrofoil and with Hydrofoils 1 and 2 can be seen in Figure 19.

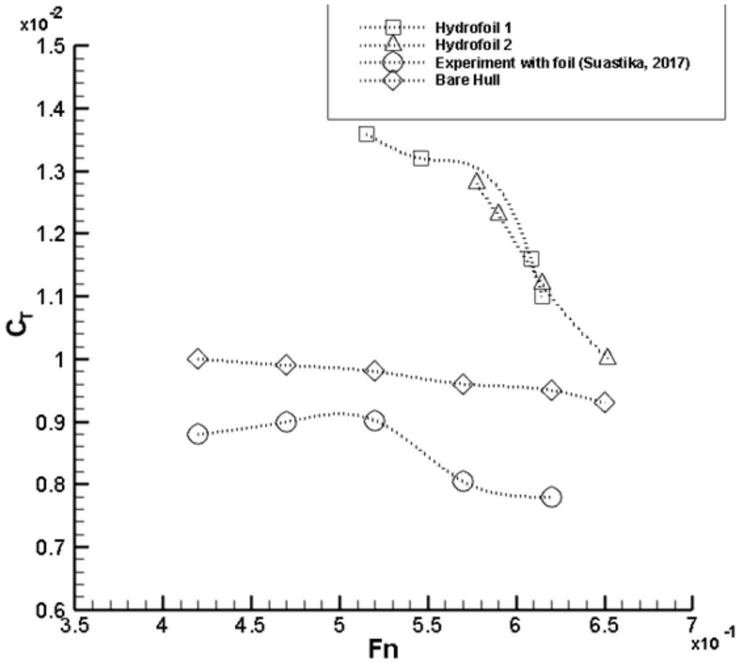

Fig. 19. The relationship between Froude number and ship drag coefficient

Figure 19 shows the relationship between the Froude number (Fn) and the ship's drag coefficient. It can be observed that for Fn>0.57Fn>0.57, both Hydrofoil 1 and Hydrofoil 2 exhibit a reduction in the drag coefficient, consistent with the findings of [8]. In that study, a planning hull boat with a length overall (LOA) of 1 m, a beam of 0.2 m, and a draft of 0.042 m was used. The hydrofoil was installed just below the transom of the boat, behind the ship's center of gravity. The model was tested in a towing tank with controlled water conditions and speeds. In contrast, the tests in the present study were conducted in a dam with differing conditions.

At Fn>0.57Fn>0.57, the hydrofoil shifts the ship from a displacement mode to a planning mode, characterized by a reduction in drag due to the hydrodynamic lift forces being greater than the buoyant forces as the ship moves.

Compared to the bare hull (without a hydrofoil), at a maximum speed with Fn=6.2Fn=6.2, the use of Hydrofoil 1 results in a 25.4% increase in the total drag coefficient (CT). For Hydrofoil 2, at a maximum speed with Fn=6.5Fn=6.5, the total drag coefficient (CT) increases by 7% compared to the bare hull.

4. Conclusions

Based on the analysis and discussion, it can be concluded that using Hydrofoils 1 and 2 both reduces the boat's operational speed. Furthermore, hydrofoils with a higher aspect ratio increase boat speed more than those with a lower aspect ratio; however, they do not lead to an increase in the boat's operational speed.

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