Analysis of Leading Edge Protuberances on Fully Submerged Hydrofoil of 15 m Pilot Boat

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Abstract: Resistance greatly affects on selection of the main engine and ship fuel consumption. To achieve the speed of the ship, the ship must be prepared to overcome resistance in the waters to be passed by choosing the right engine according to the needs of the ship. In the last few years there have been many studies on biomimetics or the use of systems in nature to be applied in a technology. Such as the use of Leading edge protuberances. Despite its large size and stiff flexibility, the humpback whale has a good maneuver even when chasing prey compared to other animals of its size. This study aims to obtain the highest lift force result and the smallest resistance with a hydrofoil model configuration of leading edge protuberances which resembles a humpback whale fin (megaptra novaenliae). The Computational Fluid Dynamics (CFD) is applied to analyse lift force and ship resistance of all models variation. The results indicates that from all variation of models at the Fn 1.356, the model has 5 ° angle of attack were able to reduce the total resistance value of Pilot Boat by 35.13%.

1. Introduction
In a previous study based on the results of the analysis of variations in the shape of a 15 meter step hull pilot boat, the total resistance value was scaled down to 16.96%, this condition occurred in variation of step hull with angle 180° at a speed is 26 knots [1]. In the analysis of the addition of a hull vane in 15 meter pilot boat can increase the lift value by 26.529 kN and reduce the total resistance of the ship by 35% in the hull vane model with an angle of attack of 2° with a depth of 100% T [2]. Then in the analysis of the addition of foil on the 15 m pilot boat with a variation of the swept foil angle model, the value of the total resistance value decreased to 38.021% than the original ship for angle of attack’s variation 4° and swept 10 degrees Fn 1.356 [3].

On hydrofoil supported catamaran (Hysucat), the use of hydrofoil on catamarans makes the lift force on the ship higher which causes the ship’s draught to be reduced, so that reduce in total resistance. In the analysis of calm water conditions it is proven to reduce the resistance value of the catamaran model sample by 30% to 50% [4, 5]. In other studies, the use of hydrofoil on catamaran vessels was proven to reduce the value of ship resistance by 35% at Fn > 1.8. [6, 7].

In the last few years there have been many studies on biomimetic or the use of systems in nature to be applied in a technology, such as the use of Leading edge protuberances. Leading edge protuberances is the shape resembles a humpback whale fin (Megaptera novaenliae) [8]. Despite its large size and stiff flexibility, the humpback whale has a good maneuver even when chasing prey compared to other animals of its size.
Watts and Fish uses the panel method on the NACA foil series 634-021 with a second aspect ratio at the angle of attack $\alpha = 10^\circ$, there is an increase in lift by 4.8% on the baseline wing and a 10.9% decrease in induced drag [9]. Humpback whale flipper model has able to increase lift force about 6% when is fitted in aeroplane wing and also increase stall angle about 40% [10]. Drag force also decreases up to 32% on angle of attack over the range of 10,3° to 11,8° when protuberances is used.

In this study, the variations used consisted of variations in wavelengths of 0.5c and 0.25c and amplitudes of 0.025c, 0.05c and 0.12c with the angles of attack 2.5° and 5°. The selection of amplitude and wavelength is based on the value associated with the characteristics of humpback whales [11]. The purpose of this study was to determine the lift and resistance of each design of the leading edge protuberances.

2. Method of Research
The Pilot Boat hull model is created using Rhinoceros v 6.0 software student version. The scaled ship model was generated by 1:30. The tandem foils is applied on the pilot boat that the position of these foils on the ship are fitted at 4.5 m from LCG aft and 4.3 m from LCG front. Figure 1 shows the result of 3D boat modeling with foils.

![Figure 1. Pilot Boat 3D Modeling with foils](image)

The models is varied based on its wavelength and amplitude of leading edge. In addition, the variation also varied with two variations of angle of attack of 2.5° and 5°. Detail of model variation of leading edge protuberances are shown in Table 1 and Figure 1.

| Model | Wavelength | Amplitude | Angle of Attack |
|-------|------------|-----------|-----------------|
| 8L    | 0.25c      | 0.12c     | 2.5° & 5°       |
| 8M    | 0.25c      | 0.05c     | 2.5° & 5°       |
| 8S    | 0.25c      | 0.025c    | 2.5° & 5°       |
| 4L    | 0.5c       | 0.12c     | 2.5° & 5°       |
| 4M    | 0.5c       | 0.05c     | 2.5° & 5°       |
| 4S    | 0.5c       | 0.025c    | 2.5° & 5°       |
Figure 2. Model variation of leading edge protuberances

Figure 3. Boundary layer of Pilot Boat domain

CFD method is applied in this study to analyse total resistance when the ship is modified using leading edge protuberances. Figure 3 shows all boundary layer on domain box is required to CFD analyse. Top boundary is opening type with zero gradient turbulence. Bottom and wall boundary is free slip. Velocity of fluid flow is applied in inlet, while static pressure is applied in outlet. Turbulence model using SST.
3. Result and Discussion

It takes two running stages to get the total resistance value of the hydrofoil craft, the first running stage is used to obtain the lift force, trim moment and heave, then the second running stage is done when the ship has been lifted and the trim and heave values are in accordance with calculation of equation (2) and (3) is inclined with the equilibrium condition when the ship moves at each speed.

| Model | Lift (kN) | Angle of Attack 2.5° (kN) | Angle of Attack 5° (kN) |
|-------|-----------|---------------------------|------------------------|
|       | Fn 0.904  | Fn 1.130                  | Fn 1.356               |
| 8L    | 121.238   | 172.494                   | 232.283                |
| 8M    | 125.015   | 171.655                   | 223.816                |
| 8S    | 115.773   | 180.427                   | 189.766                |
| 4L    | 128.293   | 183.313                   | 249.264                |
| 4M    | 133.704   | 186.829                   | 270.837                |
| 4S    | 117.709   | 177.862                   | 209.611                |

Table 2. Lift force Angle of Attack 2.5° (kN)

| Model | Lift (kN) | Angle of Attack 5° (kN) |
|-------|-----------|------------------------|
|       | Fn 0.904  | Fn 1.130               | Fn 1.356               |
| 8L    | 151.440   | 217.115                | 256.767                |
| 8M    | 136.220   | 212.533                | 261.511                |
| 8S    | 152.833   | 212.174                | 259.629                |
| 4L    | 148.645   | 216.237                | 310.041                |
| 4M    | 146.858   | 236.638                | 290.277                |
| 4S    | 141.288   | 232.831                | 247.544                |

Table 3. Lift force Angle of Attack 5° (kN)

Table 2 and Table 3 show the lift value using the CFD analysis with variations in the leading edge protuberances model. The highest lift value is 270.837 kN for the 4M model angle of attack 2.5° and 310.041 kN for the 4L model angle of attack 5°, each of these values occurs on Fn 1.356 with a Tandem configuration. Whereas in the same froude number, the smallest lift value is a 8S angle of attack 2.5° model with a value of 189.766 kN and 4S angle of attack 5° with a value of 247.544 kN.

The total resistance on ship is the sum of several other resistance components such as viscosity resistance and wave resistance. The other important thing that has a big influence on the total resistance value on the ship is Wetted Surface Area (Table 4 and Table 5). The increasing of WSA, the total resistance value on the ship will also increase.

| Model | Wetted Surface Area (m²) | Angle of Attack 2.5° (m²) | Angle of Attack 5° (m²) |
|-------|--------------------------|---------------------------|------------------------|
|       | Fn 0.904                 | Fn 1.130                  | Fn 1.356               |
| Original | 34.728                   | 32.736                    | 35.915                 |
| 8L      | 40.000                   | 30.548                    | 21.666                 |
| 8M      | 38.605                   | 31.036                    | 22.527                 |
| 8S      | 39.362                   | 29.266                    | 27.727                 |
| 4L      | 37.829                   | 29.393                    | 18.870                 |
| 4M      | 37.374                   | 28.428                    | 14.958                 |
| 4S      | 38.169                   | 29.727                    | 24.455                 |
Table 5. Wetted Surface Area with Angle of Attack 5° (m²)

| Model | Wetted Surface Area (m²) |
|-------|--------------------------|
|       | Fn 0.904 | Fn 1.130 | Fn 1.356 |
| Original | 34.728 | 32.736 | 35.915 |
| 8L | 35.000 | 24.008 | 17.858 |
| 8M | 36.986 | 24.123 | 16.593 |
| 8S | 34.014 | 24.343 | 16.629 |
| 4L | 35.047 | 23.925 | 13.195 |
| 4M | 35.159 | 20.424 | 13.359 |
| 4S | 35.876 | 20.942 | 18.447 |

Table 6 shows that the result of total ship resistance on Fn 1.356 has closed value between CFD method and analytical method (Blount & Fox, and Savitsky). It means that the CFD setup is liable to be applied to analyse other modification of leading edge protuberances on fully submerged hydrofoil of Pilot Boat.

Table 6. Validation for Ship Resistance on Fn 1.356

| Fn v (m/s) | Method       | Total Resistance (kN) | Error (%) |
|------------|--------------|-----------------------|-----------|
| 1.356      | 2.817 CFD    | 35.39                 | -         |
| 1.356      | 2.817 Blout & Fox | 36.60               | 4.077     |
| 1.356      | 2.817 Savitsky | 34.30               | 2.478     |

In Table 7 and Table 8 show that the total resistance value of ships using foil becomes smaller than original ship model, specifically in the froude number 1.356 had biggest decreased of resistance than the lower froude number.

The total resistance which had biggest reduction occurred on angle of attack of 5° with a reduction in total resistance of 35.13% for the 4L model of the total resistance of the original ship. The variation of 4L foil models had the biggest reduction in drag caused by having the greatest lift force so that it can lift the original ship completely from the water surface.

Table 7. Total Resistance Foil Angle of Attack 2.5° (kN)

| Model | Total Resistance (kN) |
|-------|-----------------------|
|       | Fn 0.904 | Fn 1.130 | Fn 1.356 |
| Original | 17.010 | 22.084 | 35.386 |
| 8L | 23.069 | 24.907 | 25.877 |
| 8M | 22.580 | 26.145 | 26.635 |
| 8S | 23.251 | 24.383 | 30.553 |
| 4L | 19.813 | 25.109 | 26.877 |
| 4M | 19.793 | 23.766 | 23.625 |
| 4S | 20.559 | 25.457 | 28.976 |
Table 8. Total Resistance Foil Angle of Attack 5° (kN)

| Model | Total Resistance (kN) |
|-------|-----------------------|
|       | Fn 0.904 | Fn 1.130 | Fn 1.356 |
| Original | 17.010  | 22.084  | 35.386  |
| 8L     | 20.473  | 24.105  | 25.371  |
| 8M     | 21.229  | 24.439  | 25.472  |
| 8S     | 20.790  | 24.317  | 24.120  |
| 4L     | 20.210  | 21.756  | 22.955  |
| 4M     | 19.820  | 21.558  | 23.484  |
| 4S     | 20.220  | 21.281  | 25.570  |

The lift value on the hydrofoil leading edge protuberances is always inversely proportional to the total resistance value of the ship. In Figure 4 taking a model with a variation of 0.5c wave length, namely 4L and 4M models at an angle of attack 5° showed the higher the lift value, the smaller from the total resistance. The 4L and 4M models on the Fn 1.356 had the highest lift forces, each worth 310.041 kN and 290.277 kN and had smallest total resistance respectively 22.955 kN and 23.484 kN.

In Figure 5 and Figure 6, showed the original model had sharper wave pattern color than 4L model at the same vulnerable wave elevation. In the 4L model the wave patterns that occur are only caused by strut and foil which are still below the surface of the water. In the final results of this study it appears that the angle of attack value is same to the value of the lift. At the Fn 1.356 the lift values of all models with an angle of attack 5° are bigger than all models with an angle of attack of 2.5°.

Figure 4. Comparison between Lift and Total Resistance Model 4M & 4L Leading Edge Protuberances Foil with Angle of attack 5°
Figure 5. Wave Pattern of the Original Model Fn 1,356

Figure 6. Wave Pattern of the 4L Foil angle of attack 5° Fn 1,356

4. Conclusion

The highest lift value is generated by the 4L model in Fn 1,356 at a 5° angle of attack of 310,444 kN. The lowest lift value occurs in the 8S model at Fn 0.904 at 2.5° angle of attack is 115,773 kN.

The lowest total resistance value is resulted by the 4L model in Fn 1,356 at angle of attack 5° with a decrease of 35.13% from the total resistance of the original ship. In the 4L and 4M foil models the hull is already above the surface of the water, so the Wetted Surface Area value is getting smaller which results in a total resistance generated at Fn 1,356 also getting smaller.

The leading edge protuberances model variation had a effective lift force to reduce the total resistance value of the 15 meter Pilot Boat is a 4L model variation or a model with a wavelength of 0.5c and an amplitude of 0.12c with angle of attack of 5°.

The variation of the leading edge protuberances model that most influences the ship's performance is the wavelength variation. The greater value of the wavelength, the foil will tend to produce a greater lift force and greater resistance reduction. Amplitude variation also affected at the value of lift and
decrease in ship resistance, the bigger the amplitude value, the lift force will tend to increase and the resistance of the ship will decrease bigger.

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