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Investigation of the Effect of Leading-Edge Tubercles on Wingsail Performance

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Abstract

In this study, effects of leading edge tubercles on a 2013 America's Cup boat wingsail are investigated by viscous Computational Fluid Dynamics (CFD). Adding tubercles on the leading edge of the sail is inspired by humpback whales, which are fast and maneuverable animals along baleen whales thanks to their distinctive flippers. It has been seen from the examined studies that tubercles on the leading edge of the wings delay stall and provide better lift/drag ratio in high angle of attacks (AoA) compared to the plain wing, which might be beneficial for wingsails.

A 2013 America's Cup boat wingsail geometry is developed for measuring the effects of tubercles on its performance. Sinusoidal tubercles are placed on leading edge with different wave lengths and amplitudes varying as a function of chord length. Post-stall performance of the wingsail has been improved whereas onset of stall has been observed to be identical to that of the base wingsail.

Keywords: *Biomimicry, Bio-inspiration, Tubercle, Wingsail, CFD.*

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1. Introduction

Sailing yacht races and events play significant role on developing technology for the faster sailing yachts. America's Cup (AC) is one of oldest and most well-known regatta's in the world. As in Formula 1 races, where technology later adapted to production cars, technologies developed for regatta yachts are eventually being adapted to other sailing vessels and boats.

Wingsails are one of the technologies that attracted attention of sailing community after such races. They became more popular after 34th America's Cup boat AC 72, which goes extremely fast on hydrofoils and powered by large wing sails.

Biomimicry has been an interesting phenomenon for engineers for a long time, especially in the field of aero and hydrodynamics. This paper presents a review of previous studies involving foils with bio-inspired leading edges. In the rest of the study, leading edge tubercles, inspired from humpback whales are applied to a wing sail designed to compete in the America's Cup on an AC72 catamaran. The effect of these tubercles on the aerodynamic performance of the wing sail has been investigated. Viscous Computational Fluid Dynamics (CFD) method has been used for the investigations following a grid sensitivity study and a validation case based on wind tunnel experiments of 2-d foil sections with leading edge tubercles.

2. Wingsail Design and Bio-Inspired Wings

Although airfoils and wing shapes have been extensively examined and utilized by aeronautics industry; wing sails have only been of interest to some enthusiasts and racing boat designers in yachting industry. Nevertheless, first wing sails have been used since 1980's and they became more popular after fast going boats of 2013 America's Cup regatta.

One of the main advantages of wing sails over soft sails is that they can generate much better pressure distribution around sail and create more lift (L) and less drag (D) with same sail area.

There are some major important subjects that need to be considered carefully while designing a wing sail. First one is, since solid wing sails cannot adjust their camber such as soft sails in both tacks; two or more element wing sails are being utilized in boats. Since the gap between flap and main sail cannot be closed perfectly, analysis regarding the extent of the slot must be carried out carefully while designing a wing sail. Another major design element for wing sails is reducing induced drag (C_{DI}) as much as possible to increase overall performance. As seen from the Equation (1) induced D is proportional to L^2 and will eventually limit the available thrust in upwind sailing [1].

$$C_{DI} = \frac{C_L{}^2 A_S}{\pi b^2} \tag{1}$$

where:
As: Sail area,
b: Span of sail.

As hydrodynamic performance and maneuvering capability of humpback whales gathered attention of researchers, morphological studies and wind tunnel tests have been based on flippers of these whales.

From the studies of Fish and Battle [2], it is seen that humpback whales utilize high aspect ratio wing like flippers which have similar sections with NACA 634-021 symmetrical airfoil. It seems from the research that tubercle distribution is stochastic, but size is gradually getting smaller while going to tip of the flipper. Symmetrical cross sections and elliptical planform of the flipper create favorable L distribution along the span and minimize induced drag. Research shows that undulations on the leading edge minimize profile drag by lowering pressure gradient due to the flow around tubercles. Therefore, reduction of this pressure gradient postpones the flow separation and allows flipper to continue generating L by minimizing energy lost in the wake.

Miklosovic et al [3] constructed a wind tunnel test based on NACA 0020 airfoil section to compare L and D of a flipper with and without leading edge undulations. They tested models with Reynolds Number (Re) around 10^6 at Mach Number 2.0 in different angle of attacks ranging from -20 to +20. They observed that stall angle increased from 12 to 16.30 and maximum lift coefficient (C_L) increased 6% in flipper with leading edge tubercles.

Wind tunnel experiments, CFD studies and panel method analysis are utilized by various researchers to examine finite and infinite aspect ratio wings with leading edge tubercles. Performance difference is examined and physics of flow phenomena in different situations are tried to be determined by these researches.

3D panel method is utilized by Watts and Fish [4] to investigate forces acting on a wing. NACA 634-021 airfoil is used in analysis and method code for analysis is based on first order vortex method by Hess, Katz and Plotkin. Since panel method constructs inviscid simulations, high Re numbers regimes are more suitable for this method as indicated by authors. It has been observed from the analysis that undulations on leading edge increased lift around 5% and reduced drag around 11% at an angle of attack of 10 degrees. Main theory from research for performance increase is that undulations delay and reduce flow separations by shifting pressure gradient in top surface without effecting mean pressure.

Johari et al [5] constructed a series of wind tunnel tests with finite wings that have sinusoidal leading-edge undulations. Undulations on wings had different wavelength (λ) and amplitudes (A) as a function of chord length(c). Wave lengths were specified as 0.25c and 0.50c while amplitudes were 0.025c, 0.05c and 0.12c. Similar results are achieved with Miklosovic's experiment while there are slight differences in pre-stall regime. Drag coefficient (C_D) of the modified wings increased more in Johari's experiments while similar stall delay and post-stall L/D ratio increase occurred in both cases. Similar result is also stated by Hansen et al [6] that tubercles on leading edge reduce L/D ratio at Re below 300000. Six of the tested airfoils with leading edge tubercles continued to provide L where baseline foil stalls.

Effects of change in amplitude and wavelength of tubercles are also studied by Johari et al. [5] and it has been indicated that while wavelength has a light effect on the performance, amplitude effects behavior of the foil significantly. According to Atkins [7], this result can be possibly explained by the vortices generated by tubercles resulting in the exchange of momentum at the boundary layer and re-energizing flow to attach to the foil and postpone stall.

Lohry et al [8] studied tubercles on NACA 0020 airfoils by using RANS solver developed at Princeton University. According to Lohry, both low Re and unusual geometry of airfoils render RANS simulation results highly responsive to turbulence models used. In their study it has been concluded that best results which are close to wind tunnel tests are achieved with Menter SST k-ω turbulence model. It has been indicated that performance of undulations relies on Re, thickness and planform shaping [8].

Hansen [9] executed several experimental and computational studies on NACA 65-021 and NACA 0021 airfoils to analyze the influence of leading-edge tubercles on wing performance and the physical phenomena behind the effects.

Tests done with different Re showed that performance increase is dependent on Re and high Re are more suitable for performance increase with leading edge undulations. Similar tests were conducted with finite and infinite spans and seen that results are free from 3D effects and tubercles do not affect tip vortices. In the studies with both airfoils, maximum L/D ratio is achieved with smallest tubercles in terms of both wavelength and amplitude. But it has been stated that there is an optimum λ/A ratio since reduction of wavelength after certain limit compared to amplitude is reduced the efficiency of the wing.

Initial studies done by Watts and Fish [4] indicated that leading edge tubercles increased wing performance by prohibiting tip vortices. However, studies executed by Hansen [9] and Johari et al [5] showed that lift and drag characteristics of a wing with leading edge undulations are independent from wingspan and 3D effects. Therefore, tip stall theory is eliminated according to the latest studies. It has been observed from the recent studies that while wavelength of the tubercle had small effect on the lift and drag characteristics, amplitude played much significant role on performance change. As indicated previously, this phenomenon can be explained by such flow behavior that vortices generated by tubercles exchange momentum in viscous layer and delay stall by delaying flow separation similar to the vortex generators [7].

The literature review on the studies regarding the utilization of tubercles indicate that performance improvements may be possible in the post-stall regime and a general insight into the flow phenomenon associated with tubercle utilization has been obtained. However, studies are based on finite and infinite aspect ratio standard foil profiles and a peculiar study on the utilization of tubercles on wing sails and its effects on the performance of the wing sail has not been observed. This study aims to investigate the effect of leading-edge tubercles on wing sail performance by viscous CFD simulations. Systematic variations of the tubercle geometry attached to the leading edge of a wing sail will be made and variations on the aerodynamic performance of the wing sail will be investigated.

3. Computational Analysis

A systematic computational study for investigating the undulations on wing sail has been executed. Unsteady Reynolds Averaged Navier-Stokes Equations (U-RANS) solver of commercial CFD code Star-CCM+ has been utilized. A time step value of 0.001s has been used in the analyses.

3.1. Methodology

As a start, mesh convergence study is executed to determine minimum number of cells required to achieve a converged result without increasing the computational cost. Then turbulence models are examined and Menter SST k-ω model is used in simulations since it gives better results in separated flows and gives consisted results when compared to data extracted from experimental works. Standard Menter Shear Stress Transport k-ω is a turbulence model comprised of two equations that solves additionally turbulent kinetic energy (k) and specific dissipation rate (ω) transport equations [10]. This model associates both k-ω and k-ε turbulence models to increase accuracy of results on inverted pressure gradients. Therefore, by combining two models, Menter SST k-ω gives accurate results in cases such as flow around airfoil in both small and high angle of attacks.

Prior to analysis of wing sails, validation of Star-CCM+ software and U-RANS numerical models is executed. Wind tunnel section and foil placement similar to experiments done by Tezel et al [11] has been constructed in Star-CCM+. Results of the CFD analyses are then compared to C_L and C_D measured by Tezel. NACA 0012 airfoils are tested in the mentioned paper from -3 to +33 degrees of angle of attacks by 3-degree increments. 3-part tubercle with 30 mm wavelength and 8mm amplitude (λ30A8) is selected for comparison with base model. Flow speed is taken 33 m/s in both CFD and experiment while corresponding Re is $3.19x\ 10^5$.

Effect of mesh cell count on C_L and C_D are examined as a first stage of validation study to achieve reliable converged results that are independent from cell numbers in the domain. Base NACA 0012 model is investigated in 12^0 angle of attack with mesh sizes shown in the Table 1. Results have started to converge after base cell size of 1.25 cm although there are slight differences in C_D. Maximum cell size chosen as 1cm and refined mesh size around wing and in wake area is taken 0.5 cm as seen on Figure 1 to achieve accurate results. Further refinement is done on the leading edge of aerofoil to define smooth leading edge as decent as possible. Figure 2 shows refined leading edge with cell size of 0.1 cm.

Table 1. *Grid Independence Study at 12^0 Angle of Attack*

Max Size	Cell Size	Cell Count	CL	CD
2.5 cm	1.25 cm	46629	0.4571	0.1308
1.5 cm	0.75 cm	122459	0.6432	0.0908
1.25 cm	0.625 cm	181913	0.6474	0.0832
1 cm	0.5 cm	306278	0.6482	0.0826
0.75 cm	0.375 cm	610824	0.6463	0.0791

Boundary layer thickness (δ) and dimensionless wall distance (y^+) are also important parameters while simulating a viscous flow. Boundary layer thickness in turbulent flow is calculated 5mm by Equation (2) found on Schlichting [12]. Boundary layer is modeled with prism layer mesher and total 12 prism layers are used

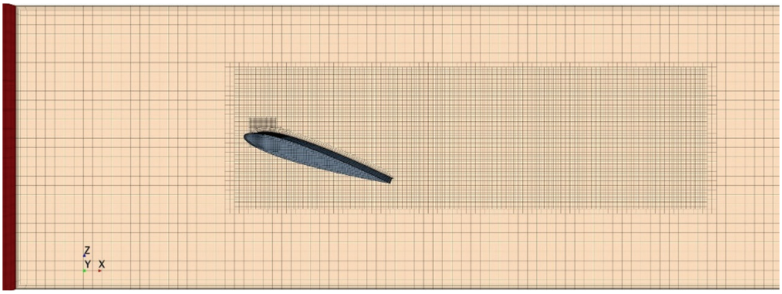

Figure 1. *Meshing of Domain and Volume Refinement*

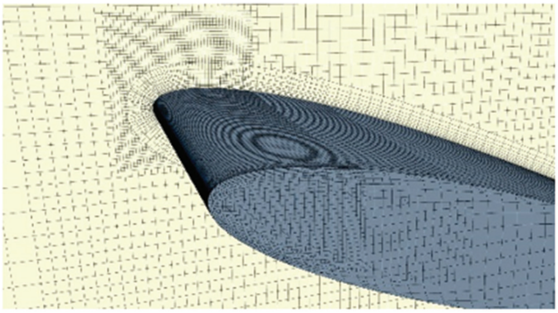

Figure 2. *Mesh Refinement on Leading Edge*

with stretching factor of 1.3. Therefore, y^+ is calculated as approximately 10 according to (Equation 3) also found on Schlichting [12].

$$\delta \approx 0.37x/Re_x^{1/5} \tag{2}$$

$$y^+ \equiv (u^* y)/\upsilon \tag{3}$$

Menter's SST k-ω turbulence model is used in analyses since literature review pointed that in almost all previous studies, best results close to experiments are achieved with this turbulence model.

Figure 3-5 demonstrate the comparison between base NACA 0012 and modified λ30A8 airfoils in both CFD and experiment. CFD results tend to over predict C_D in high angle of attack for base NACA 0012 wing however, general behavior of flow and airfoil is consistent with experimental results. Interestingly, CFD predicted C_D for λ30A8 wing close to experiment while over predicting C_L this time. However, in both case L/D ratio is consistent with experimental data.

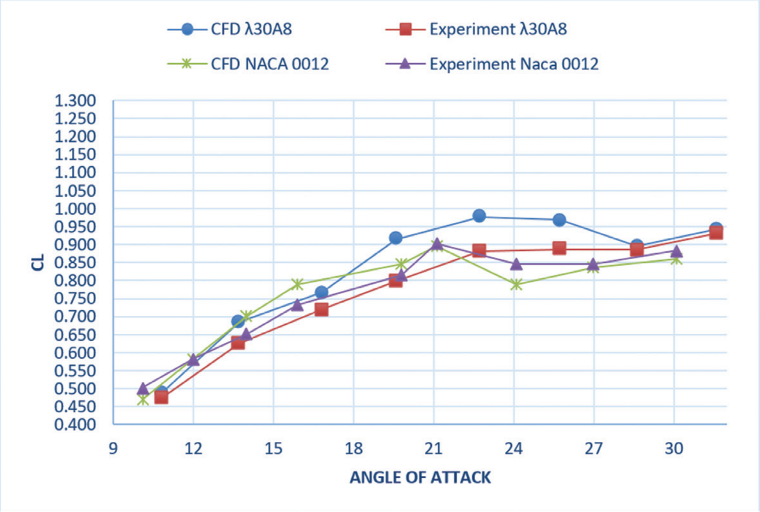

Figure 3. *Comparison of C_L Between Experiments and CFD Analyses*

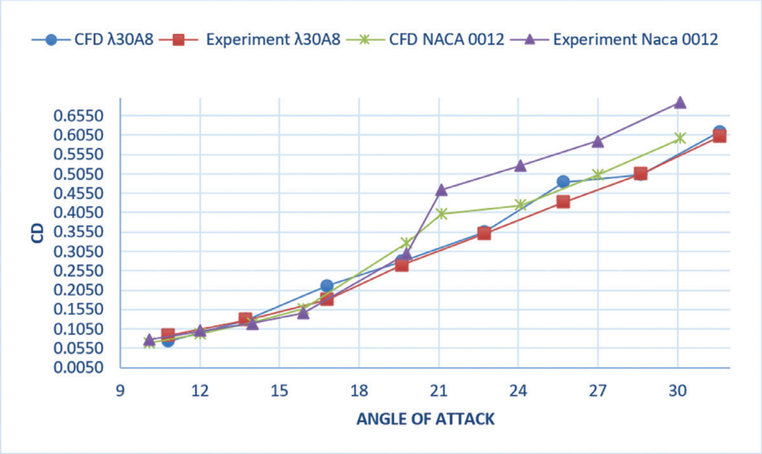

Figure 4. *Comparison of C_D Between Experiments and CFD Analyses*

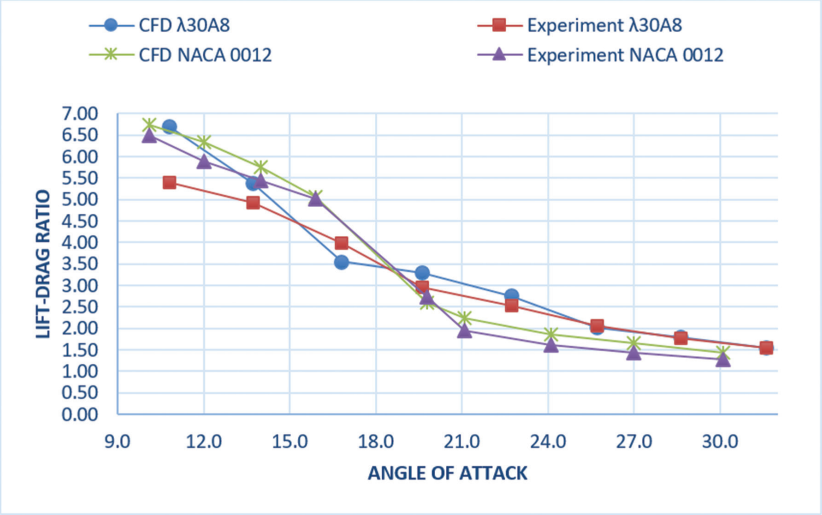

Figure 5. *Comparison of Lift to Drag Ratio Between Experiments and CFD Analyses*

3.2. Wing Sail Analyses

Geometry of the wing sail to be investigated in this study is designed according to the 2013 America's Cup rule. In the rule book, wingspan is divided into 12 segments and maximum-minimum chord lengths are restricted between certain values [13]. Also, total sail area of wing including main element and flaps needs to be between 255 and 260 square meters. Rule permits teams to design and experiment on their own profile selection and number of flaps. For the Emirates Team New Zealand, Collie et al [14] investigated effects of element number on performance and concluded that increase in element count also increases downwind performance while having negligible effects on upwind performance. Nevertheless, all teams adopted two element wing sail with one main element and one flap due to several reasons; main one is after 2 elements, increase in performance gradually becomes smaller while controlling the boat becomes practically too challenging for the crew.

As mentioned previously, slot width between main element and flap plays important role on the multi element wing sail performance. Chapin et al [15] indicate that this gap dimension alters the wake and boundary layer interaction, causing an unsteady coupling between wing elements. Also, in the same study 2D URANS analysis had been executed on 1/20 scale AC72 wing sail section and performance of wing decreased with increasing slot width which is a function of chord length [15]. Viola et al [16] constructed similar analysis in their paper and determined optimum gap dimensions.

Final wing sail design for this study has been obtained from Kemali [17] and can be seen on Figure 6. NACA 0025 and NACA 0009 airfoil sections are selected for main element and flap respectively according to Blakely et al [18]. Total sail area of the sail is 257 square meters and rotation angle of flap is fixed to 20^0 for all analyses. Gap dimensions are selected as 0.02c and 0.015c for x and y directions respectively.

As a first step for the wing sail analysis, sinusoidal tubercles are placed on a plain wing sail, then wavelength and amplitude of undulations systematically changed to construct test matrix for the study. Figure 7 shows totally 6 different wing sails with

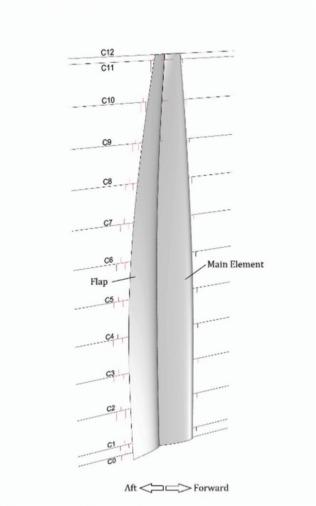

Figure 6. *Final Geometry of Plain Wing Sail for Analysis [17]*

different tubercle dimensions. Wavelength and amplitude of tubercles changed as a function of bottom chord length of the final wing sail. Final test matrix can be seen on Table 2.

All analyses are executed at 1/10 scale since available computer power does not permit full scale calculations due to substantial increase in mesh number to correctly model boundary layer with trimmer mesh and prism layer mesher in Star CCM+. In full scale, boat speed is considered as 12 knots which is approximately taken as 6 m/s. In 1/10 scale speed is calculated 60 m/s with Re similarity. In this configuration Re is 1.5×10^6 and boundary layer thickness δ is approximately 8mm. Dimensionless wall distance y+ in wing sail analyses is adjusted as 10, same as in validation study.

Second step in wing sail analyses is comparing the base plain wing sail with modified wing sails. For the performance comparison, C_L and C_D as well as L/D ratio are investigated. As a beginning, plain wing sail's lift coefficient, drag coefficient and lift to drag ratio is measured in CFD with different angle of attacks ranging

Table 2. *Test Matrix for Wing Sail Analysis with Tubercles*

Test No	m.	λ (c)	m	A (c)	Name
1	0.12	0.3	0.006	0.015	L30A15
2	0.12	0.3	0.017	0.045	L30A45
3	0.15	0.4	0.006	0.015	L40A15
4	0.15	0.4	0.017	0.045	L40A45
5	0.19	0.5	0.006	0.015	L50A15
6	0.19	0.5	0.017	0.045	L50A45

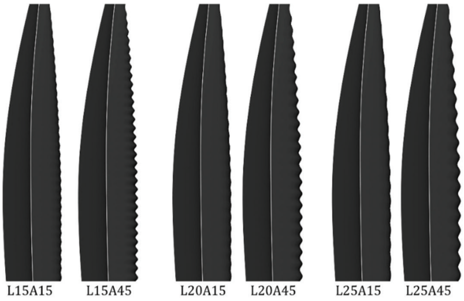

Figure 7. *Developed Wing Sail Geometries with Tubercles on Leading Edge [17]*

from 14 to 32 degrees. It has been observed that stall angle is approximately 26 degrees. Therefore, modified wing sails with tubercles are tested in CFD at angle of attacks 23 and 30 degrees to see performance change in pre-stall and post-stall regimes. Best results are achieved with largest wavelength and smallest amplitude tubercles in test matrix. Comparison of coefficients between different wing sails can be seen on Table 3.

As a final step, this best performing wing sail with tubercles is compared with plain wing sail in all angles of attack between 14 to 32 degrees with incremental step of 2 degrees. Therefore, characteristics of both wing sails can be compared more thoroughly in all regions of apparent wind angle of attacks.

Comparative results of wing sails with and without tubercles are given in Figure 8-10 respectively. In Figure 8, lift coefficients of the base sail and best performing wing sail with tubercle is presented. It is seen that the tubercles do not influence the lift generation tendency in the pre-stall regime. The stall angles are approximately identical. The gain in lift generation is achieved in the post-stall regime; the wing sail with the tubercle creates more lift force. In other words, the reduction in lift force is lesser for the wing sail with the tubercle.

Figure 9 shows the drag coefficients of both sails. It is seen that a marginal increase in drag coefficient is observed in the post stall regime due to the extra lift generation. This results an increased efficiency (L/D ratio) in the post-stall regime as depicted in Figure 10.

Table 3. *Comparison of Coefficients Between Wing Sails at 23 and 30 Degrees of AoA*

	Straight	L30A15	L30A45	L40A15	L40A45	L50A15	L50A45
AoA	CL	CL	CL	CL	CL	CL	CL
23	1.465	1.478	1.472	1.468	1.465	1.456	1.455
30	0.940	1.142	1.145	1.146	1.141	1.170	1.182
AoA	CD	CD	CD	CD	CD	CD	CD
23	0.157	0.153	0.155	0.154	0.154	0.155	0.155
30	0.321	0.365	0.322	0.383	0.378	0.315	0.326
AoA	L/D	L/D	L/D	L/D	L/D	L/D	L/D
23	9.331	9.660	9.497	9.532	9.513	9.394	9.387
30	2.928	3.129	3.556	2.992	3.019	3.714	3.627

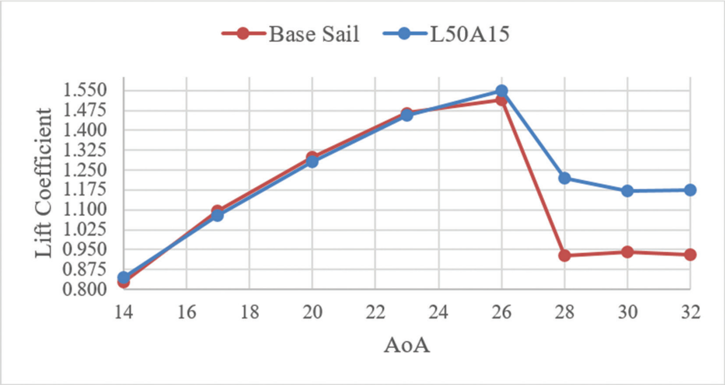

Figure 8. *C_L Comparison*

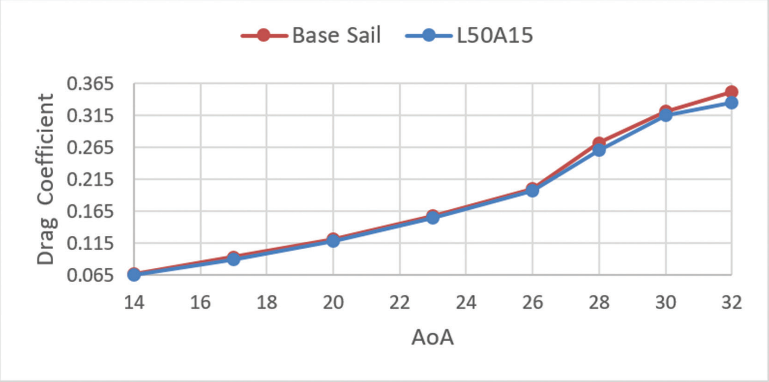

Figure 9. *C_D Comparison*

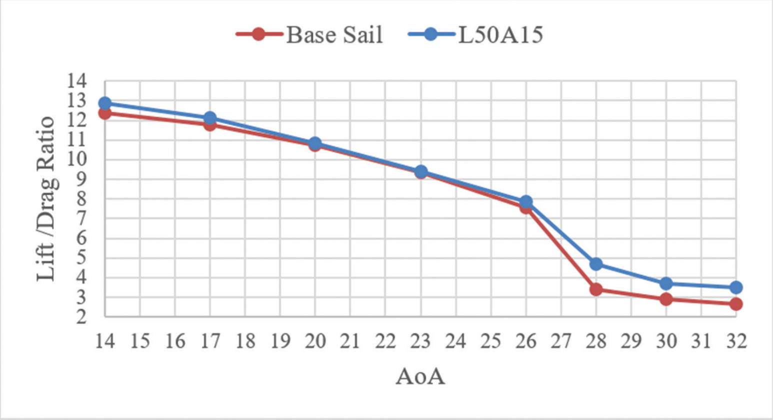

Figure 10. *Lift/drag Ratio Comparison*

4. Conclusions

Tubercle geometry on the leading edge increased wing sail performance as expected after post-stall regimes by increasing lift/drag (L/D) ratio compared to plain wing sail. Stall angle remained same with modified wing sail with tubercles while increasing L/D ratio after stall angles and having negligible negative effect in pre-stall regime. In small angles of attack performance almost remained same between two wing sails.

To increase performance of AC72 boat which mostly sails in upwind condition, improving speed made good (the vector component of the velocity towards the direction of the wind) has a significant importance. Delaying stall angle and improving performance in post-stall regime contributes to this performance increase of speed made good. Therefore, better wing sail with optimized leading-edge tubercles is expected to enable AC72 boat to complete racecourse in shorter time than other competitors with plain wing sails due to its better performance in these regions. The wing sail with tubercles, utilized in this study has slightly better performance at stall angle of attack and significantly better performance in post-stall regime.

Since determining optimum tubercle dimension for best performance increase without affecting pre-stall behavior of wing is an optimization problem, excessive amount of analyses is required to achieve detailed and meaningful outcomes. One way of overcoming this situation is using artificial neural networks and machine learning. By this method, a specific written computer code can learn performance change and generate consistent results after certain amount of analyses, since it can learn behavior and response of wing changing tubercle dimensions.

Another future study can be done on a Velocity Prediction Program (VPP) and assessing time gains of AC72 boat with tubercle geometry wing sails more especially in upwind sailing.

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