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The Effect of the Addition of Tubercles on the Performance of Moth-T-foil

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Abstract:

Tubercles have proven, in the nature (e.g., the humpback whale) as well as in engineering (e.g., rudders, wind and tidal turbine blades, propellers, etc.), to be an efficient device to control the flow and to delay stall. This study focusses on the implementation of tubercles on the main lifting foil of a moth sailing dinghy. To do so, a ‘’Bladerider’’ flapped T-foil with and without tubercles was tested in the Kelvin Hydrodynamics Laboratory in Glasgow, at a range of speeds, angles of attack, flap angles but also immersions. The results of these full-scale tow-tests, including the lift and drag data of the bare foil, are presented in this paper. The measurement data was used to investigate the effect of the addition of tubercles on the performance of a T-foil.

Keywords: Hydrodynamics; Hydrofoil; Moth; Tubercles; Biomimicry.

Figure 1 - Moth Worlds 2017 (Photo: Martina Orsini, Cat Sailing News)

Nomenclature

D [N]	Drag Force
DA [m^2]	Drag Force Area
L [N]	Lift Force
LA [m^2]	Lift Force Area
V [m/s]	Speed
ρ [kg/m^3]	Density

Other symbols are defined as required in the text.

1 INTRODUCTION

Nature is a great source of inspiration to create substantial, innovative designs and applications to solve human challenges in a variety of fields. In the energy, aero- and hydrodynamic sectors, some of the most common nature-inspired designs come from the humpback whale (Megaptera Novaeangliae, *Figure 2*); a 40-50 feet long baleen whale weighing 80,000 pounds which has been studied extensively over the last two decades due to its advantageous maneuverability and agility capabilities. In fact, its surprising dexterity is attributed, in part, to its high aspect ratio flippers, which have distinctive bumps, so called tubercles, on the leading edge (LE).

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Figure 2 - Humpback Whale Flippers with Tubercles (Photo: AAP, The Guardian)

These large and irregular protuberances are believed to act as passive flow control devices *(Fish & Battle, 1995)* and have proven to delay flow stall and maintain lift over a greater range of angles of attack (AoA) *(Miklosovic, Murray, Howle, & Fish, 2004)*. Indeed, (*Miklosovic & al. 2004)* have shown through wind tunnel experiments, that the addition of leading-edge tubercles to a scale model of an idealized humpback whale flipper delays the stall angle from 12 to 18 degrees, while increasing lift by approximately 8% and decreasing drag by nearly a third.

According to (*Fish & al. 2006, 2011)*, this is explained by the deflection of the fluid approaching the LE into the throughs and the generation of steamwise vortices. In fact, the tubercle leading edge (TLE) is believed to act as a vortex generator (i.e., similar to those used on aircraft); the wave-shaped vortices, seen in *Figure 3*, energise the fluid flow by adding momentum within the boundary layer. This results in the flow remaining attached and therefore stall to be delayed.

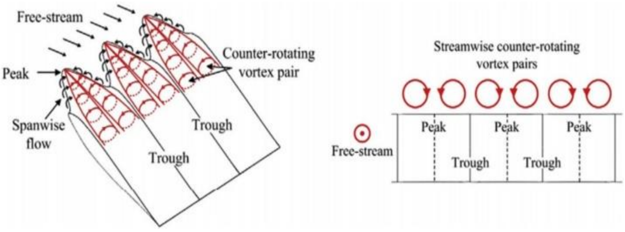


Figure 3 - Vortex Structures Resulting from the Leading-Edge Tubercles (Shin & al., 2018)

On the other hand, (*Van Nierop & al. (2008)* suggested that the tubercles essentially alter the pressure distribution on the foil so that the flow does not separate in the close proximity of the leading edge. However, their research led to different results than *Miklosovic & al.'s (2004)* (e.g., smaller maximum lift coefficient and and a less sudden stall). According to *Zhu (2008)*, these are due to the neglection of the tip effects but also the application of the potential flow theory of an inviscid and irrotational flow to a rotational flow problem *(Aftab al., 2016)*.

So even though the working mechanism of tubercles, as well as their optimum configuration, have still not been clearly understood, their implementation into the engineering domain has proven to be effective (i.e., by improving lifting surface performance) and economically feasible *(Pechlivanoglou, 2012)*. Indeed, Juan Kouyoumdjian has for example designed a dual tubercle rudder system for the ClubSwan 50 sailing yacht whereas WhalePower has integrated tubercles on the LE of wind-turbine and fan blades as seen in *Figure 4*. In fact, by using this technology, WhalePower has managed to significantly increase their efficiency by capturing more energy out of lower-speed winds (i.e., TLE ‘‘turbines generate the same amount of power at 10 miles per hour that conventional turbines generate at 17 miles per hour’’) *(Hamilton, 2008)*.

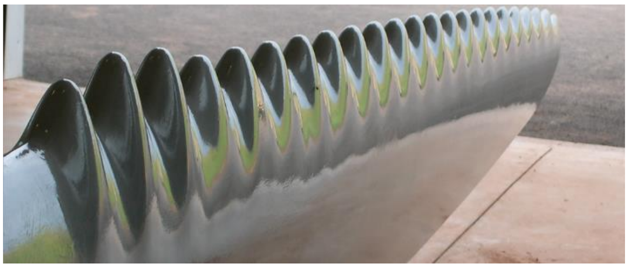


Figure 4 - WhalePower Wind Turbine (Photo: Whalepower, Earth Magazine)

It is clearly believed that the benefits of tubercles could be implemented into the design of other lifting devices and more exactly into the design of foiling vessels (i.e., sailing yacht, high speed, or support vessels). Indeed, even though hydrofoils have an old history, their evolution is still to be discussed as their use in a field such as the maritime transportation, which is driven by speed and energy efficiency, is of critical importance. This is why, this study focusses on experimentally investigating the effects of tubercles on the performance of a hydrofoil and more exactly on a Moth sailing foil. The results of these findings could then be applied and extended to any other application involving the generation of lift from an airfoil or hydrofoil and obviously to any future design of foiling vessels.

The International Moth dinghy *(Figure 5*) is actually one of the most advanced boat classes in the world, capable of reaching speeds of over 30 knots. It was invented by Len Morris in 1928 and since then has evolved to a carbon-fibre mono-hull fitted with two fully-submerged T-foils on the centreline (i.e one on the centreboard for primary support and the other on the rudder for support and control).

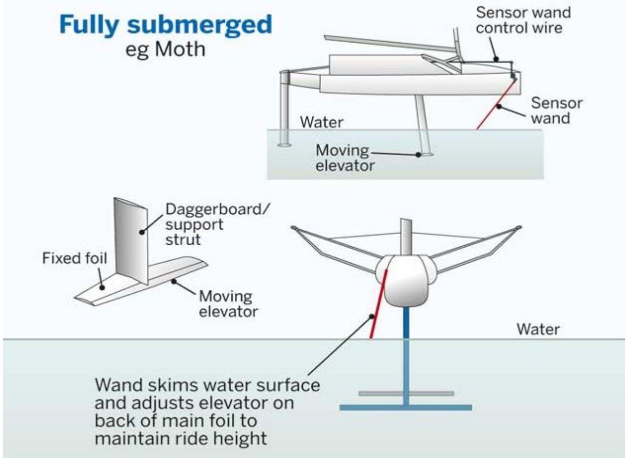


Figure 5 - Moth Foil Configuration (Photo: Yachting World)

These twin foils are capable of generating a lift that is large enough to raise the hull out of the water. Both foils have an elevator flap which is used to vary the camber of the foil. The daggerboard flap actually controls the ride height mechanically thanks to a bow-mounted wand sensor whereas the rudder one is controlled by the skipper via a rotating tiller extension.

For this purpose, the main foil of a Moth was used and fitted with 3D printed LET. This enabled to obtain experimental measurements of flapped T-foils but also to quantify the difference in the performance of the foil with and without tubercles.

2 TANK TESTING

This paper documents a series of full-scale tow-tests intended to investigate the effect of incorporating LET onto a ‘‘Bladerider’’ flapped T-foil. It was processed in two stages at the Kelvin Hydrodynamic Laboratory (KHL) at the University of Strathclyde (UoS) in Glasgow, Scotland.

The first stage was conducted in early 2018 as part of a Bachelor project aiming at studying the effect of tubercles on the performance of a foil. It enabled to commission a test rig as well as develop a valid procedure for testing flapped T-foils in a towing tank. Indeed, it was used to troubleshoot the test set-up in order to, at a later stage, with the combination of Computational Fluids Dynamics (CFD), investigate some of the complex flow phenomena associated with flapped T-foils. These include the interaction between the flow on the horizontal and vertical components of the foil, the free surface effects, the effects of the change of immersion, the effects of heel, yaw and tip immersion, ventilation, etc.

This was part of Stage 2 even though it will obviously be required to conduct more experiments in the future. Thus, the second stage took place in late 2018 and was also used to deepen the study of the effect of the addition of tubercles, which is presented in this paper. Both stages were, however, conducted using different 3D printing materials. More information is enclosed in the ‘‘Tubercles’’ sub-section.

The technique used during these experiments, including the building of the rig, was inspired by (*Beaver & Zseleczky, March 2009)*. They carried out an extensive study of the aero- and hydrodymanic flow aroud a Moth dinghy they designed and built, the ‘‘Hungry Beaver’’, considering different hydrofoil configurations.

2.1 Moth ‘Bladerider’

As mentioned earlier, as part of this project, the main (i.e., dagger board) foil of a ‘‘Bladerider’’ International Moth sailing dinghy (2006), as seen in *Figure* 6, was used. This foil belongs to one of the authors and was utilized mostly due to its availability but also because it invites comparison with the ‘‘Vendor 1’’ foil from (*Beaver & Zseleczky, March 2009)*. It is composed of two components made from carbon skins and a foam core: a vertical symmetrical strut and a horizontal assymmetric tip tapering lifting foil. These are joint together using a silicone-based sealant and reinforced by a squashed bulb. The flap, on the other hand, is attached to the foil thanks to a hinge composed of black rubber and represents around 35% of the chord of the lifting foil.

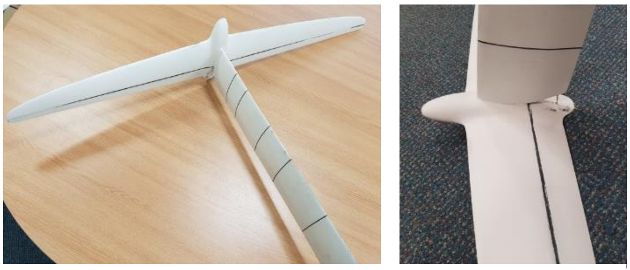
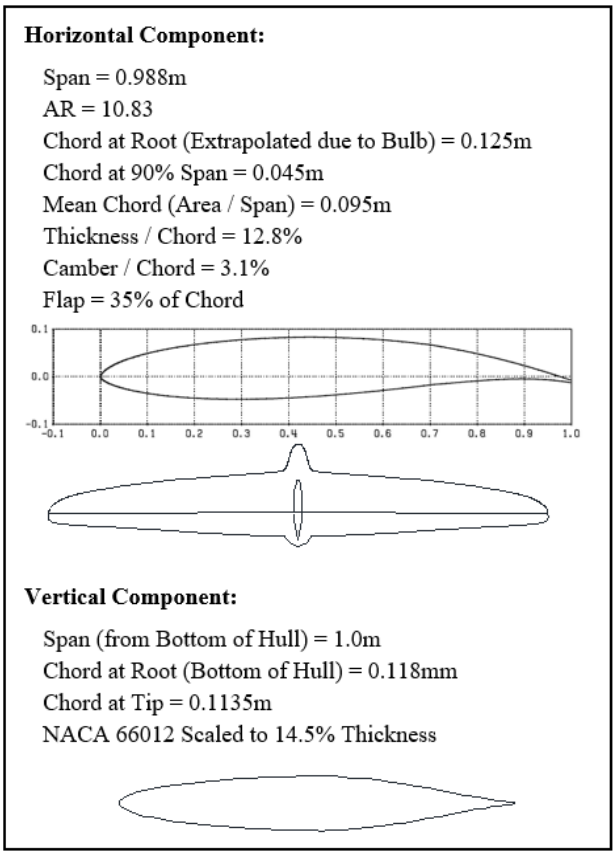


Figure 6 - ''Bladerider''-type Foil

The geometry and the main dimensions of the foil are shown in *Figure 7*. Because the sections of the foil were unknown and not published, the geometry and the main dimensions of the foil, including the wing profile, were derived from the digital representations of the hydrofoil. These 3D-scans were performed using the Advanced Forming Research Centre (ARFD). They enabled the authors to derive sections and to remodel the foil using the 3D-modeler Rhinoceros 5 for conducting Computational Fluid Dynamics (CFD) simulations to study the complex flow phenomena associated with flapped T-foil. The foil jigs, which are used to hold the flap at a neutral position when the hinge has to be renovated, were also utilized to obtain the main dimensions and the section shapes.



Horizontal Component:

Span = 0.988m
AR = 10.83
Chord at Root (Extrapolated due to Bulb) = 0.125m
Chord at 90% Span = 0.045m
Mean Chord (Area / Span) = 0.095m
Thickness / Chord = 12.8%
Camber / Chord = 3.1%
Flap = 35% of Chord

Vertical Component:

Span (from Bottom of Hull) = 1.0m
Chord at Root (Bottom of Hull) = 0.118mm
Chord at Tip = 0.1135m
NACA 66012 Scaled to 14.5% Thickness

Figure 7 - ‘‘Bladerider’’ Dagger-board T-foil Geometry and Dimensions

2.2 Tubercles

The tubercles were designed in a way that they could be attached and detached from an existing appendage easily. This was done by designing tubercles with flexible, thin but strong arms. In fact, the tubercles which are shown in Figure , were designed in a 'Taco' shape, which basically consists of two components: the arms and the protuberance. *Table 1* shows the specification of the tubercles.

Table 1 - Tubercle Specifications

Length (Extreme)	40mm
Height (Extreme)	9.2mm
Arm Thickness	0.5mm
Protuberance Wavelength	50mm
Protuberance Amplitude	11mm

During the first set of experiments (i.e., Stage 1), in early 2018, the tubercles were printed with a combination of ''TangoBlack'' and ''Tango Plus'' material (i.e., which acts as printed rubber) using a ''Object Eden 350'' printer at the Design, Manufacture and Engineering Management (DMEM) department at the UoS. However, because the tubercles, including the protuberance, were too flexible and showed signs of distortion under the loads applied and probably deformation (i.e., leading to a large drag penalty), another material, ''PolyLactitic Acid'' (PLA), was used for the second set of experiments (i.e., Stage 2). This enabled to enhance their rigidity and was done using an ''Ultimaker 2+ Extended'' printer owned by one of the authors.

A first attempt to apply the tubercles was done using ''Copydex'', a white water-based glue, but was replaced by silicon adhesive as it failed. Silicone adhesive was in fact judged as more appropriate as it enabled to smoothen the lips of the tubercle arms.

To have a better understanding of the effects of tubercles, it was decided to test different configurations of tubercle coverage during Stage 1. Indeed, three different configurations were tested: no tubercle coverage, one third tubercle coverage (i.e., 3 tubercles were fitted on each side of the foil, close to the tips) and full tubercle coverage (i.e., 8 tubercles were fitted on each side of the foil).

On the other hand, during Stage 2, only the full tubercle coverage, as seen in *Figure 8*, was investigated, as it proved to be the configuration with more effects on the performance of the foil.

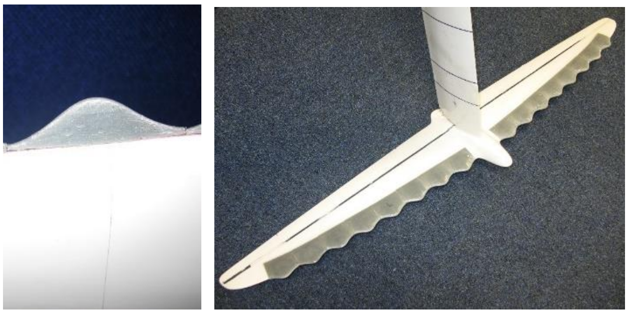


Figure 8 - Foil with Full Coverage of Tubercles

2.3 Test Rig and Instrumentation

As mentioned earlier, the tests took place in the Kelvin Hydrodynamics Laboratory (KHL) at the UoS in Glasgow; a 76m long, 4.6m wide and 2.5m deep tank equipped with a towing carriage of a maximum speed of 4.6m/s. The foil was tested upright in different conditions. Indeed, angles of attack (pitch/ trim), flap angles but also immersion were varied at a range of speed to experimentally measure their effect on lift and drag. On the other hand, tubercles were fitted to the appendage to investigate their effect on the performance of the foil.

The rig used during these experiments, a bespoke test rig shown in *Figure* , was inspired by (*Beaver & Zseleczky, March 2009). It* was restricted to zero yaw and zero roll conditions. In fact, the rig was built in a way that the foil could be mounted in a pivoting frame (i.e., which was rotating thanks to a pitch angle adjustment plate attached to the fixed part of the rig) and supported by two softwood moulds/ saddles at two points along its vertical component. These were used to adjust the angle of attack (AoA) of the horizontal foil (i.e., in one degree of increments over a range of 15 deg.) but was also an easy way to vary the immersion (i.e., by sliding the foil up and down in the saddles). On the other hand, the flap angle of the horizontal foil was controlled using the original rod/ bell crank in the strut and an extended pointer/ needle which enabled a more accurate measurement at the top of the foil. This is shown in *Figure 9.*

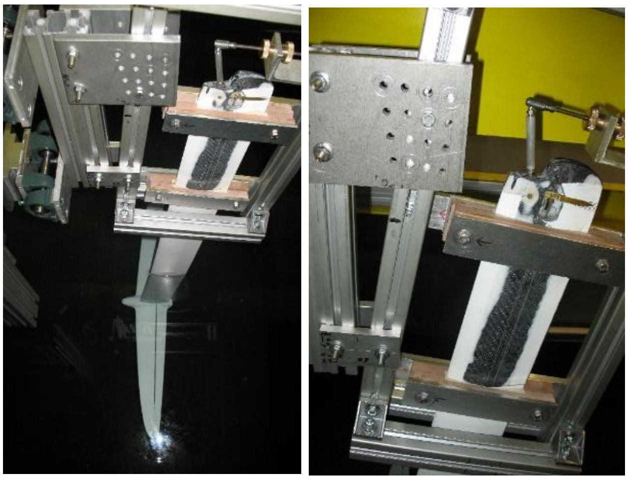


Figure 9 - Towing Tank Test Rig

The rig was then fitted to the vertical member of the standard towing post using a rig support which could be regarded as a classical simply-supported beam mounted in the vertical direction. Indeed, it was constitued of two tri-axial loadcells (i.e., with a maximum measurable load of 250kg) attached to two mounts with a bearing releasing moments in the pitch axis and for the upper mount, a low friction slide (i.e., to release the vertical force). These loadcells were calibrated individually along the X, Y and Z directions, so the cross-coupling error could be determined.

A total of close to 450 tests (i.e., including repeats) were carried out during stage 2 whereas close to 145 tests were performed during the first one. It followed a straighforwardprocedure as once the different conditions (i.e,. the immersion, the AoA, and the flap) were set, it was only necessary to accelerate the carriage up to required speed in order to measure the load in the cells (i.e. lift and drag in the X and Y directions respectively). *Figure 10* shows the foil without (left) and with (right) tubercles during the tests.

Figure 10 - Towing Tank Experiment (Stage 2)

In fact, the tests were performed with a range of speed from 0.5 to 4.5m/s, close to the maximum speed the carriage can achieve (i.e., corresponding to Reynolds numbers of $2.0 * 10^4$ to $1.8 * 10^5$). This obviously did not replicate the operational speed of a Moth in foiling conditions but was deemed satisfactory for this study as it corresponds to a speed slightly higher than the take-off speed (i.e., around 3.5m/s). It also enabled to gain some insight into the hydrodynamics of foil and tubercle technology.

During the second set of experiments (i.e., Stage 2), most of the tests were actually conducted at a submergence of 457mm. This was chosen in accordance to (*Beaver & Zseleczky, March 2009)* but also because it corresponds to a relatively appropriate depth for Moth take-off, knowing that the maximum speed which could be achieved with the carriage was 4.5 m/s. On the other hand, it was found to be convenient because it reduced the impact of wave-making and free surface effects on the horizontal foil. Other tests were carried out at an immersion of 100mm and 334mm (i.e., the speed believed to be the optimum depth for this foil) to explore the effects of immersion but also to compare the results to the first set of experiments conducted in early 2018.

Regarding the flap angle, it was decided to study the effect of positive and negative angles on the performance of the foil. This is why it was changed from -6 to +6deg. The AoA, on the other hand, was adjusted from 0 to +6deg. The test matrix of the first set of experiments is shown in *Table 2* whereas the text matrix of the second slot of experiments' is enclosed in *Table 3*.

Table 2 - Test Matrix (Stage 1)

Test Characteristics	**Immer-sion**	**Speed**	**AoA**	**Flap**
Tests 001 to 054 (w/o Tubercles)	334mm	0.5 to 4.0m/s in increments of 0.50m/s	0, 2 and 5deg.	0, 3.2 and 6.4deg.
Tests 055 to 099 (1/3 Tubercle Coverage)	334mm	2.0, 3.0 and 4.0m/s	0, 2 and 5deg.	0, 3.2 and 6.4deg.
Tests 100 to 143 (Full Tubercle Coverage)	334mm	2.0, 3.0 and 4.0m/s	0, 2 and 5deg.	0, 3.2 and 6.4deg.

Table 3 - Test Matrix (Stage 2)

Test Characteristics	**Immer-sion**	**Speed**	**AoA**	**Flap**
Tests 001 to 024 (w/o Tubercles, Deep Immersion, Neutral Flap)	457mm	0.5 to 4.5m/s in increments of 0.25m/s	0 to 6deg. in steps of 1deg.	0deg.
Tests 025 to 322 (w/o Tubercles, Deep Immersion, Different Flap Angles)	457mm	0.5 to 4.5m/s in increments of 0.50m/s	0 to 6deg. in steps of 2deg.	-6, 0, +6deg.
Tests 323 to 347 (w/o Tubercles, Optimum Submergence, Different Flap Angles)	334mm	2.5 to 4.5m/s in increments of 0.50m/s	0, 2, 5deg.	0, +6deg.
Tests 348 to 405 (w/o Tubercles, Shallow Immersion, Different Flap Angles)	100mm	3.0 to 4.5m/s in increments of 0.50m/s	0 to 6deg. in steps of 2deg.	-6, 0, +6deg.
Tests 406 to 441(With Tubercles, Deep Immersion, Different Flap Angles)	457mm	0.5 to 4.5m/s in increments of 0.50m/s for AoA 0 Flap 6, AoA 6 Flap 0 and AoA 6 Flap -6 and from 3 to 4.5m/s for others	0 to 6deg. in steps of 2deg. 0 to 6deg. in steps of 2deg. for Flap 0 and only 6deg. for Flap -6deg.	-6, 0deg.

It is important to note that the zero position of both the AoA of the horizontal and the angle of the flap were difficult to determine as they are specific to the foil arrangement/ assembly. For this foil, it was assumed that the strut was raked forward at around 7 deg. (i.e., 7deg. of pitch on the strut corresponds to 0deg. of pitch on the foil horizontal). This is usually done using shims before bonding the two components together to reduce the risk of ventilation. On the other hand, the natural resting point of the horizontal, when it is not under load, was taken as the neutral flap angle. During some tests (i.e., at high speed and large AoA/ flap angle) of Stage 2, it was noticed that the needle indicating the flap angle moved. This was associated with the bending of the slender push rods which controls the flap inside the strut and was videoed to be estimated.

3 EXPERIMENT RESULTS

This section compares the lift and drag results of the bare foil and the foil with tubercles of Stage 2. The results of Stage 1 are, on the other hand, just briefly explained but not extended. However, a comparison of both stages is included.

For this purpose, the results of the experiments are shown in terms of lift and drag areas (i.e., see equations (1) & (2)). This was judged as being more convenient as it did not require the decomposition of the forces between the horizontal and the vertical components of the foil (i.e., which have different chords, thicknesses and areas) but also because it enables to correct the issue with the flap that occurred during the tests (i.e., the flap angle moved under load especially at high speed, high AoA and high flap angle, which are however not realistic conditions for Moths). The lift to drag (areas) ratio, on the other hand, assesses the performance of the foil.

$$LA = \frac{D}{\frac{1}{2}\rho V^2}\,(1)$$

$$DA = \frac{D}{\frac{1}{2}\rho V^2}\,(2)$$

Other conclusions regarding the general trend of the lift and drag, the performance of the foil and the effect of immersion are not included in this paper but were discussed in *(Day , Cocard, & Troll, March 2019).*

3.1 Tubercles Effects

The lift and drag (area) results of the bare foil (BF) and the foil with the full coverage of tubercles (FT) over speed are shown in

Figure 11 and *Figure 12*. The empty markers show the results of the foil with tubercles whereas the full ones correspond to the foil without tubercles.

It clearly shows that for all conditions, except from the low speed (i.e., up to 1.5m/s) at zero AoA and zero flap, the retrofitting of LET results in a penalty in drag. This could be related to different reasons. One of the most obvious ones is the increase in skin friction resulting from the additional surface area of the tubercles. On the other hand, it could also be a consequence of the surface finish of the tubercles or the smoothness of the assembly. Indeed, both were just a prototype, and it was possible to see that the tubercles were rougher than the gelcoat of the foil but also that a rough edge, coming from the arms of the tubercle and the silicone adhesive, could be felt. They could have affected the flow over the leading edge of the foil.

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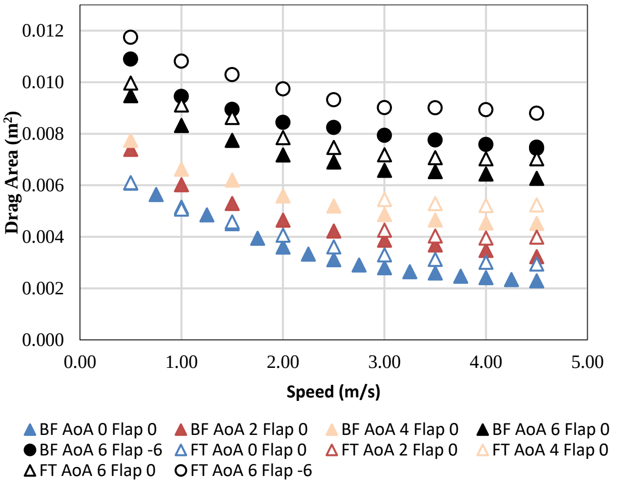

Figure 11 - Drag Area Comparison of Bare foil (BF) and Foil with Full Coverage of Tubercles (FT) (Stage 2)

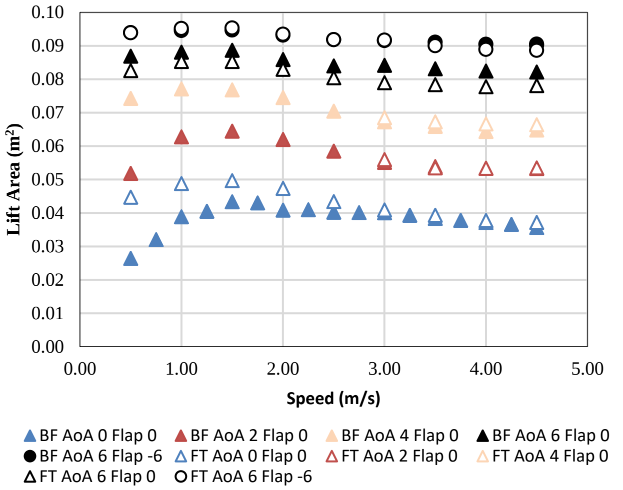

Figure 12 - Lift Area Comparison of Bare foil (BF) and Foil with Full Coverage of Tubercles (FT) (Stage 2)

On the other hand, it can be seen that fitting tubercles have a beneficial effect on the lift over the entire speed range for angles of attack up to four deg. for the zero flap conditions. Indeed, for these cases, lift increases and especially at low speeds (0 to 2.5m/s). This is clearly shown for the zero AoA case, in which the lift significantly improves up to 40% at 0.5m/s. On the contrary, for higher speeds, it only increases slightly.

The improvement in lift associated with the drop in drag results in a better performance of the foil with tubercles at low speed (i.e., up to 2m/s), as *Figure 13* demonstrates. On the contrary, at higher speed, the bare foil performs better. Actually, the performance of the foil with tubercles degrades with speed. This is due to the fact that, as speed increases, the drag penalty becomes too important and outweighs the lift generated.

At large AoA, tubercles seem to result in a drop of lift over the full range of speed whereas, at high AoA and high flap angles, tubercles do not seem to have an important effect on lift. In fact, at the lowest speeds, the foil with tubercles seem to produce more lift whereas at higher speed the bare foil produces more.

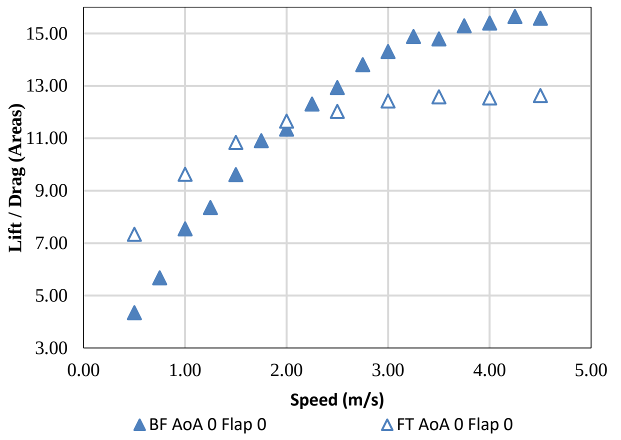

Figure *13* - Lift/Drag (Areas) Comparison of Bare foil and Foil with Full Coverage of Tubercles (Stage 2)

3.2 Stages 1 & 2 Comparison

As mentioned earlier, some of the conditions of the first set of experiment (i.e., corresponding to the 334mm immersion without tubercles) were repeated during the second stage to compare the results of both stages. This was done for the bare foil as the effect of tubercles was studied at a deeper immersion during stage 2 (i.e., 457mm compared to 334mm).

In general, there was a good agreement between the results of both stages. Indeed, the same conclusions could be drawn concerning the effect of tubercles even though the material used was not the same (i.e., the tubercles used during stage 2 were more rigid). However, it was observed that both the lift and drag forces observed during stage 2 were smaller than during the first stage. Indeed, a difference of up to 73 % in drag and 62 % in lift at neutral flap could be observed. This is shown in *Figure 14*.

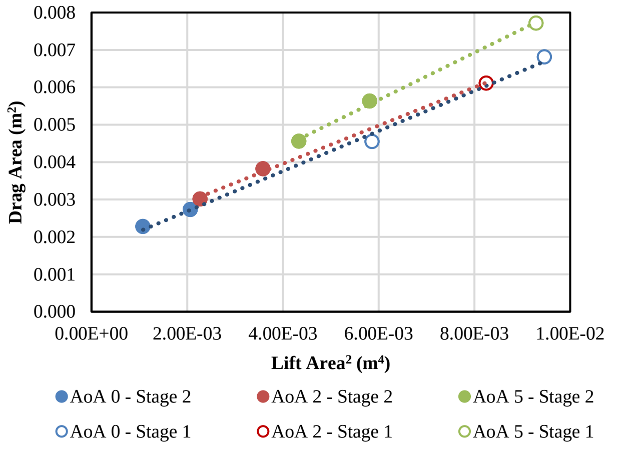

Figure 14 - Stages 1 & 2 Results Comparison

This graph shows the drag area versus the lift area of Stages 1 (i.e., solid markers) and 2 (i.e., empty marker) for the 4.0m/s condition. The first point of each case corresponds to the zero-flap condition whereas the second one (i.e., when applicable) corresponds to the six-deg. flap angle. It clearly shows that the results of both stages are quite aligned. On the other hand, the lift to drag ratios are relatively close for both sets of experiments (around 2 to 3 % at neutral AoA). This is why the difference in lift and drag is believed to result from a change in flap or AoA. Hypothetically, this could be related to the fact that the zero position of the AoA of the horizontal and/ or the angle of the flap used during both stages were not the same. Indeed, even though the hinge has not been refurbished between the two stages, the foil was used to sail. Therefore, the natural resting point of the horizontal, which was taken as the neutral flap angle, could have changed and induced some uncertainities.

4 CONCLUSIONS

Because tubercles have proven to successfully improve the efficiency of foils (i.e., blade, rudder, etc.), it was decided to study their implementation onto a Moth hydrofoil. From this study, it was found out that tubercles only improve the performance of the foil at low Reynolds Number and are, therefore, in no way beneficial for high performance foil such as the Moth foil. Indeed, such foils only perform at high speed, and it appears that at high speed, tubercles result in a large increase of drag which outputs the gain in lift. On the other hand, it was not possible to study their effect on the onset of stall and post stall regimes because these conditions could not be achieved due to the limitations of the foil, test rig, and loadcells; the maximum AoA at which the tubercles could be tested was 6deg., angle at which flow separation does not usually occur.

On the other hand, these experiments gave some valuable insights into the advantages and limitations of LET technology as it showed the conditions at which tubercles have the greatest impact. Indeed, it was clearly proven that tubercles only have a beneficial impact (i.e., by increasing the lift) at low AoA and flap angles. In fact, the greatest improvement was shown at zero pitch angle and was less substantial as the AOA of the horizontal increases.

Further studies on the effect of tubercles could be accomplished using CFD analysis. This would enable to understand if the increase in drag of the foil with tubercles is related to the material of the protuberances or the surface finish. It would also help to understand properly the flow interaction.

On the other hand, this study shows the success of using 3D printing to implement LET on an existing appendage. Indeed, the manufacturing process of the tubercles has proven to be satisfactory and therefore this technology has proven to be a cost-friendly testing approach to modify an existing model even though it would require some improvement (i.e., material, surface finish, assembly, etc.).

Finally, it enabled to design, build, and test an appropriate rig as well as develop an effective experimental procedure to study flapped T-foils. It also enabled to obtain a benchmark data set for analysis of flapped T-foils.

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