"Can a Flapless Hydrofoil Provide a Realistic Alternative To a Standard Moth Foil With a Flap?"

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Abstract

*Moth sailing dinghies are the first class to use hydrofoils throughout their fleet. The current main foil used on the moth has been fitted with a trailing edge flap, with a length of 30% of the chord. In 2006 Dr Ian Ward designed the first pivoting foil with an axel fitted at the quarter chord. This journal paper investigated the performance of a pivoting foil in comparison to a flapped foil. In order to compare the performance of the foils, numerical simulations were carried out and compared to experimental results. The experimental testing was carried out on a moth with full scale foils fitted and sailed at a range of True Wind Angles (TWA). During the tests, the boat speed was recorded at each heading in order to produce polar plots. The numerical simulation was carried out in a Velocity Prediction Program (VPP) called FS-Equilibrium. The simulation was carried out with a four degrees of freedom force balance. The wind strength was 8 m/s for experimental and numerical simulations. There was a variation between experimental and VPP results, with the un-flapped foil having the greatest boat speed in experiments and the flapped foil having the greater boat speed in the VPP. This variation was due to not all forces and moments been considered in the 4 degrees of freedom numerical model and turning manoeuvre's unable to be filtered from experimental results.***

Keywords: *Moth, Hydrofoil, Experimental, Velocity Prediction Program, Lift and Drag*

1. Nomenclature

Symbol	***Definition***	***Units***
C_l/C_d	Lift/Drag Coefficients	-
GPS	Global Positing System	-
h/c	Depth To Chord Ratio	-
TWA	True Wind Angle	*Degrees*
VPP	Velocity Prediction Program	-

2. Introduction

Sailboats fitted with hydrofoils have seen major advances over the last twenty years. The international moth class has been at the forefront of this development with world championships attracting over one hundred foil borne craft. The earliest developments were based around a tri-foiler concept and then evolved to a bi-foiler arrangement mostly developed by John Illett in Western Australia (Culnane, 2013)**.**

In this study two types of fully submerged T-Foil hydrofoils used on a moth sailing dinghy were analysed to see which provides the optimum performance. The first foil was fitted with a flap that was located on its trailing edge at a distance of 30% of its chord length. The second foil was un-flapped and incident controlled by an axel fitted at quarter chord. The first design of T-Foil is used throughout the current fleet of moth dinghies. The second design of T-Foils tested and analysed are presently believed to be superior under some circumstances (Beaver and Zseleczky, 2009)**.** In order to compare and verify the performance of the two foils, numerical simulations were carried out along with full scale testing. The wind strength for all tests was 8 m/s. In order to establish the hydrodynamic performance of each tested foil an on- and off-design condition was established to show an area of operation where each foil was operating with a high drag penalty for the same baseline lift value. The un-flapped foil had one design condition due to its constant cross sectional profile. The flapped foil had two design conditions caused by varying camber created by its constant flap deflections. The numerical simulations were carried out in a Velocity Prediction Program (VPP) called FS-Equilibrium (Stewart et al., 2012). The simulation was solved for optimum Velocity Made Good (VMG) and a steady state solution in four degrees of freedom. The velocity prediction was carried out by means of a force balance, where a set of non-linear equations are solved for each degree of freedom in the simulation. These equations defined the forces and moments acting on the rig, hull and foils. The apparent wind direction and speed were determined from the boat speed and true wind direction and speed. The VPP relies on user modules to define the forces acting on the system. The main foil user module was altered for each design condition in the simulation as it is a function of lift and drag forces over a range of foil incidences. The full scale testing was conducted on a moth with full sized foils. The moth was fitted with a Global Positioning System (GPS) (Stewart et al., 2010), that recorded headings and boat speed. A support boat was fitted with an anemometer to record wind speed and direction. The data was then used to obtain TWA and boat speed by resolving the two vectors. The experimental and numerical results are represented by two polar plots that show boat speed as a function of true wind angle. Two headings were analysed to show an optimum VMG for windward leeward course racing.

3. Literature Survey

3.1 Experimental Research

Beaver and Zseleczky (2009) analysed hydrodynamic and aerodynamic efficiency of the foiling moth. The full scale testing showed that a foil with a ~30% flap could modulate lift up to about 45% of what would be achieved by globally changing the angle of attack of the lifting foil. This means a 2.2 degree change in flap angle is required to obtain the same result as a 1 degree foil angle change for an un-flapped foil. The best lift/drag ratios were when the flap angle is zero degrees. Experiments showed there was 11% less drag for a foil with flap at zero degrees than one with a high flap angle to achieve the same lift. The un-flapped foil also has reduced parasitic drag due to the elimination of the hinge line. In the experiments the foils were altered by operating the flap angle. If a foil with a smooth operating surface was introduced, such as the un-flapped foil, the results may have had a larger variance.

Miller (2009) investigated the merits of an electronic control system that could control the flying height of the moth. The system was designed with an un-flapped forward lifting foil. The use of the un-flapped foil was seen as an unlikely option, due to it been susceptible to damage during capsize and launching. This area needed development and testing before becoming a useable foil design. Another alternative design was the flapped arrangement. The flapped foil was concluded to be less efficient due to additional drag caused by the gaps on the hinge line.

Binns et al. (2008) studied lift and drag forces on a moth T-foil rudder for different Depth to Chord ratios (h/c). Lift and drag forces varied with submergence from the free surface. As the h/c increased there was a decrease in drag and lift, due to free surface pressure relief. A simple design process was developed based on experimental data recorded. The design process was a function of skipper and boat mass, h/c ratio, angle of incidence, drag and lift forces. The results of the design process produce two simple curves that create the most efficient foil setup. These simple curves were used in this study to model the effect of the free surface on the performance of the T-Foils.

3.2 Velocity Prediction Programs

Previous work on hydrofoils in the moth class has been based on optimisation of foil systems and control. The use of VPP's has been a common tool used in new designs and optimisation of current systems used. Bögle et al. (2010) identified recent foil design was based on profile shape for reducing the drag and increasing the lift coefficient. Other parameters such as plan form area and mechanical parameters of the control system had not been published at the time of writing. In order to compare different parameters of the foil and control systems, different states and sailing conditions needed to be found. The VPP was used to solve for a steady state solution. It was recommended that the outputs could be further improved by focusing on stability and not only boat speed. In order to achieve this accuracy additional force modules needed to be defined and existing ones updated. The end result would be conditions experienced by the sailor matching the solutions given by FS-Equilibrium. The work by Bögle et al. (2010) defined that by optimisation the moth could be more efficient at various points of sail. The mechanical characteristics in regards to control systems for the flapped and un-flapped foils were not investigated. The greatest difference would be wand loading and movement, which is a part of a control system based on foil angle of attack.

Hull (2011) created a VPP to model the moth and then compared results against GPS event data collected from Whaley and Alvazzi (2013) and wind speed data from Masters (2013). The modelled degrees of freedom was from four to six. The VPP predicted the performance of the moth with good accuracy. A conclusion from this work was that aerodynamic forces due to windage and sail efficiency required revision as this is a major component of the total drag force. Hydrodynamic forces could be improved by including added resistance due to waves. Ventilation is not taken in to account as studied by Emonson (2009), as ventilation only tends to affect the boat temporarily by removing all the lifting force from the affected foil. Ventilation could be a component that may need to be accounted for when studying the actuation of the two foil systems. FS-Equilibrium user modules programmed by Hull (2011), were used by the author for the numerical analysis.

Findlay and Turnock (2009) studied the use of a VPP as a design tool and the investigations were based around the moth. Upon further refinement it was found that the VPP could be used as a coaching aid to help the sailor understand the headings for the optimum VMG. The skipper placement and varied foil configuration could also be a function of optimum VMG. The studies were carried out over two years with moth foils evolving to have an elliptical profile with increases in aspect ratios. To improve performance these design characteristics were supported by empirical results from the VPP. As the moth is always evolving the computer algorithm could be evolved to include the un-flapped foil as it was not investigated in these studies.

3.3 Hydrofoil Configurations

Hydrofoil configurations can be divided into two categories, fully submerged and surface piercing. This describes how the lifting surfaces are arranged and operate.

The surface piercing configuration is designed so that sections of the foil extend above the free surface while riding on the foils. Struts connect the foils to the hull of the vessel with sufficient length to support the hull free of the water surface when operating at design speeds. As speed is increased, the lifting force generated by the water flow over the submerged section of the foils increases causing the hull to rise and the submerged area of the foils to decrease. For a given speed the hull will rise until the lifting force equals the weight carried by the foils.

The foils of the fully-submerged configuration are designed to operate at all times under the water surface. The struts which connect the foils to the hull and support it when riding on the hydrofoils, mostly do not contribute to the total lifting force provided by the system. In the fully-submerged configuration, the hydrofoil is not self-levelling. A system must be installed in order to operate the effective angle of attack of hydrofoils to change the lifting force in order to respond to changing conditions of vessel speed, weight and sea conditions. Due to the hull flying in the air and supported by two struts, the hull is almost uncoupled from a seaway.

3.4 Types of Height Control

3.4.1 Flapless foil

The flapless foil was originally built by Dr Ian Ward (Stevenson et al., 2004) and was the basis for numerous prototypes built by the author between November 2012 to March 2013. The foil has an axel at ¼ of its chord. The foil is pivoted around the centre of pressure of the foil and allows for easy automation by a vertical push rod fitted to the trailing edge of the foil. The range of angular rotations for the foil is between 0.5 to 15 degrees. The foil used in the analysis has been built and sailed by the author over the last ten months and is shown in Figure 1. After sailing the foil for a period of time the author has found reduced gearing is required when compared to the flapped foil, as small angle changes produce large changes in lifting forces. Sailing the moth upwind the rudder lift was reduced in order to raise the bow and body weight was crucial in short step chop where the wave periods were irregular. To sail downwind the rudder lift was increased to pull the bow down and helped keep the hull in trim while running with the waves.

3.4.2 Flapped Foil

The flapped hydrofoil has become the most common foil used in the moth class (Stevenson et al., 2004). It was first used in a championship by Garth Illett in 2003 in Western Australia. The flap is usually 30% of the chord and is located on the trailing edge of the lifting foil and runs the full span of the lifting surface. A positive flap deflection increases the camber of the foil and raises the maximum lifting force, while a negative flap deflection will reduce the camber and maximum lifting force on the foil. For a flapped foil the foiling height is controlled by adjusting the flap angle from positive to negative deflections usually in a range of -5 to 15 degrees. Since the first Illett design in 2003 the forward lifting foil has evolved from square tipped foil sections designed by Tom Speer to elliptical ends with bulbs around the intersection with the vertical strut. The current Mach 2 hydrofoil used on the world championship boat has all these features coupled with a smoother hinge arrangement when compared to earlier designs. The current speeds of the top boats are approaching 33 knots for a 10 second average. The flapped foil has been very successful due to the fact that it has been mass produced over many years and sailed by experienced sailors who have refined settings and control systems (Stevenson et al., 2004). The foil used in the analysis was designed by Alan Goddard. The foil is hinged on the top surface of the lifting foil with a strip of Kevlar impregnated with Sikaflex prior to the foil being laid up in the mould and a mono film fairing is placed on the lower edge of the foil as to close the gap created by the hinged surface. The author has tried quite a lot of techniques to reduce the gap, by tongue and groove arrangement, Sikaflex joint, Dacron centre hinge. The current foil has shown on the race course to be competitive with leading production moths, such as Bladerider or Prowler (Culnane, 2013). The vertical strut on the lifting foil is the same as the flapless arrangement.

Figure 1 Fully-Submerged Foil Configurations (Left), Surface Piercing design (Middle), (Stevenson et al., 2004). Un-flapped foil sailed by the author (Right).

3.4.3 Advantages of Flapless Foil

The flapped foil requires significant flap movement to maintain the moth at a constant height while sailing in the water (Stevenson et al., 2004). At low speeds when the hull is in the water and low riding the flap is angled down and effectively increases the camber of the foil to induce lift of the hull. Though there is a high lifting force there is also a large amount of drag created at the same time. As the boat speed is increased the flap will assume a neutral position in order to reduce the lifting force generated by the foil. At this stage the foil is operating at its most efficient shape and the component of drag produced is at its smallest. The increasing speed will finally give rise to a requirement for a reduction of lift in order to maintain a constant ride height. This can also happen when the boat travels through wave peaks. At this stage the flap will be in the upward position and cancellation of lift is the result. In this operating condition the downward and drag forces are at their greatest values. The foil can do this more than twenty times in a minute and in effect the foil is not operating at the designed shape and has areas of operation where there is a high drag component generated.

The flapless foil uses the same theory for operation. This means a larger angle of attack at lower speeds and reduced angle of attack at higher speeds. The major advantage is that the cross sectional shape of the foil is constant at all angles of operation and will generate a smaller drag force than a flap except for when both foils are operating in there neutral positions. In sailing the flapless arrangement the author has found rather small movements of the foil is all that is required in order to control the ride height. The major refinement at this stage is the gearing to gain this control. In setting up the angles for flight of the foil the angle of attack is set at 0.5 degrees as a minimum and up to 14 degrees maximum. The concept is far removed from the methodology embraced by the flapped foil, where there is a negative flap angle needed for the down force. Essentially the key variable is boat speed. The slower the boat more angle of attack is required to lift the boat. As speed increases the angle of attack reduces to compensate the increase in speed in order to maintain a constant ride height. This means a negative angle of attack is never needed on the flapless foil.

4. Analysis Methods

4.1 FS-Equilibrium Velocity Prediction

The VPP software used in the analysis was FS-Equilibrium, which is distributed by Stewart et al. (2012). The velocity prediction was done by means of a force balance, where a set of non-linear equations are solved for each degree of freedom in the simulation. These equations define the forces and moments acting on the rig, hull and foils. The apparent wind direction and speed are determined from the boat speed and true wind direction and speed. The VPP relies on user modules to define the forces acting on the system. The user modules used in the analysis were originally programmed by Hull (2011). The main foil user module was altered for each design condition in the simulation as it is a function of lift and drag forces over a range of foil incidences. The main foil user module used formulas derived from experimental work done by Binns et al. (2008). Where there are four multipliers that are a function of lift and drag coefficients that are calculated and plotted against foil angle of attack. These values are then used to calculate the forces and moments on the main foil and used to obtain a steady state solution.

4.2 X-Foil

X-Foil is an interactive program for the design and analysis of subsonic isolated aerofoils (Drela and Youngren, 2008). The two dimensional lift and drag coefficients used in the analysis were obtained from X-Foil. The simulations were run with a viscous solution and a free stream velocity of 8 m/s. The Ncrit command was used to model boundary layer separation and Reynolds number affects. The two dimensional lift and drag coefficients were then converted to three dimensional values by using lifting line theory (Alberte E. Von Doenhoff, 1948). Lifting line theory is a function of foil aspect ratio which accounts for geometrical properties of the foil.

4.2.1 X-Foil Lift/Drag Coefficients

The range of flap deflections used in FS-Equilibrium were between -5 to 15 degrees relative to the neutral lift angle. The flapped foil was modelled using its 30% trailing edge flap and the un-flapped foil was an incident controlled surface with no flap. The theoretical X-Foil lift on drag coefficients (C_l/C_d) are shown in Figure 2. For angles of attack between -1 to 3 degrees the un-flapped foil is the most efficient with the largest C_l/C_d. Either side of this range the un-flapped foil has a higher drag value than that of the flapped foil.

As stated earlier two dimensional lift and drag coefficients were calculated in X-Foil. The values were converted to three dimensional values by using Lifting line theory. For the range of flap deflections specified in the main foil user module lift and drag coefficient variances were specified relative to a neutral flap angle. These inputs were then used in equations derived from experimental work conducted by Binns et al. (2008). FS-Equilibrium uses the values in its four degrees of freedom force balance.

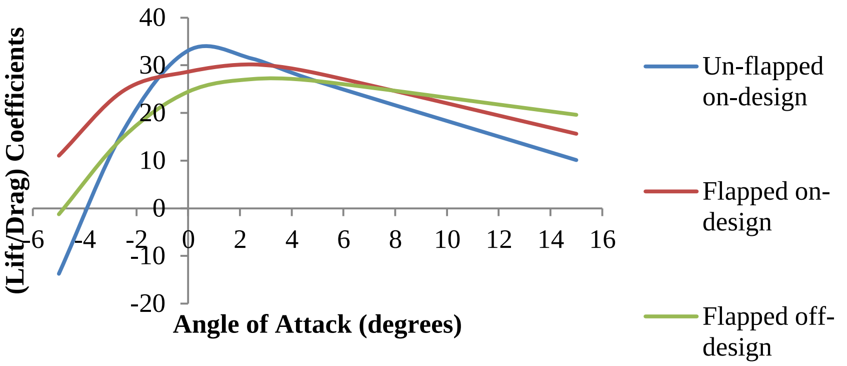

Figure 2 X-Foil coefficients for lift/drag relative to angle of attack.

4.3 Full Scale Testing

The testing was carried out on the Tamar River. Three sessions were done back to back in order to test each design condition. The wind strength ranged from 9 to 20 knots. Wind data was collected from a support boat in intervals of a minute. The average wind angle had no major shift over the three test runs. The moth and support boat were both fitted with GPS. Once the testing was completed GPS data for the moth and support boat was loaded into software from Stewart et al. (2010) called GPS action replay. The data provided individual tracking points where speed and headings were tabulated for given time steps. A screen shot of the un-flapped foil session in GPS action replay is shown in Figure 3. The data was processed around a design wind of 8 m/s. Wind recordings of 1.3 m/s either side of this value were considered acceptable for the testing. The greatest distance the moth travelled from the support boat during testing was 500 meters and considered acceptable as the wind direction was constant for all given time intervals.

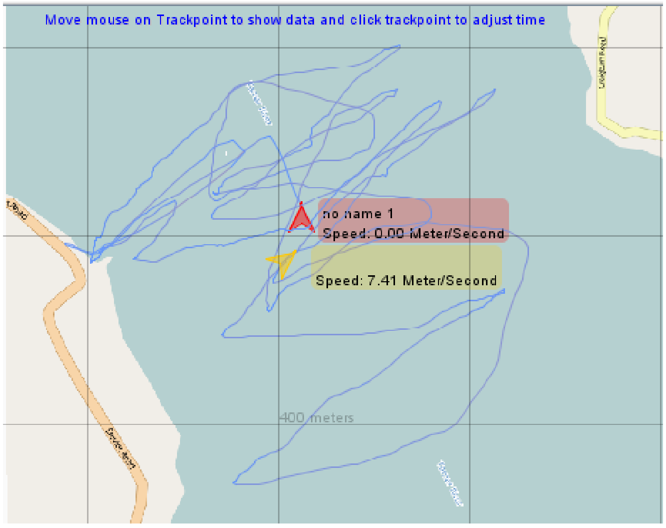

Figure 3 GPS Action replay screen shot of un-flapped foil test session. The red arrow shows the position of the stationary wind anemometer boat, the yellow arrow and blue track line shows the instantaneous position and track of the moth fitted with the un-flapped foil.

4.4 Foil Design Condition Selection

In order to evaluate the full performance envelope of each foil an on- and off-design condition was established for the analysis. When the foils were positioned at their neutral angle of attack they were required to lift 110 kg. The on-design condition was when the foil had the optimum setup for a wind of 8 m/s. At this wind strength the foil was in its most efficient shape where a high C_l/C_d was produced. The off-design condition was created to show an area of operation where the foil potentially had a reduction in efficiency. The condition was designed for light winds where a greater angle of attack is needed to lift the total mass. If the wind speed then increases whilst sailing (thus precluding, the ability to change design setups), a negative deflection of a control surface is required to provide the same lift force to that of the on-design condition. The flapped foil controls the lift force by altering its flap angle and acts as a control surface. This means the flapped foil has a varied cross sectional shape that is a function of flap deflection. As the foil cross sectional shape and camber vary two design conditions were established. Due to the off-design condition having a larger angle of attack, a greater negative flap deflection was required in order to produce the required lift force. The un-flapped foil had one design condition as the foil cross section was constant for all angles of operation. The ride height of the un-flapped foil is controlled by pivoting the whole foil at ¼ of its chord. The setup of the three design conditions for a design lift of 110 kg at 8 m/s boat speed is shown in Table 1.

Table 1 Three design conditions for a design lift of 110 kg at 8 m/s boat speed.

Foil Type	Foil Angle of Attack for 110 kg, (deg)	Flap Angle, (deg)
Un-flapped	3.86	N/A
Flapped on-design	1.54	0
Flapped off-design	10	-12.8

4.5 Flap Deflection

The foiling height of the moth is controlled by altering a control surface on the main foil. The foil deflections are created in order to alter the oncoming fluid flow and alter the lifting force as a function of foiling height in the vertical plane. In Figure 4, flap deflection and angle of attack are shown for all design conditions.

The un-flapped foil only had one design condition due to the constant cross sectional shape for all angles of incidence. The zero flap angles for all foils was set for a mass of 110 kg. The un-flapped foil had a slightly greater angle of attack due to it having a symmetrical foil section. The flapped foil was an asymmetrical foil section. The flapped off-design condition was created to show an area of operation where the foil potentially had a reduction in efficiency.

CONDITION	Un-flapped on design	Un-flapped Total lift (kg) @ 8 m/s wind	flapped on-design	flapped-on Total lift (kg) @ 8 m/s wind	flapped off design	flapped-off Total lift (kg) @ 8 m/s wind
-5 degrees		31.83		33.92		-4.06
-2.5 degrees		38.21		88.99		53.06
0 degrees		110.00		110.00		110.00
+2.5 degrees		181.23		195.72		166.31
+5 degrees		249.32		242.02		221.17
+15 degrees		391.21		341.73		398.56

Figure 4 Flap deflection & angle of attack for design conditions analysed in FS-Equilibrium.

5. Results

5.1 FS-Equilibrium Simulation

Three individual simulations were run in FS-Equilibrium. Each design condition required altering of the main foil user module in order to represent the varying change in foil cross sectional shape. Once the FS-Equilibrium simulations were completed polar plots for TWA relative to boat speed were produced. In the range of TWA there are two sailing conditions to be considered. The first is the low riding condition when the moth is predominately supported by hull buoyancy forces. The second is the foiling condition where the moth is fully supported by the two hydrofoils. Once flying on the hydrofoils the un-flapped foil outperformed the flapped foil. In respect to the flapped foil, the on-design was more efficient while foiling. In the low riding condition the flapped design conditions had a small variance on their performance with the off-design providing the greatest boat speed. The un-flapped foil produced the lowest boat speed in the low riding condition. A polar plot for all three design conditions is shown in Figure 5.

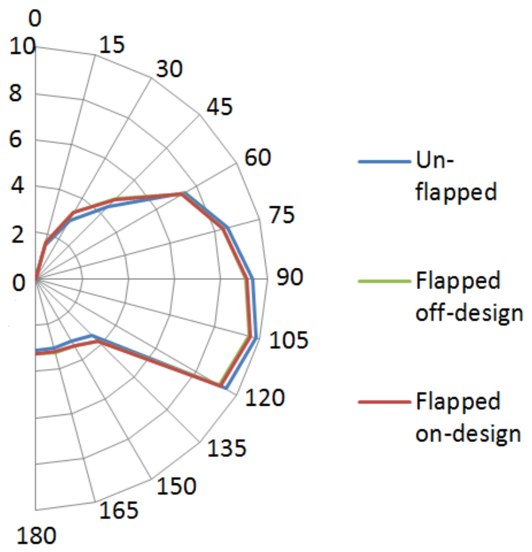

Figure 5 FS-Equilibrium polar plot of boat speed relative to TWA. Due to line weights and small variances in boat speed, the percentage differences for the flapped design conditions are also shown in Figure 6.

5.1.1 Optimum VMG

An optimum VMG for upwind and downwind sailing was selected in order to replicate windward leeward racing. These angles were selected as windward leeward courses are the standard course structure for all international moth championships (Stevenson et al., 2004). The wind strength for all simulations in FS-Equilibrium was 8 m/s. The two TWA selected for the optimum VMG was 60 degrees for upwind and 120 degrees for downwind sailing. For both selected TWA the un-flapped foil had the greatest VMG. The VMG and percentage variance relative to the un-flapped foil is shown in Table 2.

Table 2 The VMG and percentage variance relative to the un-flapped foil.

Foil Type	VMG,(m/s) @120 degrees	Δ speeds relative to un-flapped foil @120 degrees (%)	VMG, (m/s) @ 60 degrees	Δ speed relative to un-flapped foil @60 degrees (%)
Un-flapped	-4.81	0	3.64	0
Flapped on-design	-4.64	3.45	3.56	2.25
Flapped off-design	-4.62	4.11	3.6	1.11

5.1.2 Performance of Flapped Design Conditions

The flapped design conditions had two areas of operation where one out performed the other. As shown in Figure 5, the moth was foiling for TWA between 60 to 120 degrees. For TWA outside of this range the moth was low riding. For TWA between 35 to 75 degrees the flapped off-design foil had the greatest performance. This implies when wind ward sailing there is an advantage to have the foil set in the off-design condition where a greater lift force is required for the moth to remain foiling. For TWA between 75 to 130 degrees the on-design condition had a speed advantage. The greatest variance in boat speed was between TWA of 105 to 130 degrees where the on-design condition had a significant speed advantage. In this range the maximum speed was recorded in FS-Equilibrium. These headings also represented maximum angles the moth can sail without coming off its foils. This shows that a higher foil camber attracts a larger drag penalty sailing at these headings. For TWA between 130 to 180 the moth was low riding with the off-design performing the best. In Figure 6 percentage variance for the two flapped design conditions is shown, where a positive value is a performance advantage to the flapped on-design foil.

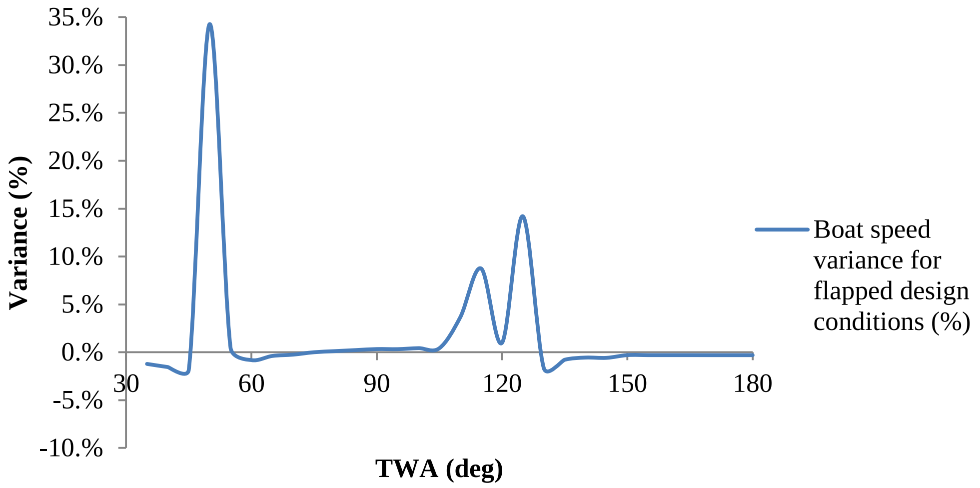

Figure 6 Percentage variance of boat speed for the two flapped design conditions. The range of TWA was between 35 to 180 degrees.

5.1.3 Performance of Flapped Design Conditions While Foiling

As shown in Figure 7, the flapped on-design foil has the greatest boat speed for most TWA while sailing on hydrofoils. For windward sailing angles there is a smaller variance when compared to downwind sailing angles. For sailing angles between 55 to 125 degrees the flapped on-design condition has the highest C_l/C_d value. At sailing angles where the moth is low riding the off-design condition has the higher C_l/C_d value. These results show that a higher C_l/C_d means greater boat speed for most TWA.

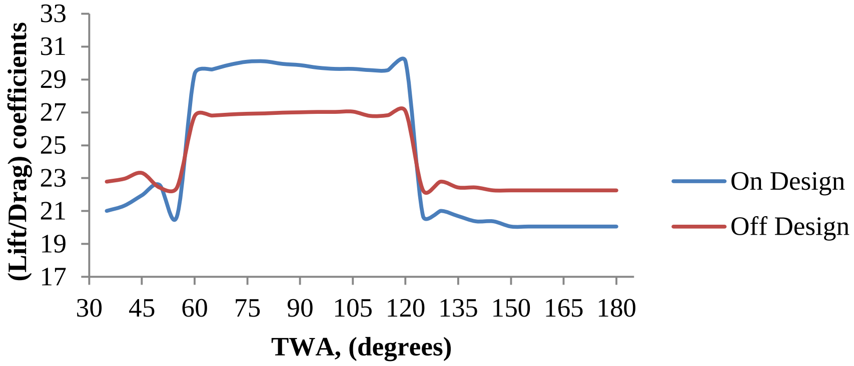

Figure 7 (lift/drag), coefficients as a function of TWA. For the 2 flapped design conditions.

5.1.4 Average Flap Angle

The average flap angle in FS-Equilibrium for all three design conditions is shown in Figure 8. The smallest flap deflections are for TWA of 60 to 120 degrees. In this range the moth is riding on hydrofoils and a smaller lift force is required from the main foil. For TWA outside of this range the moth is low riding and a greater flap angle is used in order to generate a greater lifting force.

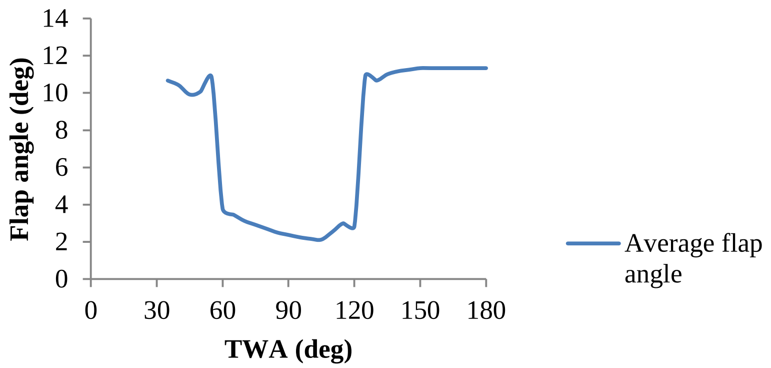

Figure 8 Average flap angle for all design conditions in FS-Equilibrium.

5.2 Full Scale Testing

The results showed a slight variance to that of simulation results. The flapped on-design foil had the greatest boat speed for all angles of sail. When sailing upwind the flapped on-design foil could foil at a TWA of 12 degrees while the other two conditions were not foiling till TWA of at least 30 degrees. As Beaver and Zseleczky (2009) showed greater flap deflections are required to generate the same base lift value to that of the un-flapped foil. The un-flapped foil requires smaller adjustments to fly and reduced gearing than that of the flapped foil. The wand gearing was kept constant for all design conditions. This may explain why the flapped foil was foiling in testing at a greater range of TWA. This variable was not picked up in the numerical analysis as it set for a steady state solution. The flapped off-design had the worst performance across most headings and concurs with FS-Equilibrium results. In Figure 9 experimental results are represented by a polar plot of boat speed relative to TWA for all 3 design conditions.

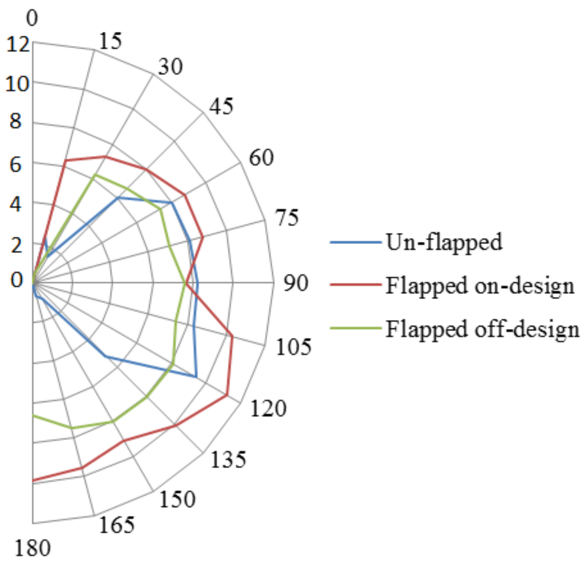

Figure 9 Polar plot of experimental results for all 3 design conditions.

5.2.1 Performance of Experimental Flapped Design Conditions

The flapped design conditions showed a variance to that of the numerical values. In full scale testing the moth was foiling for TWA between 30 to 180 degrees. Data for TWA between 0 to 30 degrees was inconclusive as the minimum leeway angle for upwind sailing was on average 25 degrees for both design conditions. This means only one the foiling state of the moth can be accurately analysed. At TWA between 110 to 120 degrees both foils reached their maximum speed and was also where the greatest variance occurred between the two design conditions. The performance of the flapped on-design verifies that it was the most efficient of the two design conditions. The averaged variance for all TWA is shown in Table 3.

Table 3 Experimental variance for flapped foil design conditions.

TWA (degrees)	Description	AVG % Variance
35-75	On design foil has speed advantage.	21.254
80-105	On design foil has its smallest speed advantage	20.3
110-120	On design foil has its largest speed advantage	39.351
125-180	On design foil has speed advantage	29.071

6. Discussion

6.1.1 Foil Efficiency as a function of Hull Speed

In FS-Equilibrium user modules are used to define foil and flap deflections. This is a function of hull sinkage and is measured from the vertical datum point. In Figure 10, coefficients for C_l/C_d are graphed with respect to boat speed. For all three foil configurations analysed the range of TWA for foiling was between 60 to 120 degrees. The boat speed where the hull became airborne was around 4 m/s for all design conditions. The speed range for the moth while hydro-foiling was between 7 to 10 m/s. In non-foiling conditions the flapped off-design had the highest C_l/C_d value. The flapped foil was more efficient at low speeds when low riding and was less efficient once foiling when compared to the un-flapped foil. This shown by the C_l/C_d value being greater than the un-flapped foil until a speed of 6 m/s. At a speed of 5.8 m/s all curves crossed and therefore all speeds were identical. Once foiling the un-flapped foil has the greatest C_l/C_d value.

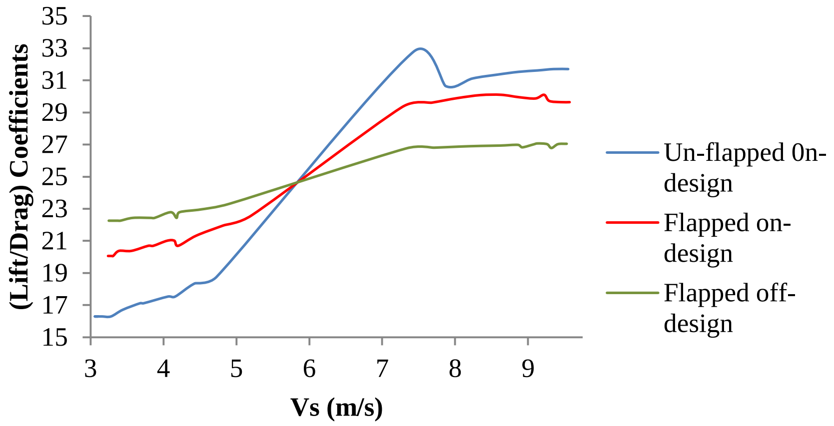

Figure 10 Coefficients of lift/drag with respect to hull speed.

6.2 Experimental and Numerical Variance

The comparison of boat speed for numerical and experimental results showed FS-Equilibrium under estimated on average 43% for all true wind angles. These results agree with studies by Hull (2011), that showed when comparing a four to a six degrees of freedom model a similar order of magnitude shift in results was obtained. The boat speed was always under estimated for most TWA. For TWA between 65 to 120 degrees, both analyses had their smallest variance with FS-Equilibrium over predicting the speed on average 13%. The maximum boat speed occurs between these TWA for all design conditions for both numerical and experimental analysis. For TWA outside of this range there is a larger variance between both analyses, however, it should be noted that most design optimisation is carried out in this range due to the high sailing speeds obtained resulting in most sailing occurring in this range.

The increase in measured performance of the flapped on-design condition when compared to the un-flapped foil could be caused by the dynamic state of the moth, that is the flapped on-design condition is far more stable in the present setup than the un-flapped foil. This dynamic stability feature of the foils is not modelled in the numerical simulation which the moth was in a steady state where pitch and heave were neglected. Another cause of experimental error was due to manoeuvring into turns which caused a spike in boat speed, as the moth stayed on its foils at TWA in which a steady state solution would result in the moth coming off its foils. These turning manoeuvres were unable to be filtered from experimental results. This is a problem as the moth is not sailing in a steady state and is under the influence of rapid accelerations and decelerations. Further testing may be needed in order to verify these results. The averaged percentage variance for all design conditions is shown in Figure 11.

Despite the differences displayed between the predicted and measured differences between flapped on-design and un-flapped foils, the flapped off-design and un-flapped foils showed very close differences for the measured and predicted cases. The primary reason for this is most likely due to the fact that the flapped off-design condition does not retain the same dynamic stability superiority due to its far from optimal configuration.

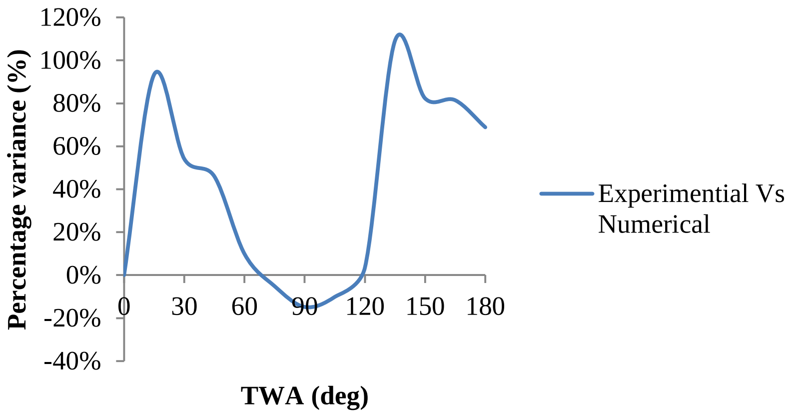

Figure 11 Average percentage variance of all design conditions for all TWA.

6.2.1 Explanation of Maximum Boat speed

In both analyses the greatest boat speed occurred for TWA between 105 to 120 degrees. These TWA represent sailing conditions where the main sail is in drag mode with low lift force produced. As a result there is a greater component of the wind pressure applied to mainsail which is aligned with the moth's course heading. The average flap angle for the moth at these TWA was on average 2.5 degrees, which was the lowest flap deflection for all headings as shown in Figure 8.

7. Conclusion

Two types of T-foils used on an international moth dinghy were tested in order to obtain optimum VMG for a windward leeward course structure. The wind strength for the analysis was 8 m/s. The first foil tested was fitted with a flap located on the trailing edge and a length of 30% of the chord. The second foil was un-flapped and was rotated about an axel at ¼ of the chord.

In order to compare the two foils and verify results full scale testing was done along with a numerical simulation involving a VPP. The two dimensional lift and drag coefficients were obtained from X-Foil and converted to three dimensional values by using lifting line theory. These results were used to set the design conditions for all foils tested. In order to compare the efficiency of each foil an off- and on-design condition was created which was a function of the camber of the foil cross section. The flapped foil had two design conditions due to flap deflections and the varying camber of the foil cross section in the longitudinal plane. The un-flapped foil had one design condition as the whole foil was pivoted and the foil camber remained constant through its range of operation. The minimum lift for every foil was 110 kg when setup for a neutral flap. The on-design condition for each foil involved no flap deflection and only needed inclination of the foil to the free stream flow till the required baseline lift was generated. The flapped off-design condition was created to show an area of operation where the foil potentially had a reduction in efficiency. The condition was designed for light winds where a greater angle of attack is needed to lift the total mass. If the wind speed then increases whilst sailing (thus precluding, the ability to change design setups), a negative flap deflection is required to provide the same lift force to that of the flapped on-design condition. The foil was inclined at 10 degrees angle of attack for the flapped off-design condition. Due to the large foil inclination a negative flap deflection of negative 12.8 degrees was required in order to produce the baseline lift.

The numerical simulation was done on a VPP called FS-Equilibrium. The VPP was modelled using four degrees of freedom force balance. Yawing and pitching were neglecting in the analysis. The FS-Equilibrium modules were originally programmed by Hull (2011) and modified by the author. For each simulation the relative lift and drag coefficients had to be modified in order to represent the three design conditions. The simulations were run for an optimum VMG and results for boat speed and TWA between 35 to 180 degrees were produced. The results showed that at a wind speed of 8 m/s the moth will foil for TWA between 60 to 120 degrees. Once riding on the hydrofoils the un-flapped foil produced the greatest VMG and boat speed, followed by the flapped on- and off-designs. At TWA where the moth hull was low riding, the flapped foil had the greatest boat speed with the off-design performing the best. The un-flapped foil was the slowest in the low riding regime. The flapped design conditions had small variances for most sailing angles with the off-design most efficient while low riding and the on-design faster while on the foils. The greatest variance was between TWA of 105 to 130 degrees where the on-design condition had a significant speed advantage. In this range the maximum speed was recorded in both analyses. These headings also represented maximum angles the moth can sail without coming off its foils in FS-Equilibrium. This shows that a higher foil camber attracts a larger drag penalty sailing at these TWA.

The full scale testing was carried out on a moth built by the author with foils setup to their prescribed design conditions. The moth was fitted with a GPS and was sailed at all TWA with the boat speed also recorded. The wind speed and direction were recorded by an anemometer on a support boat located in the vicinity of the moth. As the design wind for the analysis was 8 m/s, wind readings that were within a 1.3 m/s range were used in the GPS analysis. The average wind angle was taken over the three separate runs with no major shift in wind direction occurring. The greatest distance the moth travelled from the support boat was 500 meters during testing. The experimental and numerical results were compared and showed a variance. The author believes this is due to FS-Equilibrium only using four degrees of freedom force balance in its simulations and neglecting pitching and yawing. Pitching can have a significant effect of the affective angle of attack of the foil. The filtering of experimental data could be improved by eliminating manoeuvring, as the moth is not sailing in a steady state and is under the influence of rapid accelerations and decelerations. For all TWA the flapped on-design performed the best followed by the un-flapped and flapped off-design conditions. The performance of the flapped on-design verifies that it was the most efficient flapped design condition. Between TWA 65 to 120 degrees, the variance between experimental and numerical results was considerably small when compared to other headings. These range of headings are also when the moth is foiling and when the maximum boat speed occurs. The flapped off-design and un-flapped foils showed very close differences for the measured and predicted cases. The primary reason for this is most likely due to the fact that the flapped off-design condition does not retain the same dynamic stability superiority of the flapped on-design, due to its far from optimal configuration.

Future work on the topic could include a six degrees of freedom force balance in FS-Equilibrium so that pitch and heave are considered. Pitch has a direct effect on the foil angle of attack as it is a rotation around the boats transverse axis. The actuation and gearing of the un-flapped foil could be reduced as to allow for smaller foil deflections as shown by Beaver and Zseleczky (2009). In experimental work more accurate filtering of turning manoeuvres could help match both experimental and numerical results. The recording of boat speed and TWA could be improved if the anemometer and GPS are fitted to the moth as one unit. This would allow actual TWA, boat heading and speed to be collected and reduce error in data collection. As the moth at times can sail at the true wind speed an apparent wind angle may need to be considered in the calculations. By matching all numerical and experimental data for all sailing conditions. This allows further refinement of the VPP and allow for more accurate numerical analysis in the future.

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