Dane Philip John Hull - Final Year Thesis as part of a Bachelor of Engineering

(Naval Architecture), Australian Maritime College

Speed Sailing Design & Velocity Prediction Program

Contents

Nomenclature

Symbol	Description	Units
α	Incidence	$^\circ$
λ	Leeway angle	$^\circ$
γ	Tack/Gybe angle	$^\circ$
φ	Heel angle	$^\circ$
ρ	Density	$^{kg}/_{m^3}$
A	Area	m^2
C_D	Drag coefficient	
C_L	Lift coefficient	
D	Drag	N
D_W	Windage drag	N
DWL	Design Water Line	m
F_x	Force in the x direction	N
F_y	Force in the y direction	N
F_z	Force in the z direction	N
k	Form factor	
L	Lift	N
M_x	Moment in the x direction	$N.m$
M_y	Moment in the y direction	$N.m$
M_z	Moment in the z direction	$N.m$
V	Velocity	$^{m}/_{s}$
V_s	Hull speed	$^{m}/_{s}$
V_w	Wind speed	$^{m}/_{s}$

Acronyms

AOA	Angle Of Attack
AWA	Apparent Wind Angle
AWS	Apparent Wind Speed
CG	Center Of Gravity
COA	Centre Of Area
COE	Center Of Effort
DOF	Degrees Of Freedom
DWL	Design Waterline
GPS	Global Positioning System
IMCA	International Moth Class Association
IMS	International Measurement System
SOG	Speed Over Ground
TWA	True Wind Angle
TWS	True Wind Speed
VPP	Velocity Prediction Program

Abstract

In recent years the performance of high speed sailing craft has been increasing rapidly. One reason for this rapid development is the introduction of hydrofoils to high speed sailing craft, this has allowed sailing craft such as l'Hydroptere to reach speeds in excess of 60 knots, Hydroptere [2010].

The International Moth Class dinghy is perhaps the most significant example of these high performance craft. The performance of these craft is to be determined by the development and use of a Velocity Prediction Program (VPP). This investigation uses experimental and theoretical studies to estimate the gravitational, aerodynamic and hydrodynamic forces acting on the moth while sailing. Lift and drag data for the lifting foils is predicted using experimental results by Binns et al. [2008], at the Australian Maritime College, Tasmania. These forces are used in a force balance to predict the performance of the moth sailing dinghy, the program used to solve for equilibrium conditions is FutureShip Equilibrium.

The results of the VPP are validated using Global Positioning System (GPS) data from a race tracking website, TracTrac [2011]. Boat speed and true wind angle (TWA) data is obtained from the race tracking website, TracTrac [2011] and wind speed data from a weather history website, Wunderground [2010].

1. Introduction

1.1. High Speed Sailing

There have been many changes to the approach to high speed sailing in recent years, one of which has been the introduction of hydro-foils. The introduction of hydro-foils has led to sailing vessels being capable of speeds in excess of 60 knots, Hydroptere [2010] but however has led to an inherently unstable platform.

The most significant example of these vessels is the International Moth Sailing Dinghy, shown below in Fig. 1.1. Moths are now capable of speeds of over 30 knots, however because of the unstable nature of the moth, sailors are deterred from pushing their boats to the limit for fear of damage.

Figure 1.1.: International moth sailing dinghy, Grimm [2011]

A method to determine the probability of the boat to become unstable is needed. In order to resolve this problem the speed and trim is needed for a particular heading. Therefore a Velocity Prediction Program (VPP) is required.

1.2. Background

Studies into the performance of hydrofoil moth's have been conducted ever since their introduction in the mid 1980's, Mothosphere [2010]. These studies have been largely trial and error investigations which have resulted in a somewhat standard setup consisting of twin T-foils, with a wand controlled flap on the main foil and a skipper controlled flap on the rudder. This development is partially due to restrictions on multihulls adopted by the moth class rules, ISAF [2007]. These rules limited the development of early surface piercing V-foil designs.

Tow tank tests conducted by Binns et al. [2008], measured lift and drag data on a surface piercing T-foil at various angles and depths. These studies were conducted specifically for moth rudder foils, however both rudder and main foil designs are essentially the same. A study into the effects of Froude, Weber and Cavitation numbers on ventilation of surface piercing T-foils has also been conducted by Emonson [2009]. A study into the effects of yawed surface piercing struts was conducted by Breslin and Skalak [1959], methods and boundaries to avoid ventilation are outlined in the paper. Studies can be applied to determine the foils probability of ventilating.

A method by Bogle [2010], details the development of a VPP for a hydrofoil moth dinghy. This method will be used as a basis program for the development of this VPP. This VPP relies on the use of different solver settings within FutureShip to allow the solver to reach an equilibrium condition in both foiling and non-foiling conditions. A similar study conducted at the University of Southampton by Findlay and Turnock [2008] investigates the use of a VPP to study the effects of differing foil arrangements on moth dinghies. This study will be used to model techniques by sailors to temporarily increase sail power to enable foiling to occur, however it does not account for windward heel angles when sailing to windward.

Foil data from tow tank testing by Binns et al. [2008] will be used in place of numerical methods used by Bogle [2010]. Full scale hull aerodynamic and hydrodynamic measurements were taken by Beaver and Zseleczky [2009]. These measurements were taken for foiling and non-foiling conditions and can be used to validate the results of the VPP.

Lift and drag coefficients for varying sail types such as wing mast single skin, double skin and pocket luff sails are investigated using experimental methods by Marchaj [1996]. Current moth sails consist of a pocket luff and full cambered battens, this style of sail has a similar profile to a wing mast and single skin sail. Sail data for solid wing sails have also been analyzed by Marchaj [1996]. Using this data, the performance of a wing sail moth can be found. Development of a wing sail for a moth is currently being investigated, as seen at the 2011 Moth world championships Grimm [2011].

1.3. Project Objective

High speed sailing craft differ widely in both design and performance aspects. The aim of this project is to develop a performance prediction method capable of producing accurate results for a wide range of high performance sailing designs.

A designer of high speed sailing craft is faced with many possible designs ranging from kite and sail boards to large hydrofoil multihulls. It is important for the designer to be able to test the performance of their design before it is produced, so as to ensure it is the best possible given the design parameters.

Due to the varied and complex nature of high speed sailing craft, this project will use a simple craft for development, the International Moth sailing dinghy.

1.4. Moth Sailing Dinghy

The international moth class dinghy was first designed in 1928 by Len Morris in Victoria Australia as a simple flat bottomed scow. The class now is governed by an international body, the International Moth Class Association (IMCA), IMCA [2008] and is one of the most advanced sailing boat classes in the world. The moth is a development class, the rules enable the designer to have much freedom when designing the boat. The international class rules, ISAF [2007] are summarized below in Tab. 1.1. These freedoms have now led to the typical moth class dinghy being very narrow, with large hiking wings and fitted with hydrofoils.

Table 1.1.: International moth class rules

Rule	Dimension
Maximum Length	$3355mm$
Maximum Beam	$2250mm$
Maximum Luff Length	$5600mm$
Maximum Sail Area	$8m^2$
Minimum Displacement at DWL	$70kg$

The hydrofoil system first designed by John Illett of Western Australia, Mothosphere [2010], consists of twin surface piercing T-foils, one each on the centre board and rudder. Both of the T-foils have a movable foil or elevator flap to control the lift produced by each foil. The main hydrofoil is controlled by a sensor wand mounted on the bow of the boat to adjust the flap angle with changes to the boats height above the water surface. The rudder foil is controlled by the skipper via a rotating tiller extension to adjust the flap angle, this is primarily used to trim the boat while at full flight. This concept is illustrated below in Fig. 1.2, diagram by Jason Lee, Schmidt [2007].

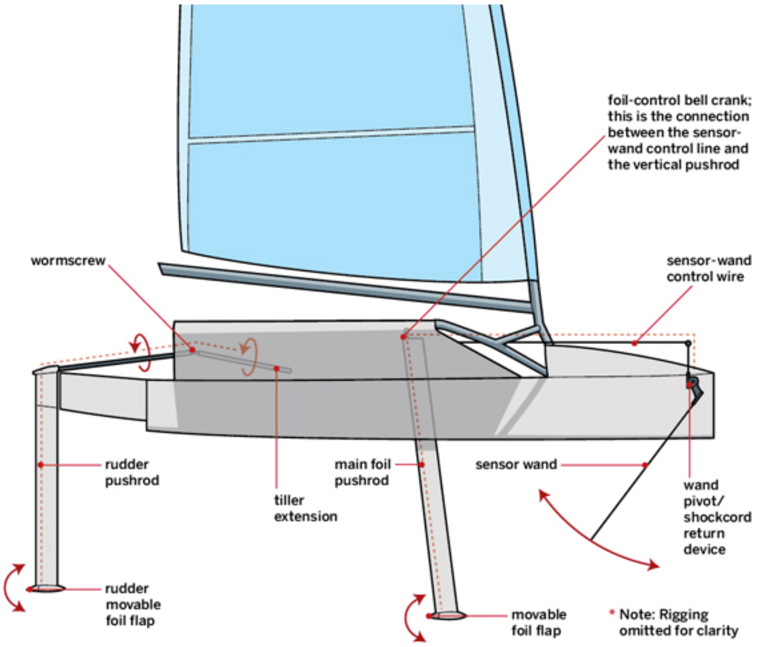


Figure 1.2.: Moth hydrofoil configuration, Schmidt [2007]

1.5. Methodology

Velocity Prediction Programs (VPP) are very common practice in the world of yacht design, however most do not allow the use of hydrofoils. The VPP FutureShip Equilibrium, is an open modular style program based on programmable force modules, FutureShip [2010]. FutureShip Equilibrium comes with a large range of predefined force modules as well as the potential for additional force modules which can be programmed using common programming languages. The program will then find the equilibrium state give a set of input parameters, this is typically used to find the speed of a vessel at a particular point of sail.

To find the speed of a hydro foiled moth, all the components affecting the forces on the hull need to be considered. Fig. 1.3 below shows the breakdown of forces effecting the boat. A summary of data sources for each force component is given in Tab. 1.2.

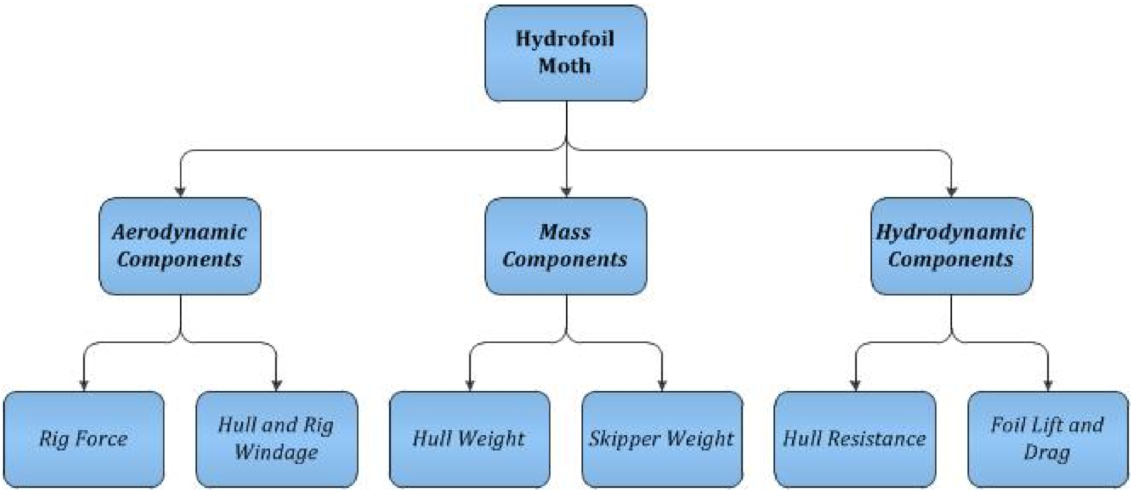


Figure 1.3.: Force components on a hydrofoil moth

Table 1.2.: Moth data sources

Force Component	Data Source
Rig Force	Lift and drag coefficients are available from Claughton et al. [1998], these coefficients are based on common sail types. Experimental data for wing mast and pocket luff type sails are given in Marchaj [1996].
Hull & Rig Windage	Drag coefficient for windage on the hull, rig and skipper can be found in Claughton et al. [1998].
Hull Weight	The weight and CG of the hull can be estimated using a weight estimate. Weight data for each component is estimated based on the hulls total weight and is available from IMCA [2008].
Skippers Weight	The weight and CG of the skipper based on the average weight. Data for the optimum skipper weight is available from IMCA [2008].
Hull Resistance	The hull resistance data is based on work by Beaver and Zseleczky [2009].
Foil Lift & Drag	Foil lift and drag data is available from experimental results produced by Binns et al. [2008].

1.6. Validation

One reason for choosing the International Moth for the development of a VPP is for ease of validation. There have been full scale tests of both hulls and foils being conducted at maritime facilities around the world, Beaver and Zseleczky [2009]. This enables readily available comparisons between VPP results and full scale data.

Due to the advances in GPS technology, many sailing races can be tracked live via the internet, TracTrac [2011]. This data is saved and can be easily accessed to watch past sailing regattas. The data given is a speed log of each individual boat in the fleet, given a SOG. The boats course is given as a trailing line, wind direction can be determined using the boats tack or gybe angle.

2. Velocity Prediction

Velocity prediction is done by means of a force balance, where a set of non-linear equations are solved, one for each degree of freedom in the VPP model. These equations define the forces and moments acting on the hull, rig and foils.

The forces acting on the hull and rig are determined by the wind angle, yaw, wind and boat speed. The program then aims to maximise boat speed using trim variables such as sail trim.

2.1. Force Balance

The forces and moments on each axis on the force balance are summed to zero for equilibrium. The following equations represent equilibrium in all six degrees of freedom.

Hull resistance and sail drive are represented by 2.1. Sail drive is maximised by the sailor in order to achieve maximum boat speed. Heeling and restoring moments are represented by 2.2. A side affect of maximising sail drive is the increasing of the heeling moment, this is counteracted by the sailors mass moment.

$$\sum F_X = 0 \tag{2.1}$$

$$\sum M_X = 0 \tag{2.2}$$

Sail and hull side forces are represented by 2.3. The sail side force is opposed by lift created by the hull and foils. Trimming moments are accounted for in 2.4. These are caused by differences in centers of weight and buoyancy as well as lifting foil moments.

$$\sum F_Y = 0 \tag{2.3}$$

$$\sum M_Y = 0 \tag{2.4}$$

Mass and buoyancy forces are represented by 2.5. Foil lifting forces are also included in this equation. Yaw moments 2.6 due to differences between the centres of sail and submerged area, also rudder angles influence the equilibrium of the equation.

$$\sum F_Z = 0 \tag{2.5}$$

$$\sum M_Z = 0 \tag{2.6}$$

Simple VPP's which use only three degrees of freedom, Larsson and Eliasson [2007] use 2.1, 2.2 and 2.3, these represent boat speed, leeway and heel angles. These three operating conditions are what the VPP is solving for. By increasing the degrees of freedom of the model accuracy, complexity and solving time increase.

2.2. Design Criteria and Parameters

In order to predict the speed and performance of a hydrofoil moth many aspects of the boat and sailing technique must be modeled within the VPP to gain meaningful results.

The forces acting on a sailing dinghy are complex, particularly in the case of a hydrofoil, where the boat is inherently unstable. The sailor must make many adjustments to weight position, foil, rudder and sail trim in order to keep the boat sailing fast. These adjustments must be modeled in the VPP.

The skipper's mass needs to be moved both longitudinally and transversely around the boat, since the skipper's mass makes up approximately 70% of the total mass, it is the main influence on trimming and heeling moments. Moths typically sail close hauled with a negative heel angle, opposite to that of a traditional sailing yacht, Grimm [2011]. Here the lift produced by the main and rudder foils is used to reduce or in some cases reverse the need of leeway angle. The skipper's weight is also used to increase the angle of attack (AOA) on the foils to assist with take off in low speed circumstances.

The design of the lifting foil system on a moth is somewhat complex. Although the mechanics of the system are relatively simple, they must provide the correct amount of lift for four different sailing conditions.

Non-Foiling: The non-foiling condition in moth sailing is when the moth does not have enough boat speed for take off. This typically comes about when sailing in light airs, close hauled ($AWA < 35°$) and square ($AWA = 180°$). At this stage, it is desired that the lift of the foils be minimised to reduce drag as there is no chance of the boat being able to take off.

Take Off For a typical hydrofoil moth dinghy, take off occurs in about 7 knots of breeze at an $AWA \approx 90°$. In this condition the lifting foil must create significant lift. As this lift decreases the draft of the moth, hull resistance decreases thus increasing speed. This in turn increases lift and the process continues until the hull is lifted clear of the waters surface. Once the hull is clear of the water surface the foils lift must be decreased to maintain the desired flying height equilibrium.

Design Speed This is the speed range at which the foil operates at flying height with a minimum of drag. Hydrodynamic drag minimal as the hull is flying clear of the water, the major drag component becomes windage from the hull and rig. It is assumed that full vertical force is supported by the main foil and the sailor adjusted rudder foil is used to maintain the boats trim.

Maximum Speed The maximum speed condition should be such that any further increase in speed will lead to ventilation of the foils and therefore crashing. It may be necessary to have a negative flap angle on the main foil to maintain the correct lift force due to high speed.

Main Foil Flap Control

Adjustments to the main foils lift is done using a wand setup, shown in Fig. 1.2. The wand is mounted on the bow of the boat, where it is forced to rotate so that the tip is in contact with the water surface. The wand is connected to the main foil flap using a Bowden cable. For this VPP, the action of this wand will be simply represented by a lift variation with height relationship.

Rudder Foil Flap Control

The rudder foil is used to adjust trim in foiling conditions, Schmidt [2007]. The trim is adjusted by the skipper via a twisting grip on the tiller extension, this adjustment alters either the AOA of the rudder foil or an elevator flap on the trailing edge of the rudder foil. The rudder itself is used to steer the boat, it is often used to alter the boat's course for a short period of time to sail the boat at a faster angle in order to achieve a foiling condition before returning to the required course.

Skipper Location Control

Skipper location is the only source of righting moment available when sailing a hydrofoil moth. The skipper will move transversely in order to counter the sails heeling moment and sail the boat at the desired heel angle. The skipper will also move longitudinally to adjust the trim of the boat. The trim of the boat directly effects the lifting foils incidence angle and is used to produce maximum lift to assist the boat to take off.

Sail Flat Control

Sail trim is used to alter the sail power. Typically the maximum power available will be utilised by the skipper, however it is also used to adjust the the heel angle when no further righting moment is available, thus the skipper is hiking out as far as possible.

2.3. FutureShip Equilibrium

2.3.1. Body Fixed Coordinate System

FutureShip Equilibrium uses a body fixed coordinate system to input the position where forces on the boat are acting, this is a coordinate system which is fixed with respect to the boat itself. Fig. 2.1 shows the origin point and directions for each of the x, y and z axes, moments about each of these axes are also shown. These moments are M_x, M_y and M_z respectively.

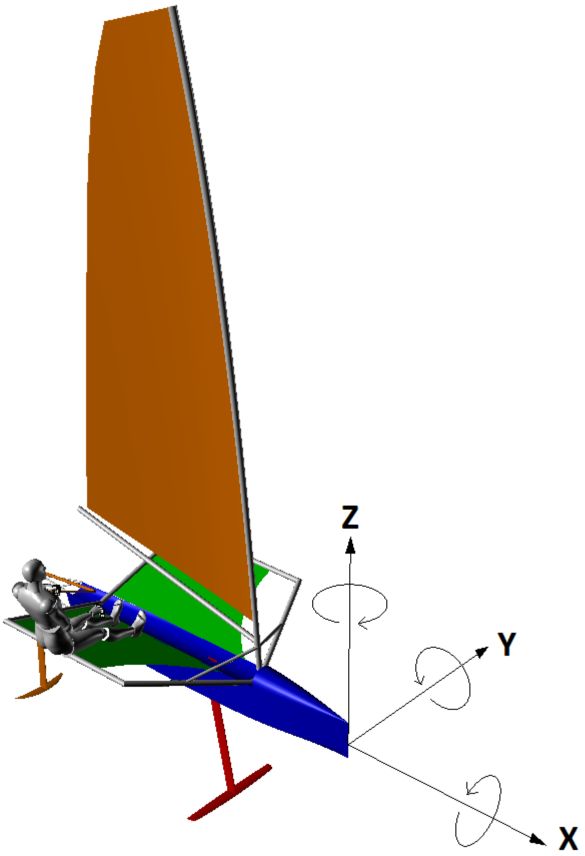


Figure 2.1.: Body fixed coordinate system

2.3.2. Force Modules

Force modules are used to break down the simulation of the boat into pieces which are easily predicted. These modules can be divided into three sections:

Gravity Forces on a moth are that of the fixed mass of the boat and the mass of the skipper which must move to trim the boat as required.

Aerodynamic Forces on a moth are the many drag forces produced by the hull and rig, as well as the major lift force produced by the sail.

Hydrodynamic Forces on a moth consist of the hull buoyancy, as well as lift and drag produced by the hull and foils

It needs to be considered that the within these modules, in particular those representing the lifting surfaces of the centreboard and rudder, that there needs to be some representation of the control of lift or otherwise by either human or mechanical means. That is, the main foil typically controlled by a wand to adjust the lift produced by this foil must be correctly represented. Also the lift of the rudder is typically controlled by the skipper, therefore the skipper's use of this control must be determined in order to model the effect correctly.

2.3.3. Input Data

Data input into FutureShip Equilibrium consists of both boat and environmental data. Boat data is input through the many force modules that represent the many aspects of the sailing boat. Environmental data is typically the conditions in which the boat is to be tested, the main data of which is TWS and TWA.

Gravity Forces

Moth Mass: A weight estimate was carried out to find the the total mass of the fully rigged moth. Details of the weight estimate are in appendix sec. D.2.1. This data is used to input the mass and center of gravity of the moth in body fixed coordinates.

Skipper Mass: The weight of the skipper input is 80kg, the maximum competitive weight of a moth sailor. The position of this mass is input as a range in both the x and y direction, as the skipper is able to shift their weight to trim the boat. Details of the skipper mass module are in appendix sec. D.2.2.

Aerodynamic Forces

Rig Force: For the calculation of rig force, data from the IMS VPP, Claughton et al. [1998] have been used to estimate mainsail lift and drag coefficients. The coefficients have then been scaled to resemble the maximum lift produced by a streamlined mast and single skin sail, Marchaj [1996]. Details of the rig module are in appendix sec. D.3.1.

Windage: Windage is calculated by using profile, plan and body areas above the waterline as well as their associated geometric centers. A drag coefficient (C_D) of 1.13 has been used to estimate the drag around the varying geometries that make up this drag force, Larsson and Eliasson [2007]. Details of the windage module are in appendix sec. D.3.2.

Hydrodynamic Forces

Buoyancy Force: The hull geometry has been input into the buoyancy force module using a hull geometry definition file (.shf). Details of the buoyancy force module can be found in appendix sec. D.4.1.

Center Board and Rudder Force: The lift and drag produced by the centerboard and rudder are defined in two separate modules. These modules detail the area, COE, C_L and C_D based on their planform area and sectional shape. Details of these modules are in appendix sec. D.4.2 and sec. D.4.3.

Main and Rudder Lifting Force: Similar to the centerboard and rudder modules above, the main and rudder lifting foils are defined using the area, COE, C_L and C_D for each foil. However additional variables have been added to represent the action of the "wand", skipper and distance of the lifting foil to the water surface. Details of these modules are shown below in sec. D.4.4 and sec. D.4.5.

Main Foil Data

The lift and drag force produced by the main foil are calculated using an equation derived from experimental results conducted by Binns et al. [2008]. In this method the lift and drag coefficient are calculated using 2.7 and 2.8, where the coefficients A, B, C and D have been derived experimentally. The coefficients are plotted with respect to the depth to chord ratio and at a constant Froude number (Fn) of 3.4. The curves for coefficients A, B, C and D are shown below in Fig. 2.2, Fig. 2.3, Fig. 2.4 and Fig. 2.5.

$$C_L = A.\alpha + B \tag{2.7}$$

$$C_D = C.C_L^2 + D \tag{2.8}$$

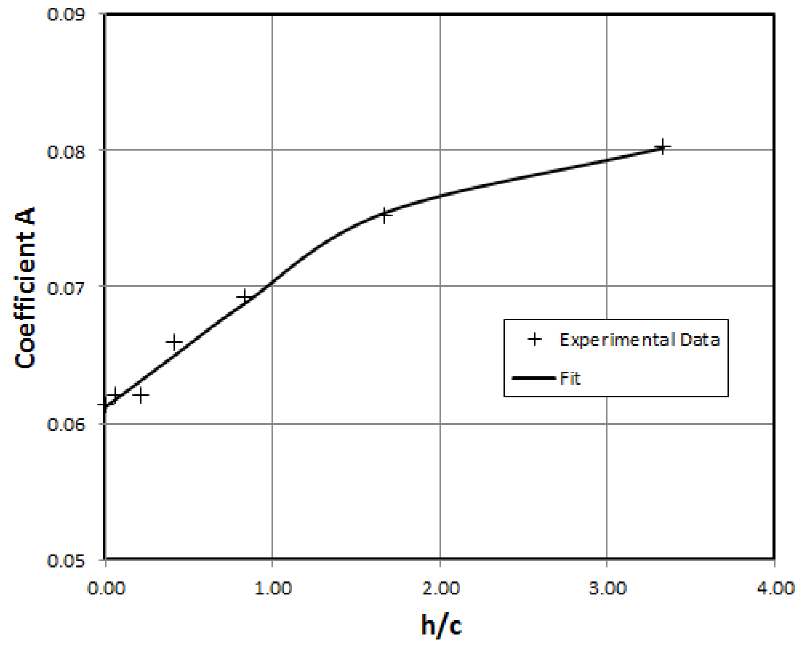


Figure 2.2.: Main & rudder foil coefficient A

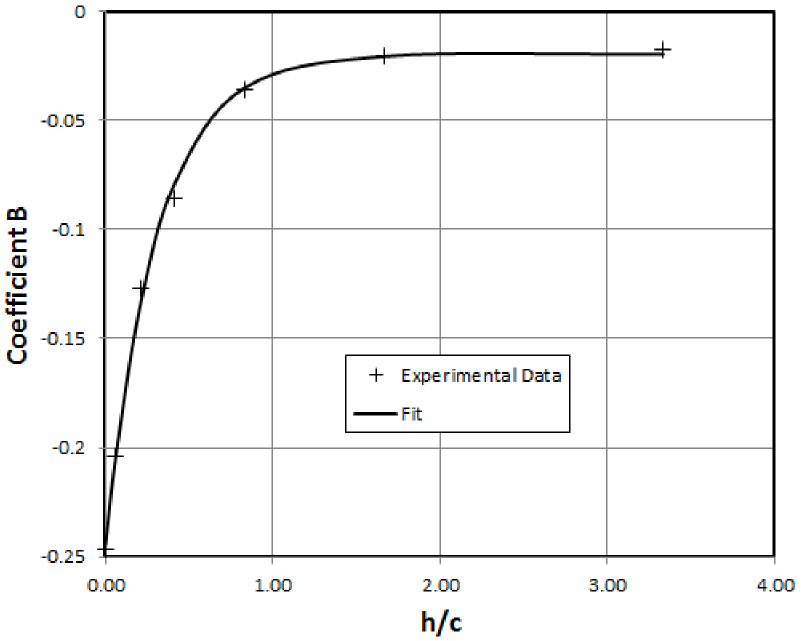


Figure 2.3.: Main & rudder foil coefficient B

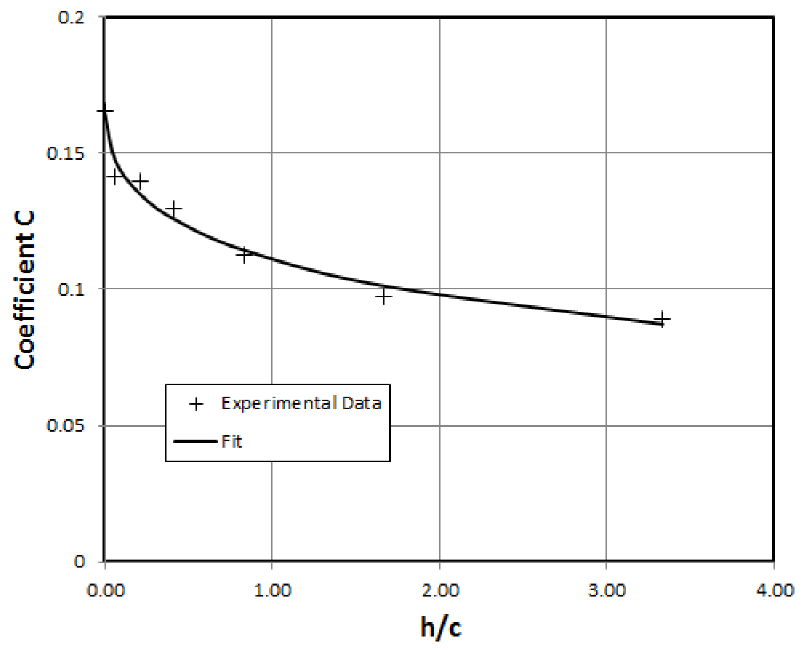


Figure 2.4.: Main & rudder foil coefficient C

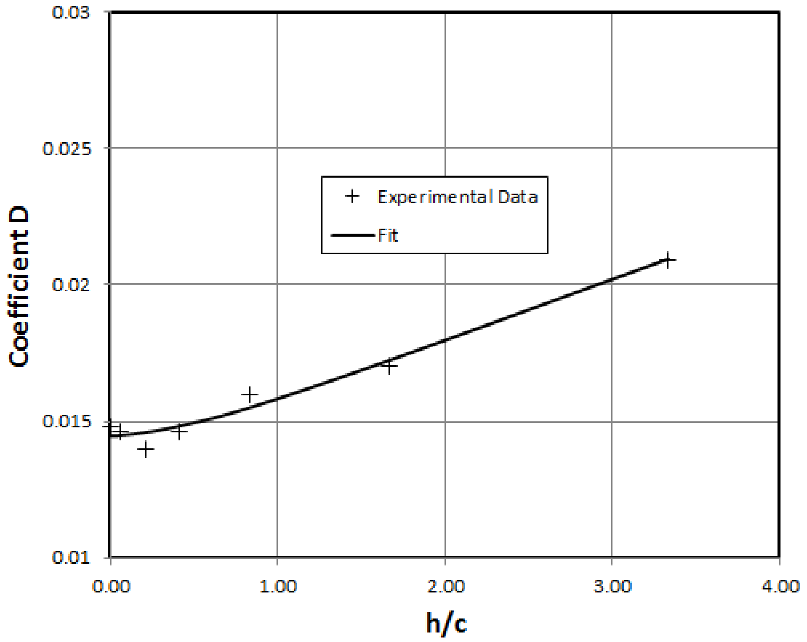


Figure 2.5.: Main & rudder foil coefficient D

The added lift and drag due to the wand controlled elevator flap is calculated with respect to the flap angle, this is directly proportional to the boat's flying height.

A curve has been derived to determine the foil's flap angle as a function of flying height, this curve has been derived to represent the wand setup to adjust the main foil flap angle. This curve can be seen in Fig. 2.6 below.

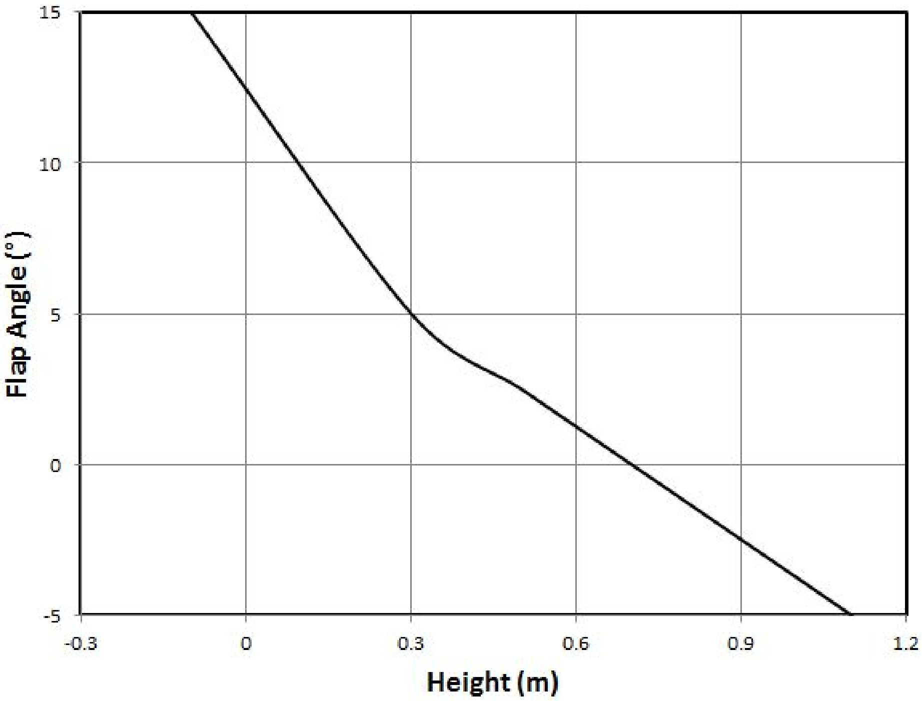


Figure 2.6.: Flap angle as a function boat height

The added lift and drag due to flap angle as determined from XFOIL are shown below in Fig. 2.7 and Fig. 2.8. As this data is determined for two dimensional sections only, some error will be present due to three dimensional effects.

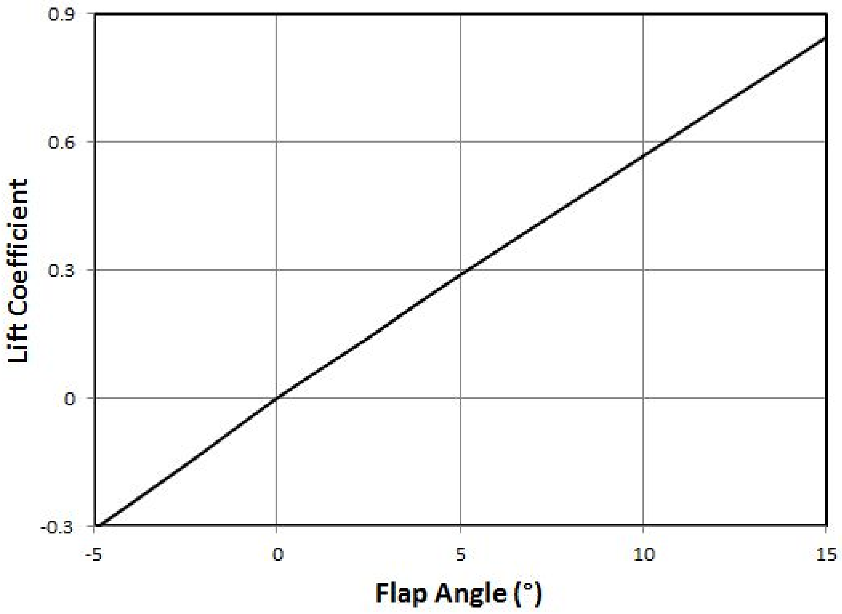


Figure 2.7.: Lift due to foil flap angle

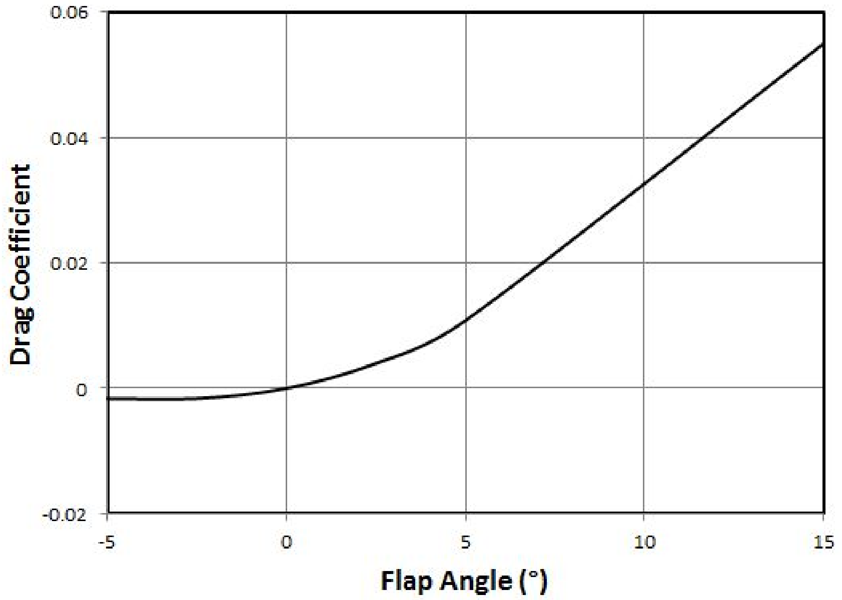


Figure 2.8.: Drag due to foil flap angle

Rudder Foil Data

The lift and drag force produced by the rudder foil are also calculated using the equations 2.7 and 2.8. The curves for coefficients A, B, C and D are shown below in Fig. 2.2, Fig. 2.3, Fig. 2.4 and Fig. 2.5.

Similar to the main foil, the added lift and drag due to the skipper controlled elevator flap is calculated with respect to the flap angle shown below in Fig. 2.9 and Fig. 2.10.

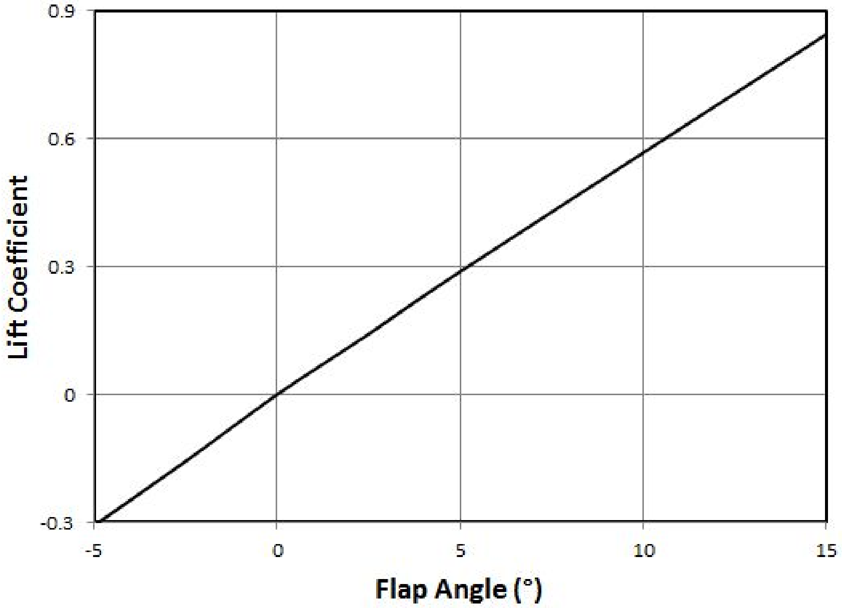


Figure 2.9.: Rudder foil lift due to foil flap angle

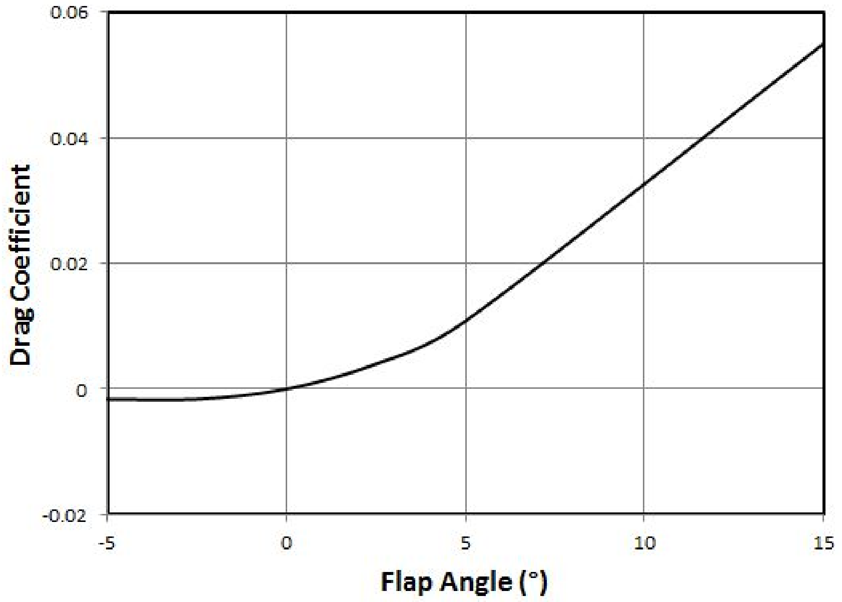


Figure 2.10.: Rudder foil drag due to foil flap angle

2.4. Results Interpretation

The output of a VPP is typically in the form of a polar plot, where the tangential axis represents the TWA relative to the boat, a performance measurement such as speed, yaw or heel angle is shown on the radial axis. Varying wind speeds plotted on the same graph gives a good representation of target speeds to the sailor. Also in the case of the foiling moth, can show the conditions in which the boat should be flying. Tab. F.1 shows a typical results output table.

3. Validation

3.1. Moth Race Data

As mentioned previously, the VPP will be validated using GPS moth race data compiled from the internet, TracTrac [2011]. As moth racing is conducted on a windward/leeward course (directly upwind and downwind), only two points on the VPP polar plot will be available. These points will be the points with the highest VMG for both windward and leeward legs.

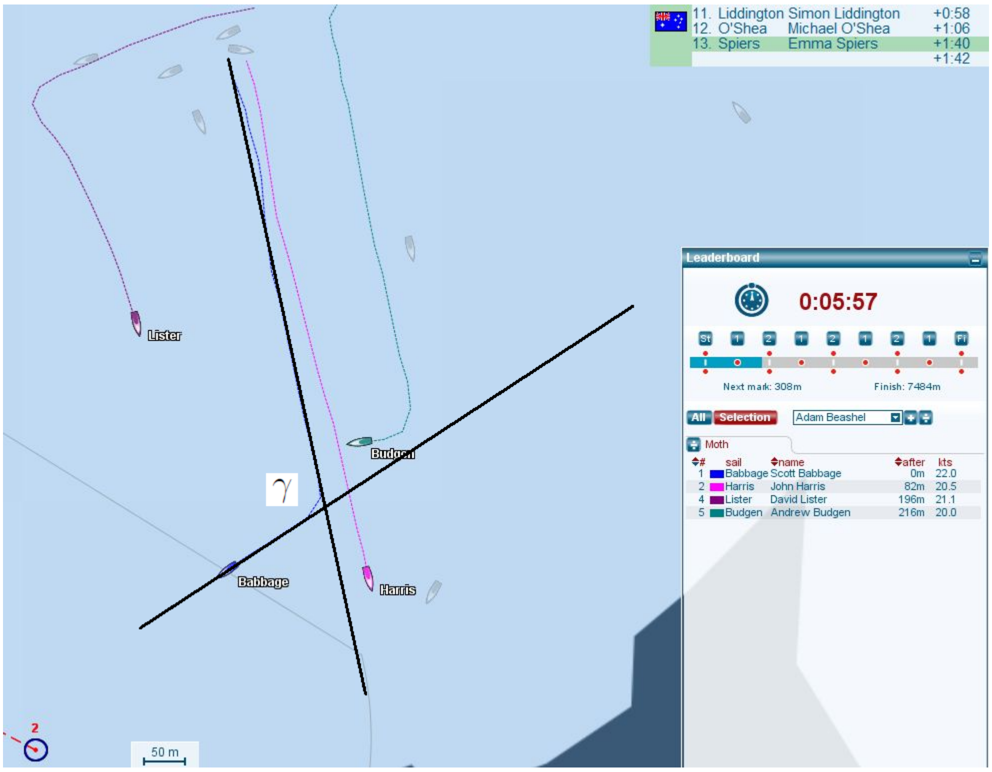
In order to compare predicted VPP data with actual moth data the boat speed (V_s), true wind angle (TWA) and wind speed (V_w) is required. The boat speed (V_s) can be taken directly from TracTrac [2011], the wind speed (V_w) and true wind angle (TWA) must be estimated. The data has been gathered from the 2010 Sail Sydney Regatta held on Sydney Harbour in December 2010. To gather the required data, the race is replayed and paused at a specific time, when the required boats are sailing in clear air and at the required TWA. To do this only four boats have been used to validate the VPP, these have been the first four boats in the fleet to ensure their sailing technique is as close to optimal as practical. To gather the validation data, a screen shot is taken at the required point in the race whereby the data can be extracted. The boat speed (V_s) can be read directly from the boat monitoring table shown on the right of Fig. 3.1. The TWA can be calculated using 3.1 and 3.2, where $\gamma = tack/gybe\,angle$.

$$TWA = 90 - \gamma/2,\ for\,TWA < 90 \tag{3.1}$$

$$TWA = 90 + \gamma/2,\ for\,TWA > 90 \tag{3.2}$$

The tack/gybe angle (γ) is obtained by measuring the angle between the boat's course before and after the tack/gybe, as shown below in Fig. 3.1. This assumes that:

1. After each successive tack/gybe the TWA is the same. It should be noted that after tacking, the skipper will often bear away to increase the TWA and therefore boat speed before coming up to the TWA with the greatest VMG. Similarly when gybing the skipper will often decrease TWA to increase speed after the gybe, this can be seen below in Fig. 3.1, Lister's course shows the variation in TWA following the gybe.
2. The wind variation in both speed and direction is minimal between tack/gybes.
3. Boat speed and therefore VMG is the same on both tacks/gybes.
4. The skipper is sailing at the TWA of greatest VMG on both tacks/gybes.



11.	Liddington	Simon Liddington	+0:58
12.	O'Shea	Michael O'Shea	+1:06
13.	Spiers	Emma Spiers	+1:40
			+1:42

0:05:57

Next mark: 308m

Finish: 7484m

Adam Beashel

#	sail	name	after	kts
1	Babbage	Scott Babbage	0m	22.0
2	Harris	John Harris	82m	20.5
4	Lister	David Lister	196m	21.1
5	Budgen	Andrew Budgen	216m	20.0

Figure 3.1.: GPS track screen shot, TracTrac [2011]

Wind data has been obtained from weather history from Wunderground [2010]. This website allows historical weather data to be seen from many weather stations around the world. The date and time of day of the race was determined using the sailing instructions issued to the competitors at the beginning of the regatta, Yachting [2010]. The weather station used is located at Potts Point, Sydney, less than three kilometres from the moth course at sea level. The wind data obtained is shown below in Fig. 3.2.

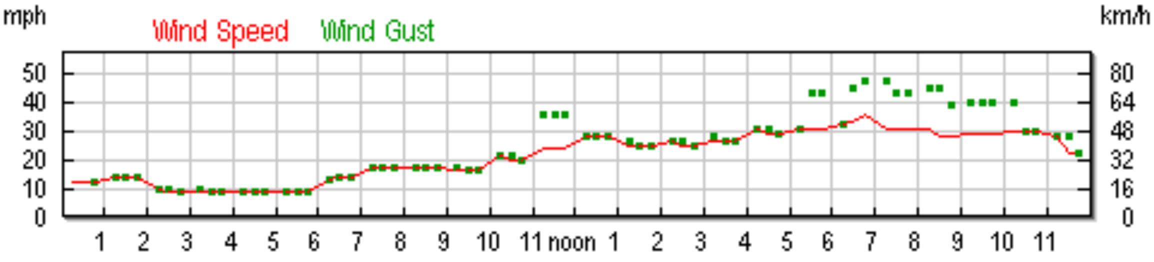


Figure 3.2.: Potts point wind data, 08/12/2010, Wunderground [2010]

Wind and boat data was gathered over the two days in which the moth class raced, however due to discrepancies in the wind/boat data, the data from the second day of racing was disregarded. A typical moth race consists of a windward/lured course, this means only data for two TWA's could be obtained and therefore only two points on the moth VPP could be validated. Tab. 3.1 below shows the validation data used.

Table 3.1.: Validation data

Wind Speed, V_w (kts)	True Wind Angle, TWA $(°)$	Boat Speed, V_s (kts)
22.59	48	12.40
22.59	47	12.68
22.59	143	20.27
22.59	143	18.87

3.2. Comparison Of Moth Data to VPP Data

The moth VPP was run with both four and five DOF VPP's, the results can be seen below in Fig. 3.3. It can be seen in Fig. 3.3 below that the five DOF VPP is very unstable for TWA's greater than 140°, this is due to a varying pitch angle. This has not affected the results as the points on the VPP curve to be compared are those where there is a sharp loss of boat speed with a small change in TWA. The skipper's weight and rudder foil elevator flap adjustment would normally stabilise pitch angle, however this did not work due to the high wind speed the VPP was tested at. The VPP was run without the use of the adjustable elevator flap on the rudder foil, this was stabilise the program when using pitching moments. Due to limited validation information available with both accurate weather and boat data, it was not possible to validate the moth VPP at a lower wind speed.

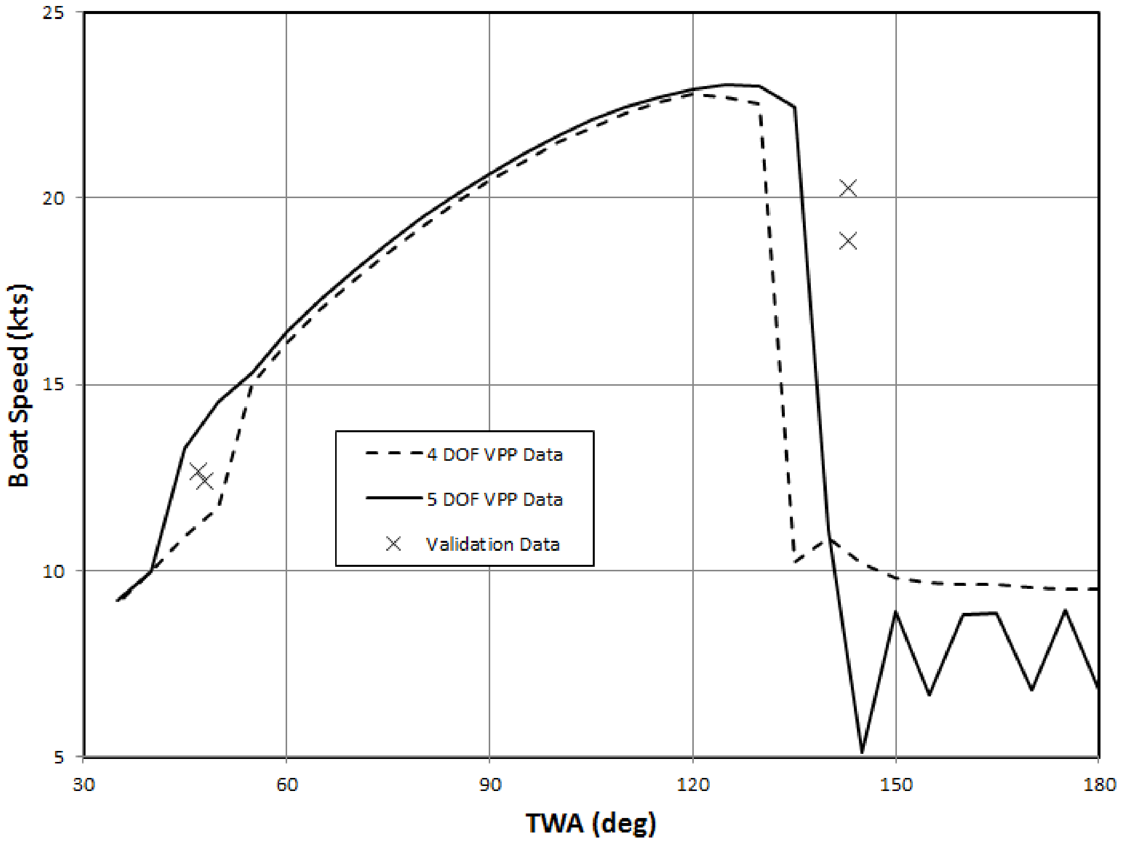


Figure 3.3.: Moth VPP validation

From Fig. 3.3, the boat speed and TWA error's are estimated for both windward and leeward sailing conditions in both four and five DOF VPP's in Tab. 3.2 and Tab. 3.3 below.

The windward boat speed error is described in Tab. 3.2 shows boat speed is slightly under estimated by the four DOF VPP and over estimated by the five DOF VPP. In leeward conditions the boat speed is over estimated in both cases.

Table 3.2.: Boat speed error

Condition	**4 DOF Error** (*kts*)	**4 DOF Error** (%)	**5 DOF Error** (*kts*)	**5 DOF Error** (%)
Windward	-1.0	-8.0	+1.0	+8.0
Leeward	+3.0	+13.0	+3.0	+13.0

The windward true wind angle error is described in Tab. 3.3 shows TWA is over estimated for the four DOF VPP and under estimated for the five DOF VPP. In the leeward sailing condition the TWA is over estimated in both cases.

Table 3.3.: True wind angle error

Condition	**4 DOF Error** (°)	**5 DOF Error** (°)
Windward	+5	-5
Leeward	-8	-16

A description of the effects of differing DOF VPP's can be found in sec. 4.1. This section describes the effects of DOF on the VPP's boat speed and true wind angle outputs.

As moth's sailing a windward/leeward course will always sail at the TWA corresponding to their maximum VMG, reference points for both speed and TWA have been taken about these point of maximum VMG. Had this not been taken into account, it can be seen from Fig. 3.3 that the boat speed discrepancy particularly on the leeward data would give an error of $\approx -70\%$. However, a small decrease to the TWA would tend to over estimate the boat speed by $\approx +10\%$, this is due to the rapid speed increase as the boat lift up on the foils.

4. Results

4.1. Variation Of The Degree Of Freedom

The degree of freedom (DOF) of the VPP model has been varied to determine the effect on the output of the VPP. The minimum DOF for a VPP is typically considered to be three (F_x, F_y and M_x), Larsson and Eliasson [2007] however due to the complex nature of the hydrofoil moth a VPP this simple would be not accurate enough. As the moth typically sails completely supported by foils, it is considered necessary that these forces should be modeled in the simplest form of VPP. Therefore considering a four DOF (F_x, F_y, F_z and M_x) VPP as the most basic scenario.

The trim variable deltaFlap has not been used in these simulations as it made the program unstable in fully foiling conditions. This did not alter the results significantly as the MassMove trim variable was still able to trim the boat to optimize the pitch and therefore maximise lift for each condition.

4.1.1. Four Degree Of Freedom Velocity Prediction Program

The four DOF VPP is run as mentioned previously, simulating forces in all x, y and z directions and the heeling moment, (F_x, F_y, F_z and M_x). Fig. 4.1 below shows the four DOF VPP run at two wind speeds. This VPP simulation does not take into account the boat's pitch, this has a great effect on the the lifting foil's ability to produce lift at low boat speeds. It can be seen above in Fig. 3.3 that the moth's boat speed can be under estimated significantly by this VPP, in windward conditions, and over estimated in leeward sailing conditions. This is due to the variation of the TWA at which the boat can lift out of the water, denoted by the sharp increase in boat speed with variation in TWA. Fig. 4.4 below shows the variation in TWA between four and five DOF VPP's.

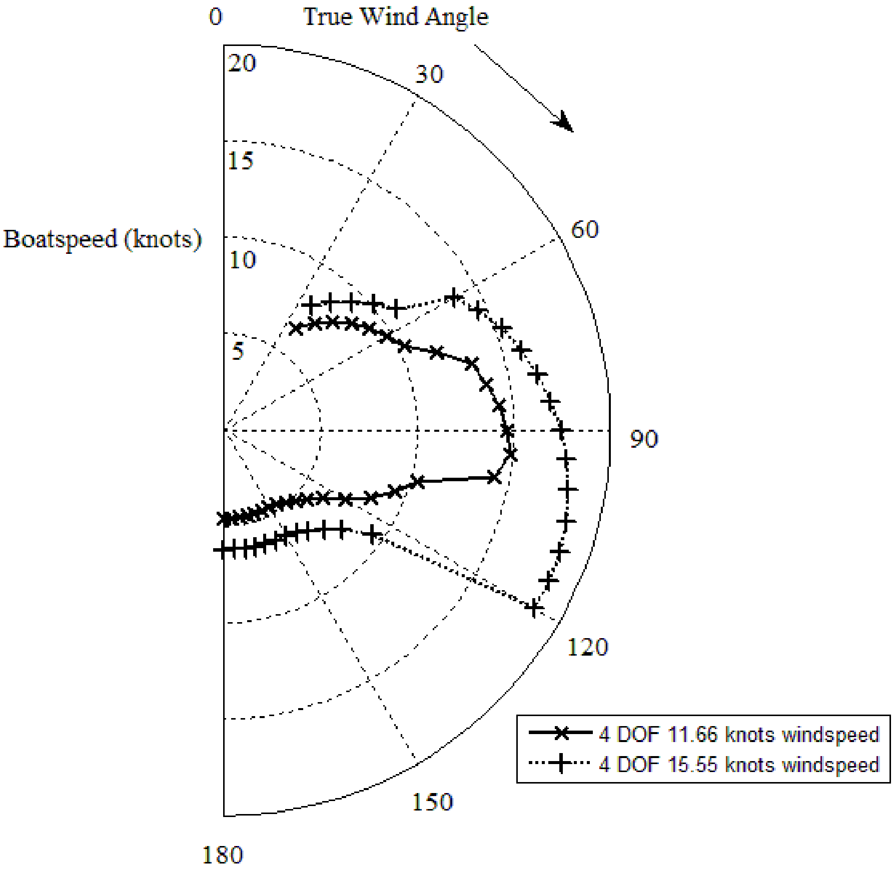


Figure 4.1.: Four DOF moth VPP

4.1.2. Five Degree Of Freedom Velocity Prediction Program

The five DOF is run as mentioned previously, simulating forces in all x, y and z directions as well as the heeling and pitching moments, (F_x, F_y, F_z, M_x and M_y). Fig. 4.2 below shows the five DOF VPP run at two wind speeds. This VPP simulation does take into account the boat's pitch, this has a great effect on the the lifting foil's ability to produce lift at low boat speeds. This can be seen as the variation of the TWA at which the boat can lift out of the water, denoted by the sharp increase in boat speed with variation in TWA. It can be seen above in Fig. 3.3 that the moth's boat speed can be over estimated significantly by this VPP, in both windward and leeward sailing conditions. Fig. 4.4 below shows the variation in TWA between four and five DOF VPP's.

Fig. 4.3 below shows the results when the five DOF VPP is run using the deltaFlap trim variable. This variable allows the skipper to control the angle of the elevator

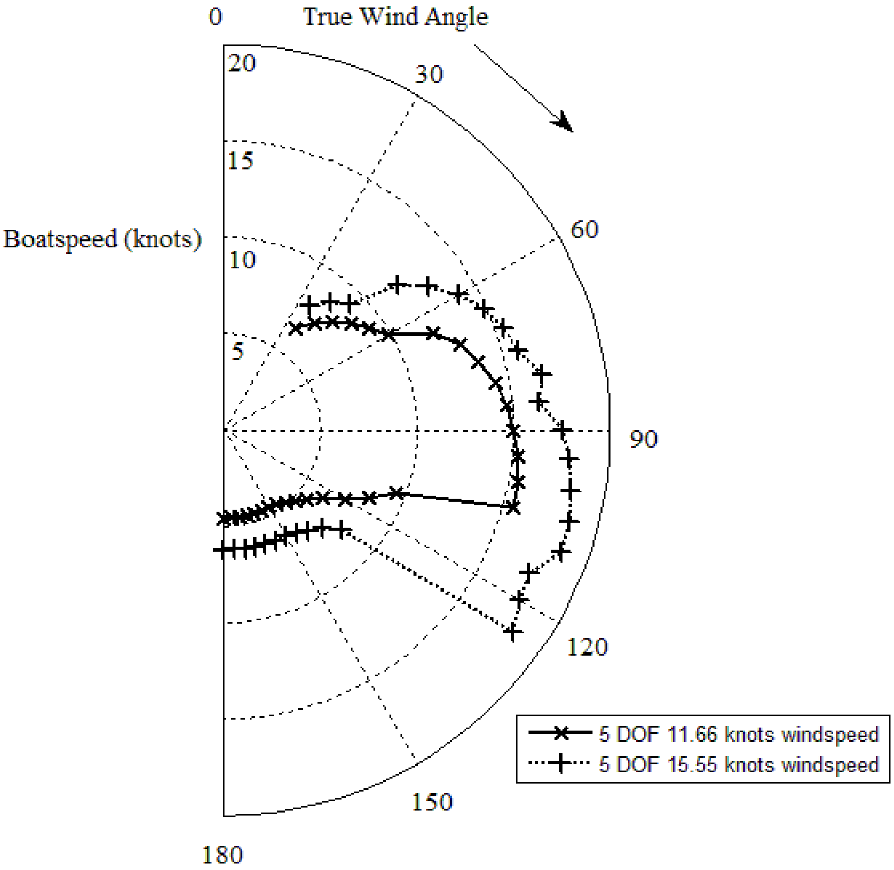


Figure 4.2.: Five DOF moth VPP

flap on the rudder foil, adjusting the boat's pitch to decrease the takeoff boat speed. When in use the flap angle is adjusted to minimise foil drag when take off speed is insufficient and maximise lift when the boat has sufficient speed to take off. However, problems with program stability occur at wind speeds greater than $6m/s$, this could be solved by introducing a function which limits the use of this trim function to only non-foiling and take off conditions.

Other VPP outputs such as heel angle also follow trends as seen in practice such as a windward heel angle when sailing to windward. This backward heel angle helps the main foil produce lift to windward in high flying conditions as very little centreboard area remains submerged. An example of the results output table from FutureShip equilibrium can be see in Tab. F.1.

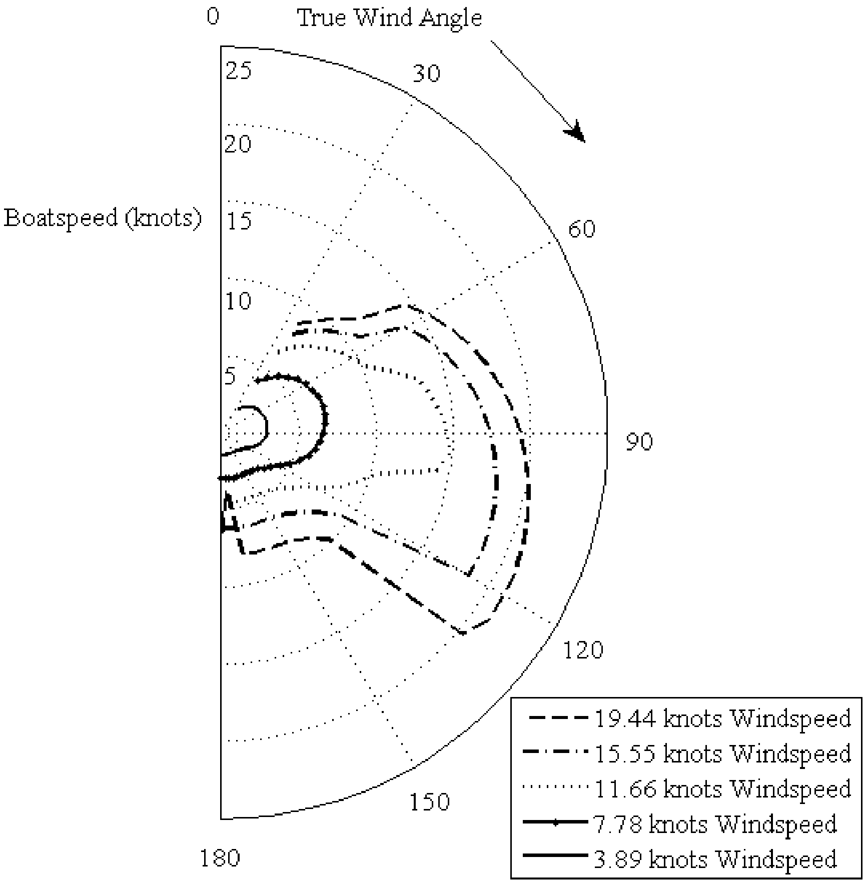


Figure 4.3.: Five DOF moth using deltaFlap trim variable

4.1.3. Six Degree Of Freedom Velocity Prediction Program

The six DOF is run as mentioned previously, simulating forces and moments in all x, y and z directions, (F_x, F_y, F_z, M_x, M_y and M_z). This VPP solves for forces and moments in all six DOF, taking into account the longitudinal centre's of effort for both the foils and sail. A six DOF VPP can determine the required rudder angle at a specific TWA and wind speed. Studies on this VPP have been omitted due to their complex nature, however it should be noted that in most sailing conditions the imbalance of the yaw moment, M_z was minimal, suggesting added drag due to the rudder angle component would be minimal.

This DOF is required if in-stationary simulations are to be run.

4.1.4. Comparison Between Four & Five Degree Of Freedom Velocity Prediction Program

A comparison between a four and five DOF VPP has been carried out to show the variations between the two. Fig. 4.4 below shows the comparison, note that the five DOF VPP will remain flying at lower and higher TWA's as compared to the four DOF VPP. The pitch angle altered by the five DOF VPP creates higher lift from the lifting foils to allow the the boat to fly through a broader range of TWA's. This is a far more realistic situation as compared to the four DOF VPP as the skipper will alter their weight position and the elevator flap on the rudder foil to maximise the lift produce by both of the lifting foils.

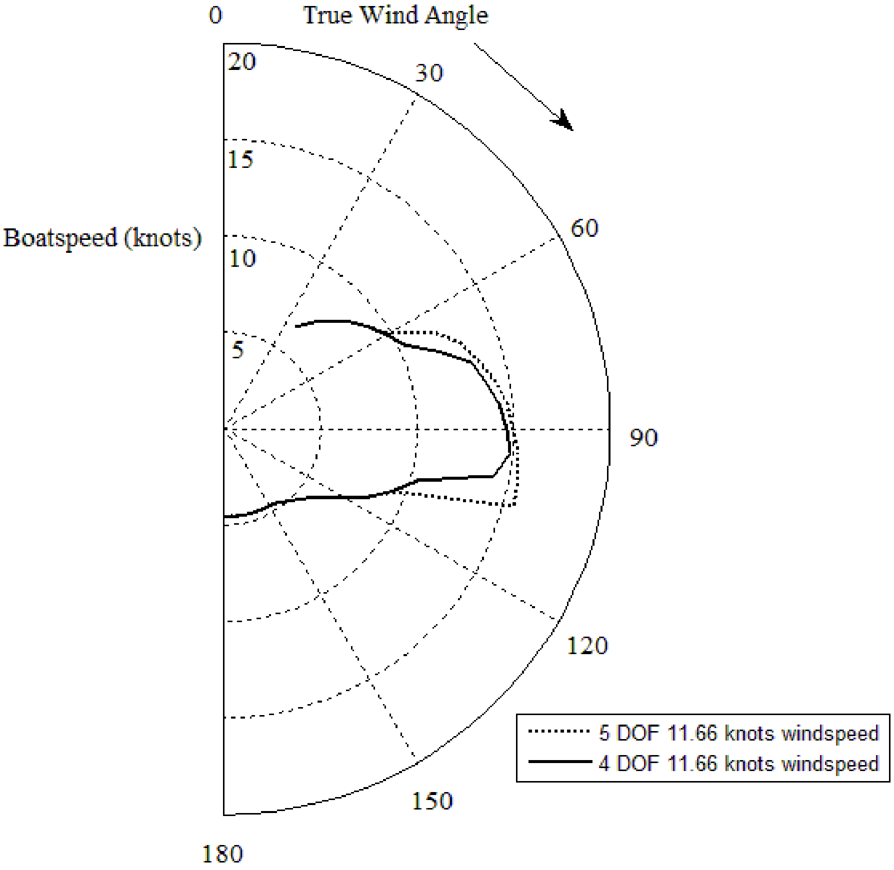


Figure 4.4.: Four & five DOF moth VPP

4.2. Variation Of Foil Lift to Drag Ratios

The lift to drag ratios of both the main and rudder foils have been varied to determine their effect on the VPP results. For this experiment the lift and drag coefficients for the lifting foils were input directly, the reduction in lift due to both the wand and the foil proximity to the surface is determined by a separate function LiftFact which has been estimated by the function of the wand as well as the influence of the free surface. This function is set to unity for all other tests.

As seen below in Fig. 4.5 below, an increase in L/D ratio will tend to increase the TWA at which the moth can take off. This allows the boat to run deeper and still remain on the foils, therefore increasing the downwind VMG. The VPP was not able to solve the similar scenario at lower TWA's, however it is assumed that a similar scenario would occur to that shown below in Fig. 4.5, allowing the boat to remain flying at lower TWA's and therefore increase the windward VMG.

As a design tool, this shows that variations in foil properties will have little effect on the moth's foiling and non-foiling speed. Therefore, to improve the moth's speed, focus should be on improving the aerodynamic efficiencies of the hull and rig. That is, increasing the driving force with respect to the side force produced by the rig and also decreasing windage drag.

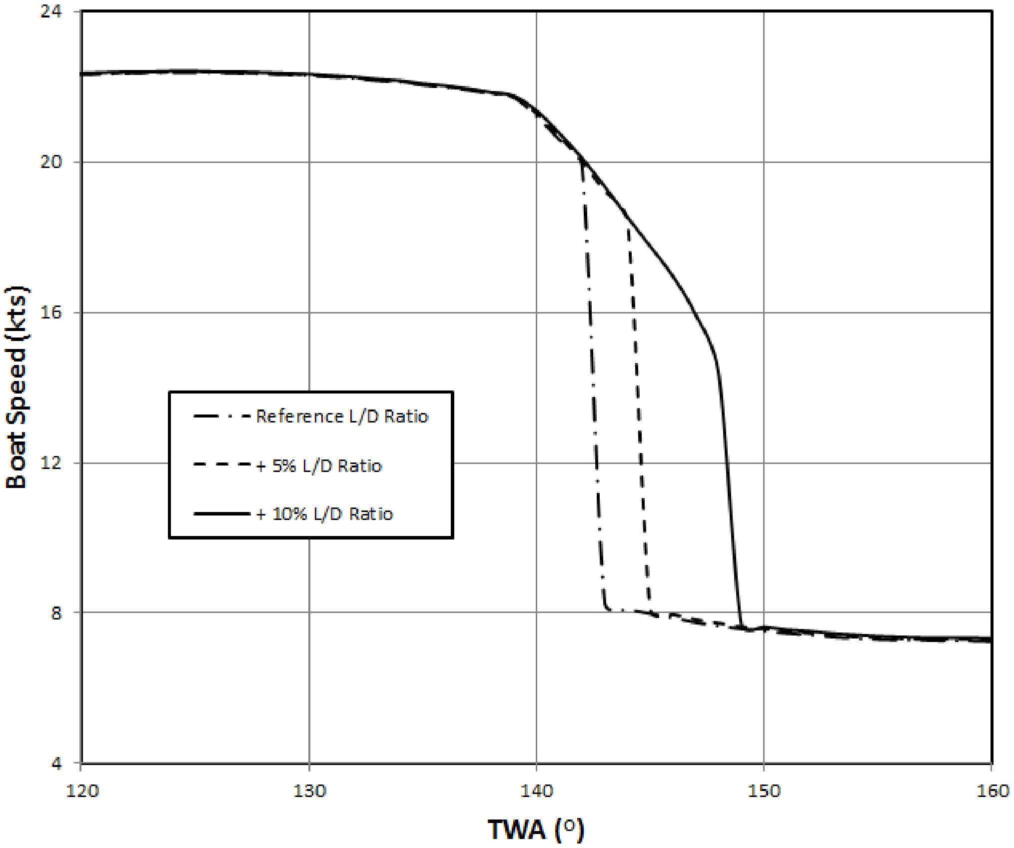


Figure 4.5.: Variation of L/D ratios

5. Conclusion

A VPP is common practice in predicting the performance of a sailing boat in a range of conditions and can be used for both design and improvement purposes. As a platform for the development of a high speed sailing velocity prediction method, it is a good solid start. The VPP developed has the ability to predict the performance of an International Moth Class dinghy with good accuracy. Improvements have been made over existing foiling moth VPP's, this has been achieved in the way of simplifing the foil force model to allow the FutureShip solver to solve for all sialing conditions, both foiling and non-foiling. Two additional degrees of freedom have been used, being both heel and pitch. These are critical components as discussed in subsection 4.1.2.

The over estimation of boat speed on both windward and leeward courses may be explained by an overly efficient rig or insufficient drag produced by hull and rig windage, as shown in section 4.2. Hydrodynamic efficiency was not considered as it is minimal in any circumstance, as only the lifting foils and a small portion of the strut are producing hydrodynamic drag and the aerodynamic drag is by far the major contributor to drag in the foiling condition.

The variation in TWA for windward courses could also be attributed to insufficient aerodynamic drag, as an increase in windward resistance will tend to increase the TWA for which the greatest VMG occurs, as discussed in chapter 3. The variation in leeward TWA could be explained by the hysteresis effect, as FutureShip Equilibrium calculates sailing conditions for TWA's in descending order. This could introduce errors in TWA for which the greatest leeward VMG occurs. As it is common for a skipper to decrease TWA to gain speed before being able to bear away to the TWA for the fastest VMG. This small variation in TWA is to allow the boat to take off, sharply increasing boat speed, allowing the boat to remain flying at greater TWA's.

The VPP is capable of predicting the performance of an International Moth Class dinghy. As a design tool, this VPP has shown the performance of a moth can be improved by increasing the foils L/D ratio, as shown in section 4.2. Allowing the moth to increase VMG when sailing both to windward and leeward. As shown in Figure 4.5 the moth's foiling and non-foiling are independent of L/D variations of the lifting foils. As discussed in section 4.2, the performance of the moth is dependant on the aerodynamic efficiencies of the hull and rig.

6. Further Work

As a result of the conclusions determined from this work, further work on developing this VPP to increase the usefulness for both design and comparison should be carried out.

Aerodynamic force due to windage and sail efficiency should be revised as this is the major drag component when the boat is flying as discussed in section 4.2. The accuracy of the VPP tends to hinge on the accuracy of this component. Increases in boat speed will also be made by increasing efficiencies in this area as discussed in section 4.2. Experimental studies conducted by Beaver and Zseleczky [2009] should be implemented to estimate these forces with greater accuracy. Due to current developments of wing sails for moth's, the effect on performance with the addition of a wing sail could be investigated.

Hydrodynamic force modules could be improved to include added resistance due to waves. These components will effect the TWA's at which the boat will take off. The effect of temporarily varying the TWA to make the boat take off, in order to increase downwind TWA and VMG as described by Findlay and Turnock [2008], has not been accounted for. This effect would also solve the hysteresis effect already mentioned in chapter 5.

This VPP does not take into account the effect of ventilation as studied by Binns et al. [2008], Emonson [2009] and Breslin and Skalak [1959]. As ventilation only tends to affect the boat temporarily, by removing all the lifting force from the affected foil, the boat then recovers, takes off and continues to sail. One way to implement this may be to assign a probability of the foils ventilating in each sailing state, which is dependant on a set of ventilation parameters.

The development of a hull resistance module to include wave making resistance and added resistance due to heel pitch and height should be implemented. Data obtained by Beaver and Zseleczky [2009] should be used to estimate these forces.

List of Figures

List of Tables

References

B. Beaver and J. Zseleczky. Full scale measurements on a hydrofoil international moth. *Chesapeake Sailing Yacht Symposium*, 2009.

J. R. Binns, P. A. Brandner, and J. Plouhinec. The effect heel angle and free-surface proximity on the performance and strut wake of a moth sailing dinghy rudder t-foil. *High Performance Yacht Design Conference*, 2008.

C. Bogle. Evaluation of the performance of a hydro-foiled moth by stability and force balance criteria. Master's thesis, TU-Berlin, 2010.

J. P. Breslin and R. Skalak. Exploratory study of ventilated flows about yawed surface-piercing struts. Master's thesis, Stevens Institute Of Technology, 1959.

Claughton, Wellicome, and Shenoi, editors. *Sailing Yacht Design*. University Of Southampton, 1998.

J. A. Emonson. An investigation into the effect of froude, weber and cavitation numbers on ventilation of surface piercing t-foils. Master's thesis, The Australian Maritime College, 2009.

M. W. Findlay and S. R. Turnock. Development and use of a velocity prediction program to compare the effects of changes to foil arrangement on a hydro-foiling moth dinghy. Master's thesis, University Of Southampton, 2008.

GmbH FutureShip. *FS-Equalibrium User Manual*, 2010.

M. Grimm. 2011 moth worlds - photo album, 2011.

Hydroptere. The sailboats - l'hydroptere, 2010. URL `http://www.hydroptere.com/index.php?page=l-hydroptere-en---presentation`.

Australia IMCA. International moth class association of australia - about, 2008. URL `http://www.moth.asn.au/moth/?page_id=2`.

ISAF. *International Moth Class Rules*. International Sailing Federation, 2007.

L. Larsson and R. E. Eliasson. *Priciples of Yacht Design*. McGraw Hill, 2007.

C. A. Marchaj. *Sail Performance - Techniques To Maximise Sail Power*. Adlard Coles, 1996.

Mothosphere. Foils history, 2010. URL `http://wiki.mothosphere.com/index.php?title=Foils`.

D. Schmidt. Learning to fly, 2007. URL `http://www.sailmagazine.com/racing/learning_to_fly/`.

TracTrac. Tractrac - live gps tracking, 2011. URL `http://www.tractrac.com/`.

Wunderground. Wunderground weather history, 2010. URL `http://www.wunderground.com/`.

NSW. Yachting. Sail sydney - sailing instructions, 2010.

A. Appendix - Weight & Buoyancy Data

A.1. Hull Weight Data

A simple weight estimation has been carried out on a moth dinghy in order to determine the total mass, center of mass and radius of gyration of the boat. The separate components which make up a moth have been broken down into masses and centers of mass and summed to find the total mass, center of mass and radius of gyration of the entire system. The weight estimation table is shown below in Tab. A.1. The radius of gyration of the hull is also calculated for use in time domain simulations as shown below in Tab. A.2.

Table A.1.: Hull weight estimation

Item	**Weight** *kg*	**LCG** *m*	**M.LCG** *kg.m*	**VCG** *m*	**M.VCG** *kg.m*	**TCG** *m*	**M.TCG** *kg.m*
Hull	*9.15*	*-1.71*	*-15.65*	*0.05*	*0.46*	*0.00*	*0.00*
Hull fittings/frame	*6.00*	*-2.24*	*-13.44*	*0.37*	*2.22*	*0.00*	*0.00*
Rigging	*3.00*	*-1.53*	*-4.59*	*2.66*	*7.98*	*0.00*	*0.00*
Sail	*3.00*	*-2.10*	*-6.30*	*3.05*	*9.15*	*0.00*	*0.00*
Centre board/foil	*1.50*	*-1.41*	*-2.12*	*-0.91*	*-1.37*	*0.00*	*0.00*
Rudder/foil	*0.85*	*-3.83*	*-3.26*	*-0.50*	*-0.43*	*0.00*	*0.00*
Outrigger	*0.65*	*-3.61*	*-2.35*	*0.11*	*0.07*	*0.00*	*0.00*
Totals	***24.15***		***-47.69***		***18.09***		***0.00***
Weight	***24.15***	*kg*					
LCG (x)	***-1.97***	*m*					
VCG (z)	***0.75***	*m*					
TCG (y)	***0.00***	*m*					

Table A.2.: Moth hull radius of gyration

Item	**yz.CG** m	I_{ROLL} $kg.m^2$	**xz.CG** m	I_{PITCH} $kg.m^2$	**xy.CG** m	I_{YAW} $kg.m^2$
Hull	*0.70*	*4.47*	*0.75*	*5.11*	*0.26*	*0.64*
Hull fittings/frame	*0.38*	*0.86*	*0.46*	*1.28*	*0.27*	*0.42*
Rigging	*1.91*	*10.96*	*1.96*	*11.55*	*0.44*	*0.59*
Sail	*2.30*	*15.88*	*2.30*	*15.93*	*0.13*	*0.05*
Centre board/foil	*1.66*	*4.13*	*1.75*	*4.61*	*0.56*	*0.48*
Rudder/foil	*1.25*	*1.33*	*2.24*	*4.25*	*1.86*	*2.93*
Outrigger	*0.64*	*0.27*	*1.76*	*2.00*	*1.64*	*1.74*
Totals		***37.89***		***44.74***		***6.85***
Gyradius, k_{ROLL}	***1.25***	m				
Gyradius, k_{PITCH}	***1.36***	m				
Gyradius, k_{YAW}	***0.53***	m				

A.2. Skipper Weight Data

The weight of the skipper has been assumed to be 80kg. This is typically the maximum weight of a competitive moth sailor. The center of mass is of a human in a seated position has been assumed to be approximately $0.2m$ from the seat base, at approximately the persons navel.

This is difficult to implement into the body fixed coordinate system of the moth dinghy as this height will change significantly due to the skippers transverse position on the boat. Because of this issue, an average height had to be found for use in the program. As the skipper would spend a significant portion of their time toward the outboard extents of the wings, the center of mass close to this position was chosen.

A.3. Hull Buoyancy Data

Hull buoyancy data is calculated directly from the hull shape itself. A generic moth hull shape has been determined from direct measurement data as well as scaling from photographs courtesy of Martin Grimm. From this data, a three dimensional model has been constructed in order to take measurements for the purpose of the VPP. This model can be seen in Fig. 2.1.

The hull's surface can be imported directly into FSE from an .iges file. Errors can often occur during this process particularly with complex geometries, this occurred around the turn of bilge on the moth model. In this case a hull definition offset file (.shf) can be imported.

A series of sections and offsets was defined and exported from Rhino surface modeling software as a points file. This data has to then be arranged in the format shown below in Fig. A.1in a text editor. The file extension must then be changed to .shf.

Offset file format

```
#x y z flag
Hull-Offsets      // group name
0    0     -0.5 1 // First point of section has flag value 1
0    0.5   -0.4 0 // Other points of section have flag value 0
0    1      0   0
1    0     -1   1
1    1     -0.8 0
1    2      0   9 // Last point of shape has flag value 9
end
```

Figure A.1.: Hull definition file format

B. Appendix - Aerodynamic Data

B.1. Sail Data

The sail planform is taken directly from photographs, the area is set to the maximum allowed by the rules of $8m^2$, ISAF [2007]. Sail lift data was determined from both experimental studies conducted by Marchaj [1996] and the IMS sail data from Claughton et al. [1998]. As the moth dinghy only utilises a main sail, the lift and drag data for a main sail was used to determine the shape of the curve before scaling to the theoretical maximum lift coefficient determined by Marchaj [1996], for a single skin, wing mast sail. The sail lift coefficient is shown below in Fig. B.1. The drag coefficient curve was also scaled, however only for TWA of between 0 and $\approx 160°$. This was done so as to increase the lift induced drag, but not to increase the drag for an incidence of $\approx 90°$. The sail drag coefficient is shown below in Fig. B.2. Sail lift and drag are then calculated using B.1 and B.2.

The experimental investigations used to obtain these coefficients were conducted in a wind tunnel on a varying sail types. To record the coefficients which result in the highest driving force (in the x direction), the sails are trimmed with respect to the TWA to maximise the driving force, the lift and drag force are then recorded. The sail lift and drag coefficients are then calculated using B.1 and B.2 respectively.

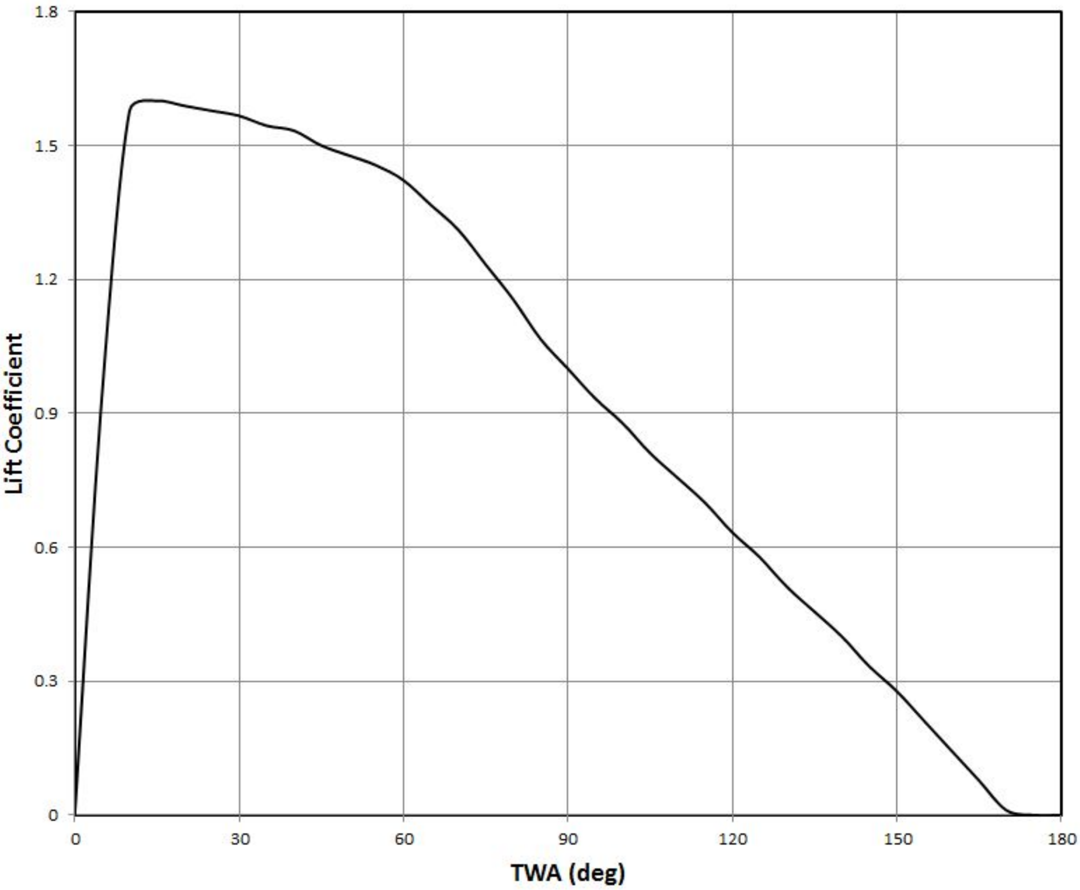


Figure B.1.: Sail lift coefficient

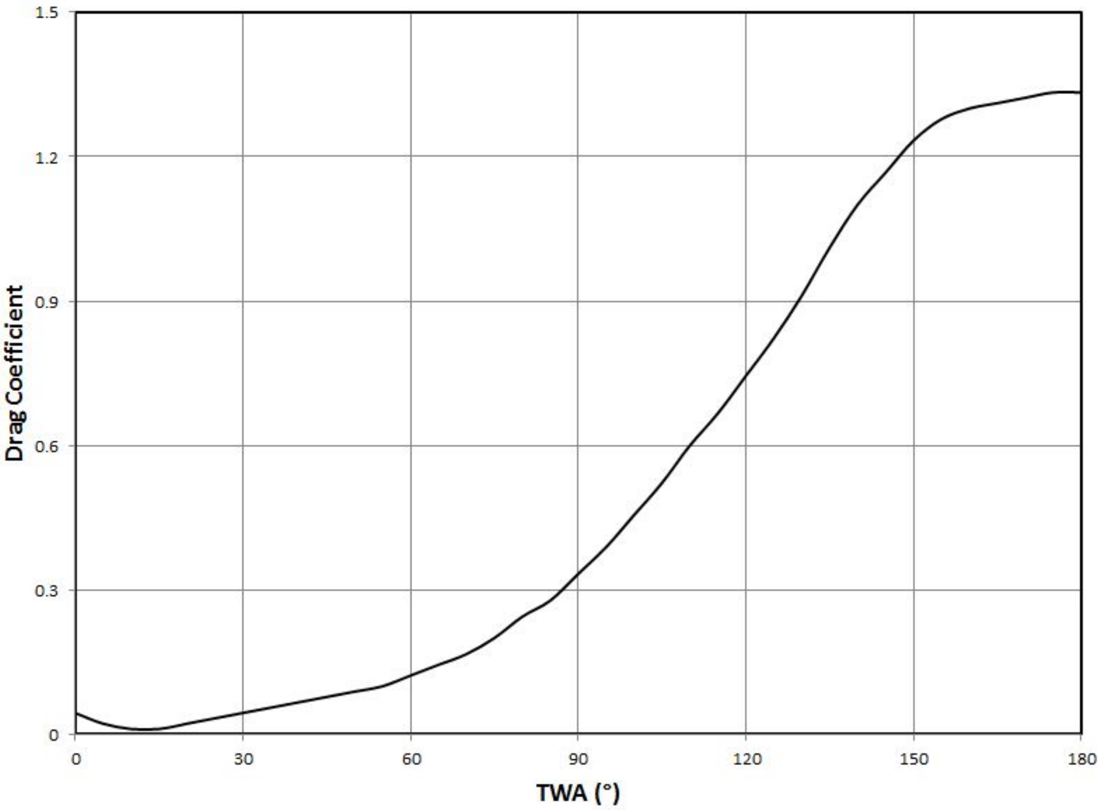


Figure B.2.: Sail drag coefficient

$$L = {}^1\!/\!_2.C_L.\rho.V^2.A \tag{B.1}$$

$$D = {}^1\!/\!_2.C_D.\rho.V^2.A \tag{B.2}$$

B.2. Windage Data

The windage drag force is calculated using B.3. The projected areas used for the windage calculations have been determined using Rhino surface modeling software. The projected areas in each plane are summarised in Tab. B.1. The drag coefficients used for drag in each plane have been estimated to 0.8.

$$D_W = {}^1\!/\!{}_2 . C_D . \rho . V^2 . A \tag{B.3}$$

Table B.1.: Moth projected areas

A_x	$0.97m^2$
A_y	$2.87m^2$
A_z	$3.87m^2$

C. Appendix - Hydrodynamic Data

C.1. Hull Data

As geometrical hull data is not available, the hull model was determined from the international moth class rules ISAF [2007] and pictures taken at the 2011 world championships courtesy of Martin Grimm. The design is based around the Prowler design by John Illett of Western Australia. The imported hull lines can be seen below in Fig. C.1.

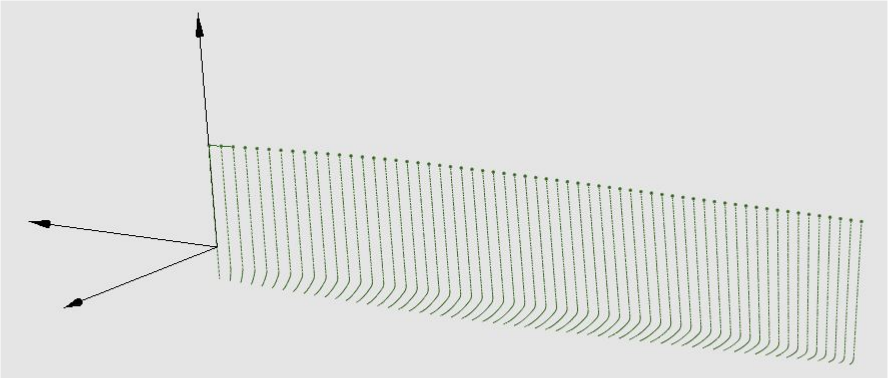


Figure C.1.: Imported hull lines

Hull resistance is managed by an over estimated form factor (k). This is done as resistance modules do not take into account the flying height of the boat, this means the hull resistance force would not reduce to zero upon the hull leaving the water surface.

C.2. Centre Board Data

The centre board lift and drag force is calculated in a similar way to that of the sail, using B.1 and B.2. The planform and position data was measured from photographs taken by Martin Grimm. The lift and drag coefficients have been determined for the from the program XFOIL, this program determines the two dimensional lift and drag coefficients of the foil section. The lift and drag coefficients used are shown below in Fig. C.2 and Fig. C.3.

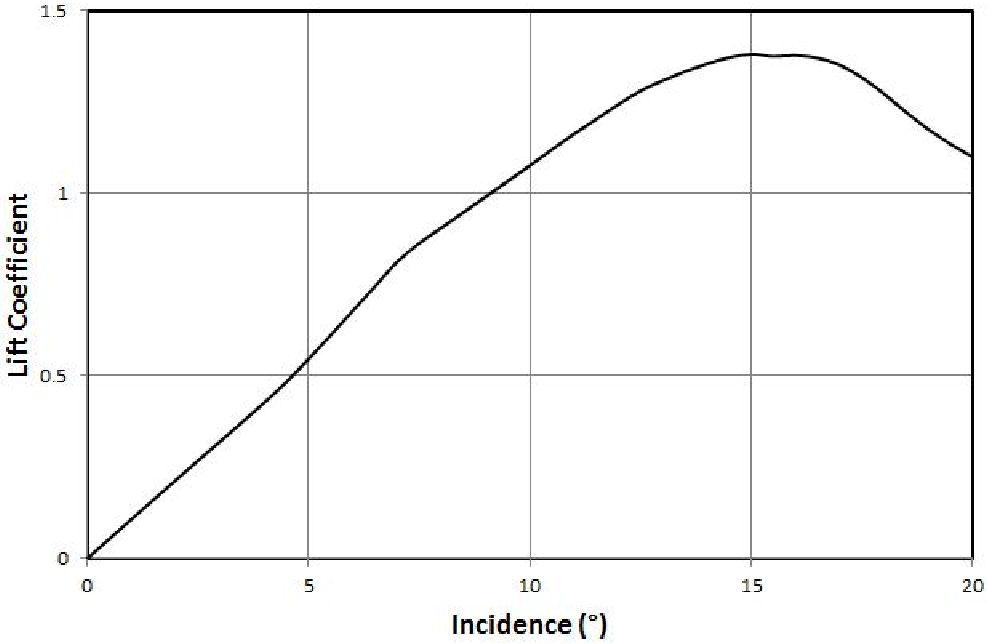


Figure C.2.: Centreboard lift coefficient

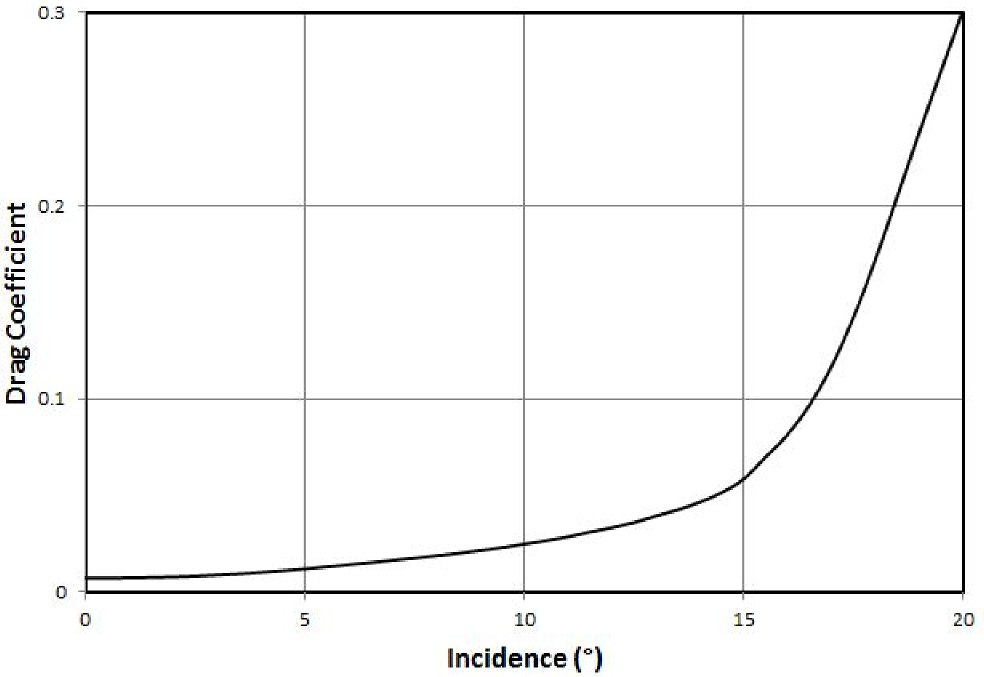


Figure C.3.: Centreboard drag coefficient

The calculation differs from that of the sail because as the boat's flying height increases, the effective area and therefore force is reduced. As the boat lifts out of the water the vertical centre of effort lifts, this is best described in Fig. C.4, diagram courtesy of Christian Bogle Bogle [2010]. It can be seen that the COE represented by F_{res} acts above the COA on a centre board without a hydrofoil, this is due to wing tip losses due to tip vortices. With a T-foil centre board, the COE acts at the COA due to the effects of both the T-foil and the hull, the COE drops below the COA in the foiling condition due to the absence of the hull at the surface. The vertical COE as a function of boat height is shown in Fig. C.5.

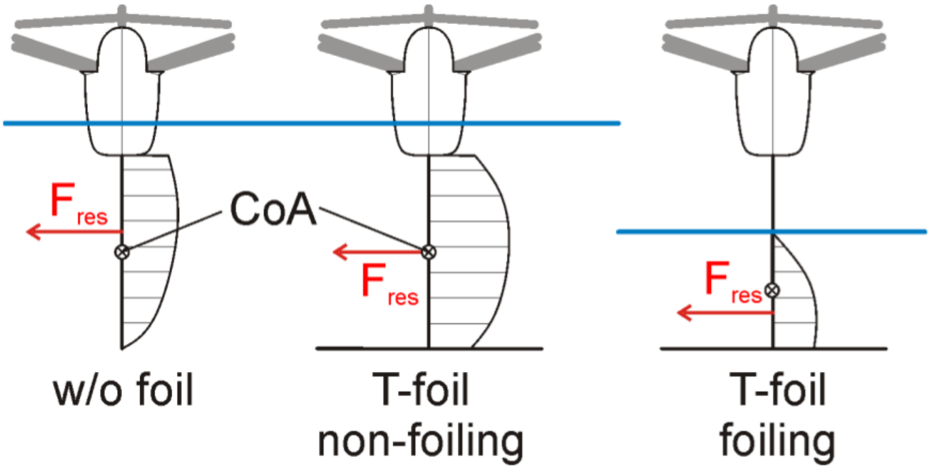


Figure C.4.: Vertical COE at varying flying height, Bogle [2010]

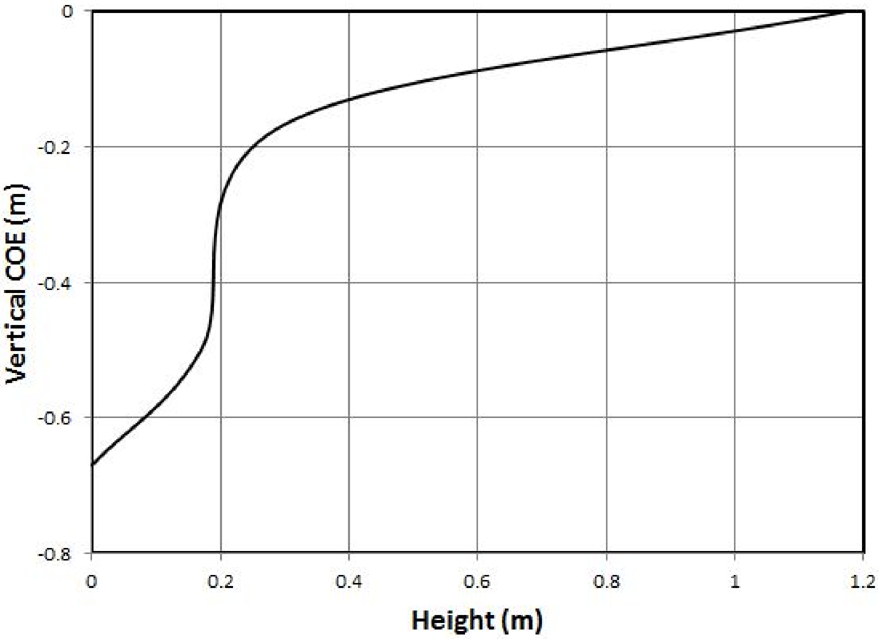


Figure C.5.: Vertical COE of centre board

C.3. Rudder Data

The rudder lift and drag force is calculated in a similar way to that of the sail, using B.1 and B.2. The calculation differs from that of the sail because as the boat's flying height increases, the effective area and therefore force is reduced. The planform and position data was measured from photographs taken by Martin Grimm. Data for the rudder is the same used for the centre board, the lift and drag coefficients for the rudder are shown above in Fig. C.6 and Fig. C.7 respectively. The vertical COE is effected in the same way as the centreboard shown above in Fig. C.4. As the hull is not located directly above the rudder the vertical COE is always below the COA. The COE with respect to the flying height can be seen below in Fig. C.8.

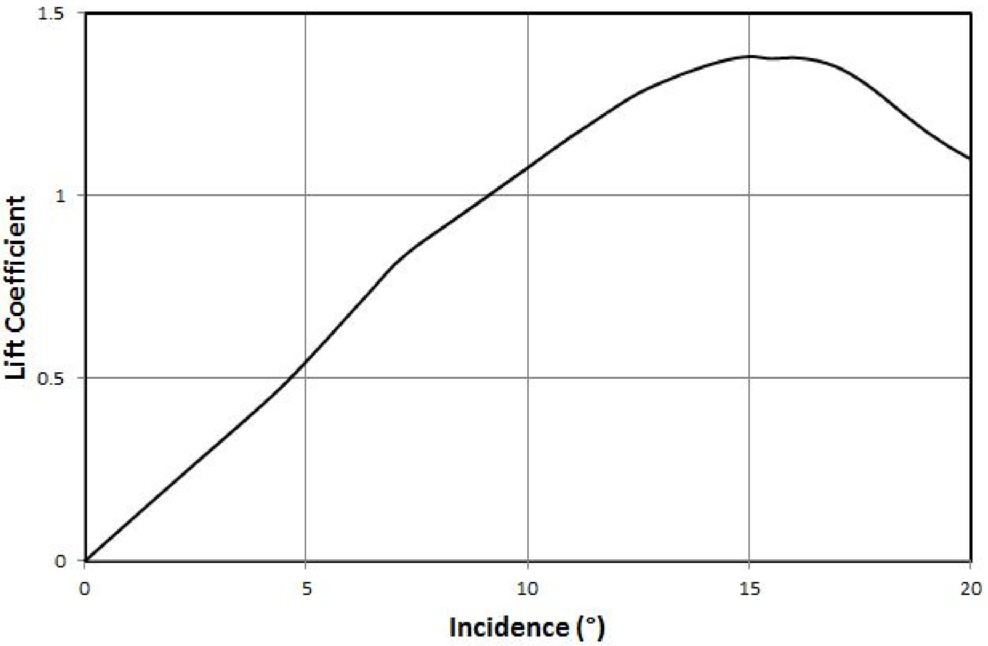


Figure C.6.: Centre board lift coefficient

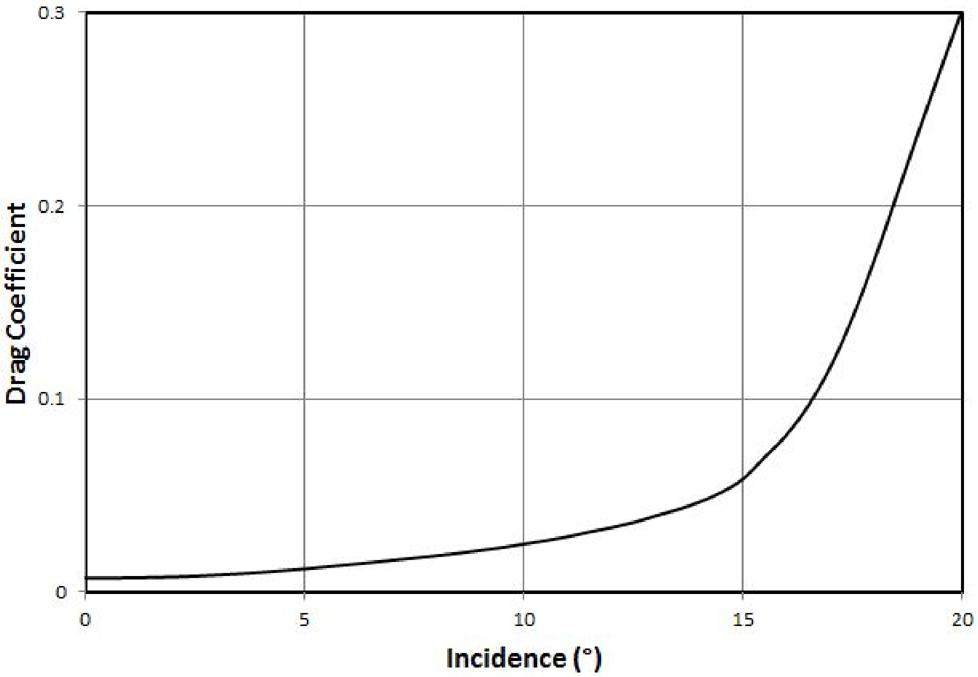


Figure C.7.: Centre board drag coefficient

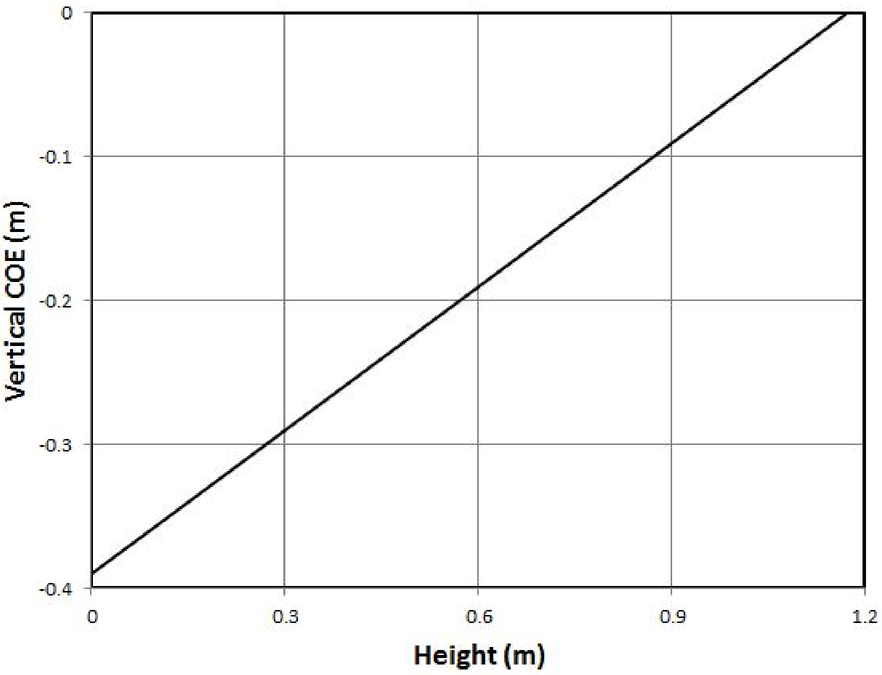


Figure C.8.: Vertical COE of rudder

D. Appendix - FutureShip Equilibrium

D.1. Standard Units

The standard units for the following dimensions are as follows in Tab. D.1.

Table D.1.: FutureShip standard units

Dimension	**Unit**
Length	m
Mass	kg
Time	s
Force	N
Angle	deg

D.2. Mass Modules

D.2.1. Hull Mass

This module calculates the effect of a point mass located at a point on the boat in body fixed coordinates, this point mass represents the mass of the hull and rig. Here data from appendix sec. A.1 has been used to determine the data input. This module is a standard FSE module.

Input Data

Mass The mass in kg

Centre The center of gravity in body fixed coordinates (x, y, z)

Gyradius The gyradii with respect to the CG (not used in steady state simulations)

Cross Product Gyradius The radii of the products of inertia with respect to the center of gravity (not used in steady state simulations)

D.2.2. Skipper Mass

This module calculates the effect of a moving point mass in two directions. As heeling and trimming moments are the most significant these directions were chosen (y and x directions respectively). The range in which this mass can move is set in, program settings>valid range or alternatively directly into the modules source code. Data for this module can found in appendix sec. A.2. This module is a standard FSE module.

Input data

Mass The mass in kg

Centre The center of gravity in body fixed coordinates (x, y, z)

Gyradius The gyradii with respect to the CG (not used in steady state simulations)

Cross Product Gyradius The radii of the products of inertia with respect to the center of gravity (not used in steady state simulations)

MassMove1 First direction, input as vector $< x, y, z, >$

MassMove2 Second direction, input as vector $< x, y, z, >$

D.3. Aerodynamic Modules

D.3.1. Rig Force

The rig force module calculates the aerodynamic forces produced by the rig at the centre of effort. The modules uses curves to describe the longitudinal and vertical position of the centre of effort, the lift and drag coefficients of the sail. De-powering parameters of TWIST and FLAT are used to reduce the sails efficiency to reduce the heeling moment on the boat. The REEF parameter is also used to to physically reduce the sail area, this parameter is not used in this case as a moths sail cannot be reefed. Data for this module can found in appendix sec. B.1. This module is a standard FSE module.

Input Data

DWL The design waterline length of the boat

Mast Height The height of the mast above the still waterline

Boom Height The height of the boom above the still waterline

Sail Area The reference sail area

Centre Of Area The centre of area with reference to the zero point in the x and y axes and the still waterline

Efficiency The increase of induced resistance compared to elliptical loading

Separation Constant The separation constant

Twist Weight The influence of the TWIST parameter

Twist Weight Lift The influence of the TWIST parameter of lift

Sopt Optimum position of the COE as a fraction of mast height

Fluid The fluid properties to use

CL The lift coefficient with respect to TWA

CDp The drag coefficient with respect to TWA

XCE Longitudinal COE position with respect to the COA, normalized by the waterline length

ZCE COE height with respect to the COA, normalised by the waterline length

REEF The REEF trim parameter

FLAT The FLAT trim parameter

TWIST The TWIST trim parameter

D.3.2. Windage Force

The windage module calculates the aerodynamic drag of the hull and rigging. The module uses the projected areas in each plane and a respective drag coefficient to calculate the drag in each plane. The COA is also used to calculate the moments produced. Data for this module can found in appendix sec. B.2. This module is a standard FSE module.

Input Data

Area The projected area in each plane

CD The drag coefficient in each plane

Centre The centre of area

Force Type Aerodynamic or hydrodynamic drag

Fluid The fluid property to use

D.4. Hydrodynamic Modules

D.4.1. Buoyancy force

The hull buoyancy force is calculated from the submerged portion of the hull. The hull is defined by a hull definition file (.shf), a series of hull offsets defined in a text file. The buoyancy force is calculated by adjusting the vessels draft to balance the vertical forces. Data for this module can found in appendix sec. C.1. This module is a standard FSE module.

Input Data

Edit Offset Spec The offset set is input and modified, this can be done by a hull definition file (.shf) or by importing an .iges file. The imported surface can be scaled and translated to the required orientation with respect to the zero point

Form Factor The form factor (k) used in the calculation of frictional resistance

Fluid The fluid property to use

Impermeability The impermeability of the hull. 1 for closed compartments and 0 for flooded a compartment

Plate Thickness Additional volume due to plate thickness

Added Mass The added mass in each axis direction of the body

Wave Height The wave height as a function of the x position along the boat

Wave Scale The factor to scale the wave height

Sectional Drag The sectional damping coefficients

D.4.2. Centerboard Force

The centre board force module calculate the lift and drag due to the vertical centre board. The lift and drag force is calculated for the relative boat flying height to account for the reduced effective area. The aerodynamic force due to the emerged foils are neglected in this module. Data for this module can found in appendix sec. C.2. This module was compiled by Bogle [2010].

Input Data

TopLE Top leading edge point on the centre board

Length Strut length

Thickness Thickness of section as percentage of chord length

Chord Chord length of the centre board

VCOE Vertical COE as distance from COA normalised by immersion with respect to immersion normalised by length

alpha The forward angle of the strut

fAReff Factor for calculating the effective aspect ratio (Oswald factor e included) with respect to immersion normalised by length

Foil

CoP2D The COE of the foil as percentage of chord length

cL The lift coefficient with respect to the incidence

cD The drag coefficient with respect to the incidence

D.4.3. Rudder Force

The rudder force module calculate the lift and drag due to the vertical rudder. The lift and drag force is calculated for the relative boat flying height to account for the reduced effective area. The aerodynamic force due to the emerged foils are neglected in this module. Data for this module can found in appendix sec. C.3. This module was compiled by Bogle [2010].

Input Data

TopLE Top leading edge point on the rudder

Length Strut length

Thickness Thickness of section as percentage of chord length

Chord Chord length of the rudder

VCOE Vertical COE as distance from COA normalised by immersion with respect to immersion normalised by length

alpha The forward angle of the strut

fAReff Factor for calculating the effective aspect ratio (Oswald factor e included) with respect to immersion normalised by length

Foil

CoP2D The COE of the foil as percentage of chord length

cL The lift coefficient with respect to the incidence

cD The drag coefficient with respect to the incidence

D.4.4. Main Foil Lifting Force

The main lifting foil force module calculates the force due to a horizontal lifting foil on the centre board. The lift force due to the foil determined by a procedure outlined by Binns et al. [2008].The elevator flap angle is defined with respect to the boat's flying height as shown above in Fig. 2.6. The additional lift and drag due to the flap is defined with respect to elevator flap angle as shown above in Fig. 2.7 and Fig. 2.8. Additional data for this module can found in appendix sec. 2.3.3. This module is a modification of the original work compiled by Bogle [2010].

Input Data

Foil

CoP The centre of pressure of the foil in body fixed coordinates

Planform The planform area of the foil

AReff The effective aspect ratio of the foil

Chord Length The foil chord length

A Coefficient A as a function of depth to chord ratio

B Coefficient B as a function of depth to chord ratio

C Coefficient C as a function of depth to chord ratio

D Coefficient D as a function of depth to chord ratio

critAoA Critical incidence, as a warning message only

LiftFact Scale the lift force as a function of flying height

WandLift Increase in lift as a function of elevator flap angle

WandDrag Increase in drag as a function of elevator flap angle

FlapAngle Elevator flap angle as a function of flying height

D.4.5. Rudder Foil Lifting Force

The rudder foil force module calculates the force due to a horizontal lifting foil on the rudder. The lift force due to the foil determined by a procedure outlined by Binns et al. [2008]. The elevator flap controlled by the skipper is determined by a TRIM function to adjust the boats trim and flying height. The additional lift and drag due to the flap is defined with respect to elevator flap angle as shown above in Fig. 2.9 and Fig. 2.10. Data for this module can found in appendix sec. 2.3.3. This module is a modification of the original work compiled by Bogle [2010].

Input Data

Foil

CoP The centre of pressure of the foil in body fixed coordinates

Planform The planform area of the foil

AReff The effective aspect ratio of the foil

Chord Length The foil chord length

A Coefficient A as a function of depth to chord ratio

B Coefficient B as a function of depth to chord ratio

C Coefficient C as a function of depth to chord ratio

D Coefficient D as a function of depth to chord ratio

critAoA Critical incidence, as a warning message only

LiftFact Scale lift force as a function of flying height

WandLift Increase in lift as a function of elevator flap angle

WandDrag Increase in drag as a function of elevator flap angle

E. Appendix - User Modules

In order to calculate the lift and drag due to the main and rudder foils, a Dynamic Link Library (.DLL) had to be compiled. A sample code is provided with the FutureShip software which is able to be modified to produce the desired force.

The code below in section E.1 and section E.2 is written in C++ and is a modification of the work done by Bogle [2010]. The code is used to estimate forces on both the main and rudder foils respectively, given a set of input parameters as described in section 2.3.3 and section 2.3.3. The code used is shown below for the main and rudder foil respectively.

The software package used to input the code is Microsoft Visual Studio 2008, it was found that newer versions of this software were not capable of successfully compiling the code to produce a .DLL. The compiled .DLL is copied to the FutureShip program files > Plugins > Win32 folder for the modules to be available for use with the software.

E.1. Main Foil

```
#include <string> #include <iostream> #include<fstream> #include <cmath>

#include "fsequi_api.h"

#define OPTION_DEBUG 1<<0 #define OPTION_WARNING 1<<1 #define OPTION_USRFCTN 1<<2

#define OPTION_2DData 1<<3 #define CLASSNAME ControlSysFoilModul #define MODULENAME "ControlSysFoil"

#define DBG if(mOptions & OPTION_DEBUG) outFile <<getName()<<": "

#define WRG if(mOptions & OPTION_WARNING) cout <<getName()<<": "

using namespace std;
```

```
class CLASSNAME : public FEQ_ForceModule { // define class data // Geomery Data FSE_Vector mCoP; FSE_Double mplan; FSE_Double mAReff; FSE_Double mChord;

// Profile Data

FSE_NResponseFunction mcoA;

FSE_NResponseFunction mcoB;

FSE_NResponseFunction mcLiftFact;

FSE_NResponseFunction mcWandLift;

FSE_NResponseFunction mcoC;

FSE_NResponseFunction mcoD;

FSE_NResponseFunction mcWandDrag;

FSE_Double mcritAoA; FSE_Double mfAReff;

// Flap FSE_NResponseFunction mcFlapAngle;

FSE_Optionset mOptions;

FSE_Fluid mFluid; ofstream outFile;

public:

CLASSNAME()

:mcoA("A",1), mcoB("B",1), mcLiftFact("cLiftFact",1),

mcWandLift("cWandLift",1), mcoC("C",1),mcoD("D",1),

mcWandDrag("cWandDrag",1), mcFlapAngle("cFlapAngle",1)

{

// define which high level data objects you want to // have accessible from the graphical editor

// Geometry Data

defineDataObject("Foil.CoP", &mCoP, "Center of pressure foil");

defineDataObject("Foil.Planform", &mplan, "Planform area of foil");

defineDataObject("Foil.AReff", &mAReff, "Effective aspect ratio");

defineDataObject("Foil.Chord", &mChord, "Foil chord length");

// Profile Data
```

```
defineDataObject("Foil.A", &mcoA, "'A' coeff. as function of h/c");
mcoA.setLabel(0,"h/c");
defineDataObject("Foil.B", &mcoB, "'B' coeff. as function of h/c");
mcoB.setLabel(0,"h/c");
defineDataObject("Foil.C", &mcoC, "'C' coeff. as function of h/c");
mcoC.setLabel(0,"h/c");
defineDataObject("Foil.D", &mcoD, "'D' coeff. as function of h/c");
mcoD.setLabel(0,"h/c");
defineDataObject("Foil.critAoA", &mcritAoA, "Critical angle of attack (Warning message only)");
defineDataObject("Foil.LiftFact", &mcLiftFact, "Lift factor as function of flying height");
mcLiftFact.setLabel(0,"height");
defineDataObject("Foil.WandLift", &mcWandLift, "Lift increase due to wand as function of flying height");
mcWandLift.setLabel(0,"FlapAngle");
defineDataObject("Foil.WandDrag", &mcWandDrag, "Drag increase due to wand as function of flying height");
mcWandDrag.setLabel(0,"FlapAngle");
//Flap
defineDataObject("Foil.FlapAngle", &mcFlapAngle, "Flap angle as a function of flying height");
mcFlapAngle.setLabel(0,"height");
// Option for DeltaFlap = Response Function of VS and SINK
mOptions.defineOption(OPTION_DEBUG,"Debug");
mOptions.defineOption(OPTION_WARNING,"Warning messages");
mOptions.defineOption(OPTION_USRFCTN,"Use_FlapNResFctn");
defineDataObject("Options",& mOptions,"Various Options");
mFluid.setFluid("Water");
defineDataObject("Fluid",& mFluid, "fluid to use");
```

```
outFile.open("debugF.txt");

};

virtual const char* getDocu() const{ return "Lift and Drag of a horizontal hydrofoil
with Flap, controled by a predefined ditcher or a control surface delta(flap)=FCTN(VS,Z)";
}

virtual std::string getType() const { return MODULENAME;}

// you need to implement this one virtual

FSE_Motor computeForces(const FEQ_Condition& fc){

double pi = 3.14159265;

// get density

double rho = mFluid.getDensity();

// Common Values

double pitch = fc.getPitch();

double heel = fc.getHeel();

double Vs = fc.getVs();

double height = fc.getX(2); //added on the foil depth

double h_c = min(3.3,(-mCoP[2]+height)/mChord);

h_c = max (0.0, h_c); double Flap = mcFlapAngle(height);

// compute the local flow direction at the position of the Foil in body fixed coordi-
nates

FSE_Vector localFlow = fc.getLocalVelocityB(mCoP);

double Va = sqrt(pow(localFlow[2],2)+pow(localFlow[0],2));

double aoa = -atan2(localFlow[2],localFlow[0]) * 180./pi;

// calculate CL and CD

double cL = (mcoA(h_c)*aoa+mcoB(h_c))*min(mcLiftFact(height),2.0)+

mcWandLift(Flap);

double cD = (mcoC(h_c)*cL*cL+mcoD(h_c))+ mcWandDrag(Flap);

DBG << "height: " << height << " cL: " << cL << " cD: " << cD << " Wan-
dLift " << mcWandLift (Flap) << " WandDrag " << mcWandDrag (Flap) << "
```

```
LiftFact: " << min(mcLiftFact(height),2.0) << endl; FSE_Vector coeff; coeff[2] = cL*cos(heel*pi/180.); coeff[1] = - cL*sin(heel*pi/180.);
coeff[0] = - cD;
return force; };
static FEQ_ForceModule* createMyself(){ return new CLASSNAME();};
};
static FEQ_RegisterForceModuleType
myCreator(MODULENAME,CLASSNAME::createMyself);
```

E.2. Rudder Foil

```
#include <string> #include <iostream> #include<fstream>
#include <cmath>
#include "fsequi_api.h"
#define OPTION_DEBUG 1<<0
#define CLASSNAME TrimVarFoilModul
#define MODULENAME "TrimVarFoil"
#define DBG if(mOptions & OPTION_DEBUG)
outFile <<getName()<<": "
#define WRG if(mOptions & OPTION_DEBUG) cout <<getName()<<": "
using namespace std;
class CLASSNAME : public FEQ_ForceModule {
// define class data
// Geomery Data
FSE_Vector mCoP;
FSE_Double mplan;
FSE_Double mAReff;
FSE_Double mChord;
// Profile Data
```

```
FSE_NResponseFunction mcoA;
FSE_NResponseFunction mcoB;
FSE_NResponseFunction mcLiftFact;
FSE_NResponseFunction mcSkipLift;
FSE_NResponseFunction mcoC;
FSE_NResponseFunction mcoD;
FSE_NResponseFunction mcSkipDrag;
FSE_Double mfAReff;
// Flap
FSE_Double mdeltaFlap;
FSE_Fluid mFluid;
ofstream outFile;
FSE_Optionset mOptions; public:
CLASSNAME()
:mcoA("A",1), mcoB("B",1), mcLiftFact("cLiftFact",1),
mcSkipLift("cSkipLift",1), mcoC("C",1),mcoD("D",1),
mcSkipDrag("cSkipDrag",1)
{ // define which high level data objects you want to
// have accessible from the graphical editor
// Geometry Data
defineDataObject("Foil.CoP", &mCoP, "Center of pressure Foil");
defineDataObject("Foil.Planform", &mplan, "Planform area of foil");
defineDataObject("Foil.AReff", &mAReff, "Effective aspect ratio");
defineDataObject("Foil.Chord", &mChord, "Foil chord length");
// Profile Data
defineDataObject("Foil.A", &mcoA, "’A’ coeff. as function of h/c");
mcoA.setLabel(0,"h/c");
defineDataObject("Foil.B", &mcoB, "’B’ coeff. as function of h/c");
mcoB.setLabel(0,"h/c");
```

```
defineDataObject("Foil.C", &mcoC, "’C’ coeff. as function of h/c");
mcoC.setLabel(0,"h/c");
defineDataObject("Foil.D", &mcoD, "’D’ coeff. as function of h/c");
mcoD.setLabel(0,"h/c");
defineDataObject("Foil.LiftFact", &mcLiftFact, "Lift factor as function of flying height");
mcLiftFact.setLabel(0,"height");
defineDataObject("Foil.SkipLift", &mcSkipLift, "Lift increase due to skipper control");
mcSkipLift.setLabel(0,"deltaFlap");
defineDataObject("Foil.SkipDrag", &mcSkipDrag, "Drag increase due to skipper control");
mcSkipDrag.setLabel(0,"deltaFlap");
defineDataObject("Foil.fAReff", &mfAReff, "Factor for calc. of eff. AR (+Oswald factor) ");
mOptions.defineOption(OPTION_DEBUG,"Debug");
defineDataObject("Options",& mOptions,"Various options");
mFluid.setFluid("Water");
defineDataObject("Fluid",& mFluid, "fluid to use");
outFile.open("debugR.txt");
defineTrimParameter("deltaFlap",-5,5,0,true,"Flap-angle"); };
virtual const char* getDocu() const{ return "Lift and Drag of a horizontal hydrofoil with Flap, controled with a TRIM Variable"; }
virtual std::string getType() const { return MODULENAME;}
// you need to implement this one virtual
FSE_Motor computeForces(const FEQ_Condition& fc){
double pi = 3.14159265;
double rho = mFluid.getDensity();
// Common Values
double Vs = fc.getVs();
```

```
double pitch = fc.getPitch();
double heel = fc.getHeel();
double height = fc.getX(2);
//added on the foil depth
double h_c = min(3.3,(-mCoP[2]+height)/mChord);
h_c = max (0.0, h_c);
// compute the local flow direction at the position of the Foil in body
// fixed coordinates
FSE_Vector localFlowB = fc.getLocalVelocityB(mCoP);
FSE_Vector localFlowA = fc.getLocalVelocityA(mCoP);
// FSE_Vector localFlowB = localFlowA.transform(fc.getTransformationMatrixAB());
double Va = sqrt(pow(localFlowB[0],2) + pow(localFlowB[2],2));
double aoa = -atan2(localFlowB[2],localFlowB[0]) * 180./pi;
// get Trimvariable
double deltaFlap = fc.getTrimValue("deltaFlap");
double cL = (mcoA(h_c)*aoa+mcoB(h_c))*min(mcLiftFact(height),2.0)+
mcSkipLift(deltaFlap);
double cD = (mcoC(h_c)*cL*cL+mcoD(h_c))+mcSkipDrag(deltaFlap);
//DBG << "height: " << height << " cL: " << cL << endl;
// calculate Forces in Bodyfixed CSYS B
FSE_Vector coeff;
coeff[2] = cL*cos(heel*pi/180.); coeff[1] = - cL*sin(heel*pi/180.); coeff[0] = - cD;
// transform cL and cD in Body fixed Coordinate System
// coeff.transform(fc.getTransformationMatrixAB());
// calculate cL in CSYS B
//coeff[2] = mcL(deltaFlap, aoa);
//DEBUG DBG << "pitch: " << pitch << " aoa: " << aoa << " deltaFlap: " << deltaFlap << " cL: " << cL << " cD: " << cD << " SkipLift " << mcSkipLift(deltaFlap) << " SkipDrag " << mcSkipDrag(deltaFlap) << " h_c: " << h_c << " height: " << height<< " chord: " << mChord <<endl;
```

```
// Calculation of Lift and Drag in B FSE_Motor force = coeff; force *= rho * 0.5 * pow(Va,2) * mplan;

// Calculate Momenets FSE_Vector CoP = mCoP;

CoP.transform(fc.getTransformationMatrixBA()); force.setCenterOfEffort(CoP);

return force; };

static FEQ_ForceModule* createMyself(){ return new CLASSNAME();};

};

static FEQ_RegisterForceModuleType

myCreator(MODULENAME,CLASSNAME::createMyself);
```

F. Appendix - FutureShip Results

F.1. Output Table

Table F.1 below shows a basic output table produced by FutureShip Equilibrium at a wind speed of $5m/s$. The output table can be modified to show any trim variable or boat data, the following lists some of the data which can be shown:

TWA the true wind angle with respect to the boats heading

V_s the boat speed

VMG the velocity made good

Leeway the boats leeway angle

Heel the boats heel angle

Pitch the boats pitch or trim angle

SkipperHike the transverse distance of the skippers CG to the boats centreline

SkipperLong the longitudinal distance of the skippers CG from the zero point

Flat a sail de-powering factor

Twist a sail de-powering factor

deltaFlap the flap angle of the rudder foils elevator flap

Sink the distance of the boats zero point to the water surface (-ve is up)

Table F.1.: FutureShip output table

TWA	V_s	VMG	Leeway	Heel	Pitch	SkipperHike	deltaFlap	Sink
180	1.95	-1.95	0.07	-1.66	-0.44	-0.02	-0.048	-0.03
170	1.95	-1.92	0.15	0.52	-0.49	-0.03	-0.42	-0.03
160	1.96	-1.84	0.24	0.54	-0.49	-0.06	-0.41	-0.03
150	1.97	-1.71	0.27	0.73	-0.49	-0.06	-0.40	-0.03
140	2.08	-1.60	0.24	0.92	-0.50	-0.06	-0.29	-0.04
130	2.35	-1.52	0.24	1.04	-0.52	-0.08	-0.07	-0.04
120	2.93	-1.48	0.32	1.26	-0.53	-0.17	0.34	-0.06
110	3.69	-1.29	0.48	2.13	-0.52	-0.4	0.33	-0.08
100	4.25	-0.79	0.70	1.35	-0.52	-0.72	0.15	-0.09
90	4.63	-0.07	0.87	2.02	-0.53	-1.04	-0.37	-0.10
80	4.79	0.74	1.06	2.47	-0.53	-1.33	-0.49	-0.11
70	4.70	1.51	1.29	2.76	-0.54	-1.53	-0.20	-0.11
60	4.35	2.07	1.62	2.60	-0.51	-1.62	-0.28	-0.10
50	3.80	2.34	2.08	3.10	-0.42	-1.57	-0.32	-0.08
40	3.11	2.28	2.90	2.84	-0.49	-1.43	-0.11	-0.06
30	2.27	1.88	4.27	2.06	-0.53	-1.11	-0.48	-0.04