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Assessing Human-Fluid-Structure Interaction for the International Moth

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Abstract

The International Moth is an ultra-lightweight foiling dinghy class. Foil deflections and dynamic sailor-induced motions are identified as two key areas relating to foiling moth performance that are currently ignored in Velocity Prediction Programs (VPP). The impact of foil deflections is assessed by measuring the tip deflection and twist deformation of a T-foil from an International Moth. The full field deformation due to an applied load is measured using Digital Image Correlation (DIC). The foil's structural properties can then be determined based on the measured structural response. The deformations are then calculated for an estimated steady sailing force distribution on the T-foil and their impact on performance is evaluated. To investigate the impact of dynamic sailor motions a system is developed that allows a sailor's dynamic pose to be captured when out on the water by determining the orientations of key body segments using inertial sensors. It is validated against measured hiking moments and is demonstrated to work out on the water whilst sailing. Both these studies pave the way towards developing a Dynamic VPP for the international Moth, which can include unsteady human and foil interactions.

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Keywords: Sailing performance prediction; foil deformations; fluid structure interaction; dynamic hiking moment; inertial sensors; Digital Image Correlation.

1. Introduction

The International Moth is an ultra-lightweight foiling dinghy class. The craft has an overall length of 3.355m, a beam at the waterline of 0.3m, a sail area of 8 m^2 and a weight greater than 30kg. The large sail area leads to a large power to weight ratio allowing the foils to lift the hull up out of the water with only 5 knots of wind [1]. Sailing boat performance is commonly assessed by the time required to complete a mile-long racecourse. This is calculated using a velocity prediction programme (VPP). The resultant race time is derived by balancing the resistive and propulsive forces acting on the vessel at different points of sail to determine the maximum Velocity Made Good (VMG) around the course. For this method to accurately predict course times sophisticated force modelling is required. This must include the predominant sail and hydrodynamic forces but also the effect of perturbations caused by the naturally varying wind and wave environment as well as the motions of the sailor.

To the author's knowledge, the only two VPPs published specific to the International Moth [1]–[3] were based on quasi-static assumptions which neglected dynamic aspects induced as a consequence of inertia and fluctuating forces from the wind, waves and actions of the human crew. The hydrodynamic forces acting on the foils can be determined using lifting line methods or determined from full scale wind tunnel experiments such as those conducted by [4]. However this type of analysis assumes that the foils remain rigid so that any deflections do not affect the performance of the foil. One study has also tested foils in a towing tank [5] where the foil exhibits realistic hydrodynamic loads up to speeds of 4 m/s. The lift and drag data for this condition will include the effects of foil deformations however it has not been established if these deformations have a significant impact on the performance of the foils, or how these deformations might change with increased speeds, commonly seen whilst racing. As the

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hydrodynamic force will vary with speed the deformations and therefore lift and drag coefficients will also be speed dependant. It is therefore important to establish if foil deformations have a significant impact on performance and how these deformations will vary for different sailing speeds.

To assess if a dynamic VPP, which includes the unsteady sail and foil forces, is required the unsteady inputs must first be defined. The most significant contributions to this arise from the actions and motions of the human sailor and the time varying wind and sea state. Although dynamic body motions are acknowledged in sailing literature [2] to react to short term changes in wind speed and to promote foiling no VPPs or studies into the sailor's motions have yet been published. This is despite international sailing rules being developed to prevent sailors from overusing such methods [6].

This paper aims to investigate two aspects of foiling moth performance which are currently neglected from VPP analysis. Firstly an analysis of T-foil deflections will be conducted to assess if these need to be included in the hydrodynamic force models. Secondly a methodology will be developed to assess the dynamic position and therefore induced loads of an athlete whilst out sailing. Finally a discussion about how these developments could be used to extend VPP analysis in the future is presented.

2. Assessing the impact of foil deformations

The experimental method used to measure likely foil deformations is the Digital Image Correlation (DIC) technique. DIC has been used at a variety of scales from high magnification [7], to large-scale structures [8] and has previously been used to measure foil deflections under fluid loads [9]. This technique involves the use of digital cameras that register a series of images of a surface onto which a randomised speckle pattern is applied. The key advantages are the use of simple equipment (i.e. cameras, lenses, lights and a computer), the fact that it is a non-contact measurement and its high fidelity of precision [10]. Within DIC software, the speckle pattern is mapped to calculate the deformed shape, thereby allowing the derivation of the deflections and strains of the investigated object [11]. The use of a single camera allows for the measurement of deformation in a single plane normal to the camera, i.e. 2D DIC. The use of two cameras, in a stereo configuration, allows for the measurement of deformations both in the plane normal to the camera and out of plane, i.e. 3D DIC.

2.1. Measuring the structural properties of the foils

In order to estimate the deflections of the foils whilst sailing the bending and torsional stiffness needed to be assessed. To do this one half of the horizontal T-foil was clamped onto a lab workbench while a known load was applied to the other half of the foil. Figure 1 shows the DIC setup used, including the randomised speckle pattern that was applied to the tip region of the free end of the foil (speckle size of approximately 15 pixels).
Two DIC cameras were used in a stereo configuration to be able to capture the out-of-plane deformation of the specimen. The stereo angle was set to 45 degrees in order to maximise the out of plane resolution as discussed in [12]. The DIC methodology and calibration procedure is the same as previously described in [9].

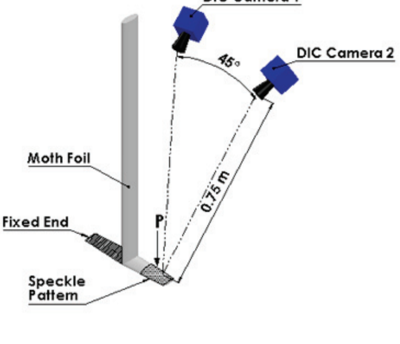


Figure 1: Digital Image Correlation setup in laboratory environment.

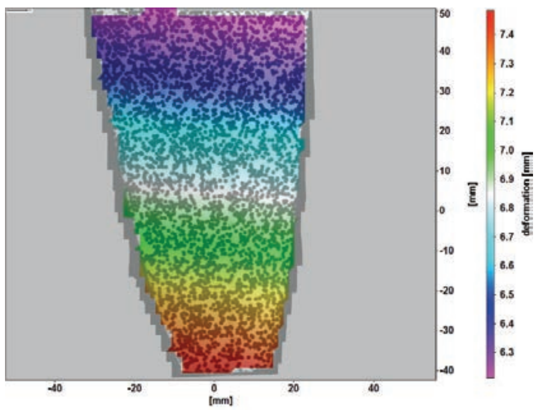
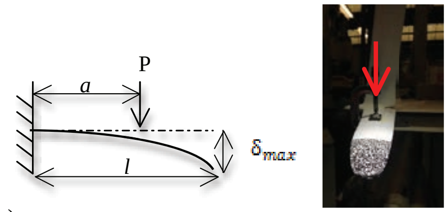


Figure 2: Example of the DIC deformation field for 177.82 N applied 14mm behind the leading edge.

A load of 177.82 N was applied at 45% of the half foil span based on an estimated position of the centre of pressure. Due to space limitations in the lab the load was applied vertically downwards on the foil as opposed to up. The load was applied at two different chord locations, 14 mm behind the leading edge and 14 mm upstream of the trailing edge, in order to assess the torsional stiffness of the foil. An example of the recorded deflection field at the tip can be seen in Figure 2, resulting in a maximum deflection δ_{max}= 7.5 mm.



a) b)

$$\delta_{max} = \frac{Pa^2}{6EI}(3l - a) \quad (1)$$

$$I = K_I ct(t^2 + h^2) \quad (2)$$

$$\vartheta = \frac{Tl}{JG} \quad (3)$$

Figure 3: a) Free-body diagram of applied force on free-end of T-foil. b) Applied load on T-foil.

Figure 3 depicts the loading condition applied to the foil. Assuming the beam has an aerofoil cross-sectional area it is possible to evaluate the Young's modulus of the foil with Euler beam-theory, as described by equation 1. The second moment of area of the aerofoil *(I)* is calculated following equation 2, where *c* is the chord, *t* is the thickness, *h* is the max camber and the proportionality coefficient is assumed to be $K_I \sim$ 0.036 as for most common aerofoils. The torsional stiffness (modulus of rigidity *G* x sectional moment of inertia *J*) can be assessed given a known twist deformation for a given torque *T* applied at a known span location *l* (see equation 3).

The averaged tip deflection obtained from the two load cases provided a Young's Modulus *E* = 70.88 GPa. However to calculate the torsional stiffness we first need to determine what the lever arm is between the applied load and the shear centre of the foil, thus generating a moment. The shear centre is a point through which an applied load will generate no torque, and therefore no twist deflection.
The angle of twist is measured for the two load cases (i.e. applied 14 mm behind the leading edge and 14 mm upstream of the trailing edge) by comparing the deformation at the leading and trailing edges with the local chord. These twist values are plotted against the load position on the chord in Figure 4. Assuming the twist will vary linearly we can determine the shear centre as the point where the applied load would generate no twist (i.e. 17.9 mm, or 22% of the chord, behind the leading edge)

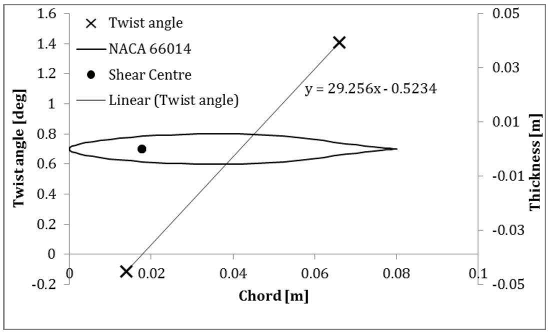


Figure 4: T-foil profile showing the twist angle measurements at the two locations of the load and the shear centre. (Positive twist increases the local angle of attack moving the foil section closer to stall).

Having calculated the shear centre from the angle of twist measured with DIC, it was possible to evaluate the torsion on the T-foil and therefore the modulus of rigidity following equation 3. The averaged value for the shear modulus of an elliptical section considering the different load cases is calculated as being *G* = 5.81 GPa.

2.2. Estimating the steady deformations whilst sailing

The average lift force applied to the foil whilst sailing was estimated as 739N based on a total sailing weight of 113 kg (boat ~ 35 kg and sailor ~ 78 kg) and assuming that 2/3rd of the total sailing weight is supported by the forward daggerboard T-foil, as measured for the Vendor 1 T-foil configuration in [4]. Therefore 367.87 N is experienced by each ½ of the T-foil.

Having assessed the material properties and the shear centre location of the T-foil, it is possible to investigate the estimated deflection whilst sailing. Based on the sailing load of 367.9 N being applied vertically upwards, the maximum expected deflection would be δ_{max}= 15.8 mm. The twist deflection depends not only on the load but its centre of pressure. From previous experiments of a NACRA C-foil in a wind tunnel it was seen that the centre of pressure in the chord-wise direction varies between 25-30% of the chord in pre-stall cases but increases to 40% of the chord once the foil stalls [9]. The estimated twist deflections for the Moth's T-foil based on similar pressure distributions can be seen in Table 1.

Table 1: Twist values for an estimated sailing lift force located at different centre of pressure positions *Cp*, presented as percentage chord from leading edge. (Positive twist increases the local angle of attack moving the foil section closer to stall)

Cp	22.5%	25%	30%	40%
Torque [Nm]	-0.037	-0.77	-2.24	-5.19
Twist [deg]	-0.004	-0.08	-0.23	-0.54

2.3. Impact on performance

The change in lift coefficient with angle of attack for a Vendor T-foil was presented in [4]. Based on this data an increase in the local angle of attack of 0.23 degrees (associated with a centre of pressure at 30% of the chord) results in a 5% decrease in the generated lift force. Therefore it is clear that even under steady sailing loads the foil deflections will have a noticeable effect on their performance. It should also be noted that the tip deflection will also have the effect of changing the direction of the lift force generated in the tip regions. As both sides of the T-foil curve upwards the resultant vertical force will reduce slightly whilst the drag force will remain the same. A similar effect was observed with the curved NACRA foil in the wind tunnel [9]. Therefore to maintain the lift force required to support the flying hull the active ride height control system will have to increase the angle on the trim tab, potentially increasing the drag further. For a VPP to accurately assess the performance of an International Moth the speed specific foil deflections should be included based on a local change in angle of attack using the presented bending and torsional stiffness.

The presented analysis assesses the performance impact based on steady sailing loads, however these effects will be significantly greater when larger unsteady loads are applied. These unsteady loads could arise from dynamically changing sea states or sailor induced motions. If these unsteady loads could be captured within a dynamic VPP then the unsteady foil response could also be investigated.

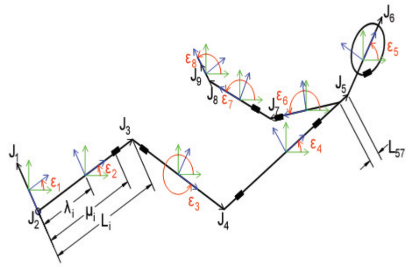
3. Measuring sailor induced loads

It is challenging to directly measure a sailor's loading whilst on the water. This is due to the generated hiking moment being transmitted to the hull through a combination of the deck, tow straps and the mainsheet. Therefore a method based on wireless inertial sensors is presented to estimate the athlete loadings exerted on the boat. Alternative approaches to capturing motion can include automated video capture. Phillips et al [13] compared the use of inertial sensors and video motion capture for a swimmer's underwater flykick and demonstrated comparable accuracy. The advantage of the sensors is that they do not rely on high quality images at all times. Disadvantages of using the inertial sensors are associated with sensor drift and ensuring they are operating all the time. For a multi sensor system the latest sensors are now much more reliable which offers the opportunity to capture on –the-water motions as long as issues with waterproofing can be addressed. Similar challenges have been overcome for use in capturing model ship motions [14].

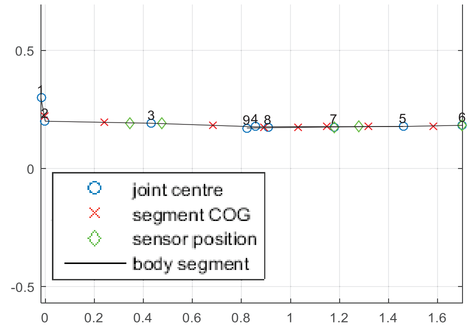
The method we adopt to control the influence of drift is to use our knowledge of the fixed geometry of the sailor. From this the sailor's motion is based on using a kinematic chain. 9 DoF inertial sensors placed on key body segments allow the sailors pose to be captured. Figure 5 (a) illustrates the main segments and key dimensions of the sailor. For this work the body is assumed to be symmetric. To convert this this athlete pose into the forces imposed on the boat the segment masses and center of gravities are required. A regression based mass model presented in [15] is used to estimate the athlete mass distribution based on key body dimensions such as height and weight. Currently several key modeling assumptions have been made to simplify the kinematic model:

- The head and neck are ridged and pivot about the palpable point of the 7th vertebrate;
- the back is straight and its orientation can be approximating by taking the mean of the upper and lower back orientations;
- the left limbs mirror right limbs;
- the anthropometric model accurately predicts the segment's centre of gravity;
- only the mass distribution is adjusted to fit a specific athlete.

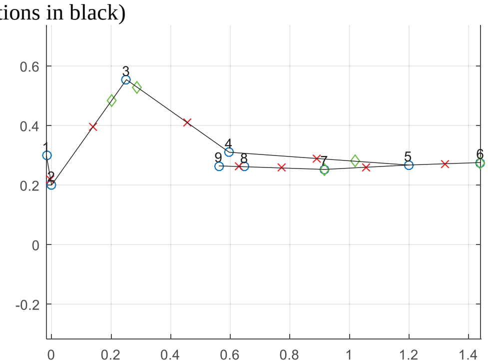
To validate this model a series of 13 different poses were captured whilst the moment generated about the ankle was measured using a board with one end on a pair of scales. Given the length of the measurement board and the total mass of the subject their centre of gravity about one end of the board (their ankles) can be calculated. Three example poses captured by the sensor system are provided in Figure 5 (b-d), along with the estimated hiking moment generated and the percentage error. The average absolute error across the 13 poses was 3% compared to the measured values, with a maximum error of 7%. It was observed that poses with highly curved back positions were least well captured and that an improved model to account for a flexible body segment would be required in the future. A detailed explanation of the developed sensor system and its validation is presented in [16].



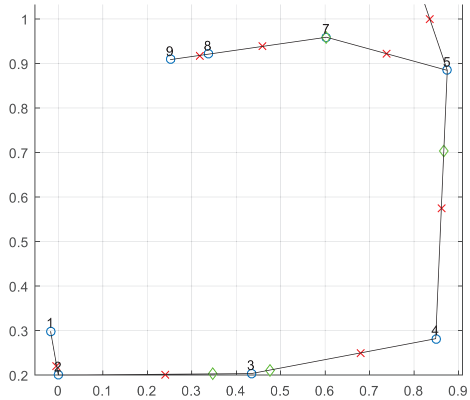
(a) Sailor Position model schematic (approximate sensor locations in black)



(b) Pose 1 (lying flat), Hiking Moment 707 Nm (Error -1%)



(c) Pose 3 (knees raised), Hiking Moment 534 Nm (Error 2%)



(d) Pose 10 (sitting arms out), HM 531 Nm (Error -1%)

Figure 5. Validation of sailor pose capture system using inertial sensors. Horizontal and vertical scales are given in meters.

3.1. On the water measurements

To establish that the developed system could be used out on the water a proof of concept experiment was conducted using a laser sailing dinghy, seen in Figure 6. To enable the boat motions to be captured the same model Xsens IMU was attached to the right of the dagger-boards leading edge. A 10Hz GPS receiver is used to track the boat's speed and course over ground. The inertial sensors used to capture the athlete's pose wirelessly stream the data to a tablet that logs the data. A representative plot of the unsteady Hiking moment acquired by the pose capture system is provided in Figure 7. This initial study shows that the developed system can work in a real sailing situation enabling valuable dynamic hiking moment data to be obtained in the future. This data can then be used to assess the dynamic nature of sailor-induced motions to determine if they need to be included into a dynamic VPP to assess dinghy performance in the future.

Figure 6: On the water tests of pose capture system

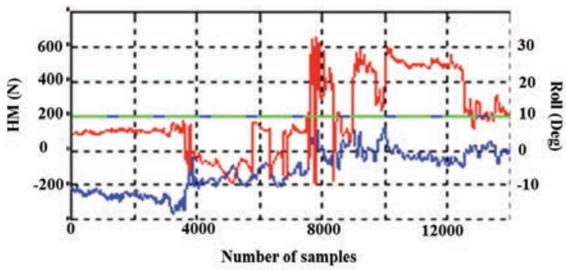


Figure 7: Light wind example of measured Unsteady Hiking Moment (Red) compared to roll angle (Blue) from on the water tests.

4. Conclusions

Foil deflections and dynamic sailor induced motions are identified as two key areas relating to foiling moth performance that are currently ignored in Velocity Prediction Programs (VPP). The impact of foil deflections were assessed by measuring the tip deflection and twist deformation due to an applied load using Digital Image Correlation (DIC), thus determining the foil's structural properties.

The tip deflection under normal sailing loads was estimated to be 15.8 mm, based on an estimated sailing load and pressure distribution. This will reduce the component of lift in the vertical direction as each end of the T-foil curves upwards. The estimated twist deformations will reduction the local angle of attack by 0.23, resulting in a 5% reduction in lift force from the undeformed geometry. These reductions in lift force due to deformation should be included in future hydrodynamic force models in VPP's. The presented structural properties of the T-foil also allow the effects of different loading conditions to be assessed, including the dynamic boat motions observed in maneuvers and initiating foiling.

A system has been developed that allows a sailor's dynamic pose to be captured when out on the water based on determining the orientations of key body segments using inertial sensors. Its validity was checked for 13 different athlete positions adopted whilst measuring the generated hiking moment. An average error of 3% was achieved with a maximum error of 7%. A proof of concept study successfully obtained dynamic sailor pose data whilst out on the water demonstrating that unsteady sailor induced loads can be obtained for the international Moth in the future.

The presented studies provide the tools necessary to developing a Dynamic VPP for the international Moth, which can include dynamic human motions and the unsteady foil forces and deflections that these induce.

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