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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].

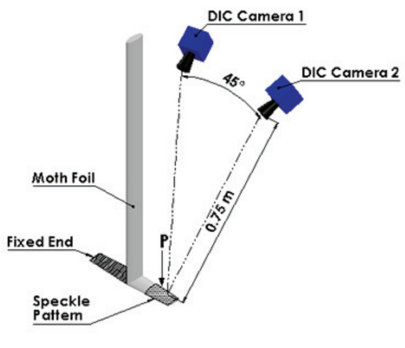

Figure 1: Digital Image Correlation setup in laboratory environment.

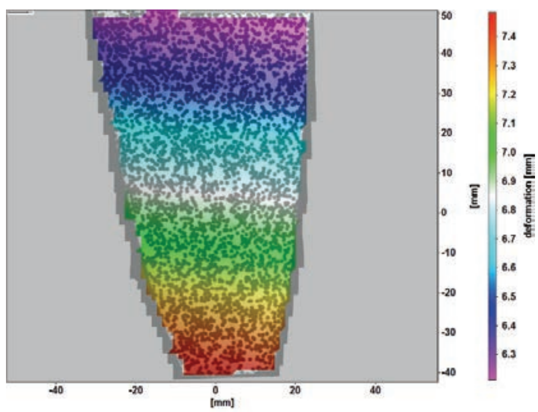

Figure 2: Example of the DIC deformation field for 177.82 N applied 14mm behind the leading edge.

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