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Toward the development of a hydrofoil tailored to passively reduce its lift response to fluid load

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ABSTRACT

The objective of this research is to explore the possibility of using Passive Adaptive Composite (PAC) on structures to help control the lift generated by hydrofoils on boats such as the International Moth. Introducing composite fibres oriented at off-principal axis angles, allow a foil to passively control its pitch angle to reduce the lift generated at higher boat speeds helping to achieve a stable flight in a wide range of weather conditions. PAC utilises the inherent flexibility of a composite structure to induce a twist response under bending load which could be used to minimise the use of active control systems, or even improve the dynamic response of foils in waves. However, to design flexible foils requires numerical and experimental tools to assess the complex fluid structure interactions involved. This paper evaluates a simplified hydrofoil geometry designed to reduce its lift coefficient with increased flow speed. A coupled Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) methodology is presented to predict flexible foil performance. Validation of these numerical tools is achieved through the use of wind tunnel experiments including full field deformation measurements. Twist deformations resulted in a reduction in the effective angle of attack by approximately 30% at higher flow speeds reducing the foil lift and drag significantly.

1. Introduction

The International Moth is a single-handed ultra-lightweight foiling development class boat (International Moth Class, 2013). When foiling the mass of the boat and helm remains constant but the lift produced by the daggerboard and rudder T-foils increases with the square of the boat speed. The daggerboard T-foil is formed of two elements with an adjustable rear flap to modify the lift produced based on the vessel ride height. This constant movement of the rear foil changes the viscous drag of the whole foil section. Meanwhile, the angle of attack of the forward main element is slightly adjusted with dynamic body movements of the helm. The importance of being a lightweight sailing boat enhanced the use of composite materials. Using composite materials it is possible to design a structure tailored to a certain load, in this case the mass of the boat plus the crew. Introducing plies oriented at angles different than zero, 90 or 45° that are normally used in quasi-isotropic structures, it is possible to change the response of a composite structure under load.

Moreover, with the recent increase of foiling boats there is still a lack of accurate measures of structural response and shape of the hydrofoils. This gives rise to scientific questions on whether there is a manufacturing consistency between the port and starboard foil on a catamaran or different batches of foils on mono-hulls.

The aim of the current research is therefore to develop numerical and experimental tools capable of accurately describing the structural response of a foil under fluid-load and to design and develop a foil structure tailored to decrease its lift coefficient as the flow speed increases. In order to do so a coupled CFD and FEA methodology is developed and validated using full-field measurement techniques within a wind tunnel environment.

Those techniques are described in section 2 together with the advantages of developing a robust and repeatable Fluid Structure Interaction (FSI) experimental methodology. The FSI experimental technique was initially developed at the University of Southampton (Banks et al., 2015; Marimon Giovannetti et al., 2017; Marimon Giovannetti, 2017) and provides not only a measure of synchronised structural deformation and fluid response but also the uncertainty values associated with coupling the two optical systems.

Moreover, in section 3 two techniques that can be used to change the performance profile of an hydrofoil are described, namely Passive Adaptive Composites (PAC) that tailors the response of a structure by changing the orientation of the composite plies (Veers et al., 1998) and Differential Stiffness Bend-Twist (DSBT) that utilises the internal stiffness of a structure to change the aero-hydrodynamic response to fluid

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Nomenclature

A	Area [m^2]
A_{ij}	In-plane stiffness [**A**]
B_{ij}	Bending-extension coupling [**B**]
C	Asymmetric aerofoil constant
CFD	Computational Fluid Dynamics
C_D	Drag coefficient
C_L	Lift coefficient
D_{ij}	Bending stiffness [**D**]
DIC	Digital Image Correlation
DSBT	Dirrential Stiffness Bend-Twist
FEA	Finite Element Analysis
FSI	Fluid Structure Interaction
K	Lift curve slope
k	Number of layer
$k_{x,y,xy}$	Laminate curvature
L	Lift force [N]
M_{ij}	Moments per unit length [Nm]
N_{ij}	Forces [N]
PAC	Passive Adaptive Composites
PIV	Particle Image Velocimetry
Q_{ij}	Stiffness matrix components
t	Layer thickness [mm]
V	Wind speed [ms^{-1}]
W	Weight [kg]
y^+	y-plus value
z	Layer distance from the ref. plane [mm]
α	Angle of attack [deg]
γ_{xy}	Shear strain
Δt	Exposure time PIV camera [μs]
$\frac{\partial \alpha}{\partial L}$	Bend-twist coupling term
ε	Strain
ρ	Density [kgm^{-3}]
σ	Stress [MPa]
τ_{xy}	Shear stress [MPa]

load (Raither et al., 2012). These two techniques, if used in parallel, can substantially change the effective angle of attack of a foil structure under load. The current research presents the first steps in investigating the possibilities of applying those techniques to the design of a daggerboard T-foil of the International Moth. PAC have been researched in applications for wind-turbine blades (De Goeij et al., 1999; Lin and Lai, 2010; Maheri and Isikveren, 2009), tidal turbines (Nicholls-Lee et al., 2009; Barber, 2017), propeller blades (Khan et al., 2000; Young and Motley, 2011) and Micro Air Vehicles (Hu et al., 2008; Tamai et al., 2008), so it is now possible to use the knowledge from other applications for high performance sailing boats.

After the two background sections, an idealised section that can be adapted in future research to high speeds boats such as the International Moth is presented. Utilising the inherent flexibility of PAC at high speeds and relatively large tip deflections the angle of attack can be passively reduced to decrease the induced drag. Twisting an aerofoil section toward feather indeed reduces the effective angle of attack of the foil. The equations of an analytical model that relates the lift force to the plies orientation within the structure are also described.

The design of the flexible aerofoil is presented in section 5. The position and layup of the internal stiffener are presented as well as the manufacturing techniques.

Finally, the full-scale experimental and numerical setup as well as the results from an idealised section are presented to demonstrate the passive-adaptive response to fluid load. This research merely represents the findings on FSI of a full-scale flexible model. Those results can be used in future projects as base to build a main element foil of the International Moth.

2. Background on FSI experimental measures

Within the available literature there is a lack of analytical solutions and experimental measures of FSI problems (de Borst et al., 2013; Hou et al., 2012). Therefore, research in this area has mainly focused on coupled numerical solutions or approximations extensively utilising Blade Element Momentum (BEM) theory, Computational Fluid Dynamics (CFD) and structural Finite Element Analysis (FEA) simulations. Even though numerical studies have been extensive, especially in recent years with the increase in computer power, there is a lack of experimental validation cases for FSI problems and, for the limited cases that there are, the uncertainty in measurements is often unknown.

The first FSI experiments were developed with known experimental techniques re-adapted to allow the capture of both structural deformations and load capture. Fedorov (2012) presents a numerical and experimental approach where the effects of loads on a composite bend-twist full-scale wind turbine blade are measured. In particular they measured deflection and twist using Digital Image Correlation (DIC). However, his research lacks the dynamic coupling from the aerodynamic forces, as a known hydraulic load was applied whereas in a complete FSI experiment the aerodynamic force will actually change due to fluid-induced deformation and twist.

High speed cameras and laser Doppler vibrometers were employed to measure the pitch motion of a flexible hydrofoil and the areas of cavitation by Ducoin et al. (2012). These experiments present the displacement and pitch angle for the tip section of a two-dimensional hydrofoil under real flow conditions. The study developed by Ducoin et al. (2012) provides useful validation material for cavitation simulations, including structural deformation, but does not provide the hydrodynamic forces or flow field information to assess non-cavitating CFD models. Malijaarsl and Kaminski (2015) present a review of the published studies on flexible propellers. The possibility of using composite propellers to reduce cavitation problems is addressed, but they identify a need for experiments to validate the hydro-elastic numerical simulations, as well as measurements of the deformed shape of flexible propellers. More recently, Barber (2017) tested in a flume-tank two sets of PAC marine hydrokinetic (MHK) turbine blades alongside one non-adaptive composite and a set of aluminium blade. The magnitude and direction of the torque on the rotor applied by the flow were measured with two load cells. The flow velocity was recorded so that the capacity for power generation could be calculated. Those tests were however performed at model scale, meaning that the bend-twist coupling of the composite structure could not be related to a full-scale MHK turbine as the composite blades were composed of a flat carbon fibre spar, twisted to follow the chord line of the blade geometry and a semi-flexible urethane body cast around the spar to create the hydrodynamic blade shape.

To assess the validity of numerical FSI simulations we require the ability to measure the influence of fluid load on the structural response. It is important that this is conducted in a controlled manner, to provide data with known uncertainties for comparison with numerical FSI simulations. CFD is often validated in isolation using flow field data captured with Particle Image Velocimetry (PIV) and measured aero-hydrodynamic forces (Jones et al., 2008). Similarly FEA models can be validated against full-field deformation measurements acquired using DIC (Siddiqui, 2014).

In order to fully capture the behaviour of a structure or a fluid under investigation without interfering with it, full-field non-contact measurement techniques can be used. These techniques have been