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Assessment of Digital Image Correlation as a method of obtaining deformations of a structure under fluid load

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ABSTRACT

Digital Image Correlation (*DIC*) is employed for the measurement of full-field deformation during fluid–structure interaction experiments in a wind tunnel. The methodology developed for the wind tunnel environment is quantitatively assessed. The static deformation error of the system is shown to be less than 0.8% when applied to a curved aerofoil specimen moved through known displacements using a micrometre. Enclosed camera fairings were shown to be required to minimise error due to wind induced camera vibration under aerodynamic loading. The methodology was demonstrated using a high performance curved foil, from a NACRA F20 sailing catamaran, tested within the University of Southampton RJ Mitchell, 3.5 mx2.4 m, wind tunnel. The aerodynamic forces induced in the wind tunnel are relatively small, compared with typical hydrodynamic loading, resulting in small deformations. The coupled deflection and blade twist is evaluated over the tip region (80–100% Span, measured from the root) for a range of wind speeds and angles of attack. Steady deformations at low angles of attack were shown to be well captured however unsteady deformations at higher angles of attack were observed as an increase in variability due to hardware limitations in the current DIC system. It is concluded that higher DIC sample rates are required to assess unsteady deformations in the future. The full field deformation data reveals limited blade twist for low angles of attack, below the stall angle. For larger angles, however, there is a tendency to reduce the effective angle of attack at the tip of the structure, combined with an unsteady structural response. This capability highlights the benefits of the presented methodology over fixed-point measurements as the three dimensional foil deflections can be assessed over a large tip region. In addition, the methodology demonstrates that very small deformations and twist angles can be resolved.

1. Introduction

Fluid Structure Interaction (FSI) studies have been mainly focused on the coupled numerical modelling of structural deformation under fluid loading utilising Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD) for the structures and fluids respectively (Lee et al., 2012; Nicholls-Lee et al., 2009; Fedorov, et al. 2009; Maheri et al., 2006). In

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Nomenclature

α	foil angle of attack
θ	camera stereo angle
φ	camera to tunnel transformation angle
ρ	air density
s	specimen distance to the cameras
c_b	blur circle
c	foil chord
C_D,C_Y,C_Z	drag , side and vertical force coefficients
D_F	distance from the lens to the far limit of the depth of field
D_N	distance from the lens to the near limit
f	the lens focal length
L	foil span
N	the lens *f*-number
Re	Reynolds number
V_S	wind speed

Coordinate systems:

x_c, y_c, z_c	camera (DIC system)
x_t, y_t, z_t	dynamometer (foil forces)
x_d, y_d, z_d	dynamometer (foil forces)

isolation there are many methods for the validation of FEA and CFD. However, there is a lack of experimental validation data for FSI investigations associated with accurate measurement of structural deformation under fluid loading.

Wind tunnel testing provides a controlled environment for the fluid loading of structures. The forces developed during testing are acquired via a dynamometer. However, standard wind tunnel testing often employs stiff structures such that the geometry remains effectively constant with respect to fluid loading. In reality structures will deform with increasing fluid loading, particularly where fibre reinforced composites are employed. The current research focuses on the assessment of an experimental technique that can be used to quantify the deformation and the bend–twist coupling for aero-elastic tailored composite structures under fluid loading, i.e. FSI.

In the past two decades, the trend of investigating the potential applications of composites structures has widely increased. Composite materials not only present a high stiffness to weight ratio, but also a better fatigue resistance compared to metallic components (Lee and Lin, 2004). Using the anisotropy of the material, it is possible to design components presenting elastic couplings that will enhance the performance of the whole structure (Veers and Bir, 1998; Fedorov, 2012; Shirk and Hertz, 1986; Liu and Young, 2009; Young, 2008). Careful directional placement of fibres and design of the composite architecture can result in an additional coupled response that will affect the effective angle of attack of the foil structures. In order to investigate this process an accurate full-field technique is required to measure the deformation whilst under fluid loading.

The experimental method used is the highly established Digital Image Correlation (DIC) technique. DIC has been used at a variety of scales from high magnification (Crammond et al., 2013) to large-scale structures (McCormick and Lord, 2012). This technique involves the use of digital cameras that register a series of images of a surface on 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, (Zhengzong et al., 2011). 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, (Rastogi and Hack, 2012). 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. For 3D DIC the angle between the cameras controls the measurement accuracy of the out of plane deformation (Sutton et al., 2009; Zhengzong et al., 2011; Rastogi and Hack, 2012; Reu; 2013). For a foil structure the difference in leading and trailing edge deformation, normal to the chord, determines the impact of the deflection on effective angle of attack. Therefore optimising the stereo angle between the two cameras for out of plane accuracy is essential (Reu, 2013, 2012a; Ke et al., 2011). DIC has been widely used and validated for two-dimensional and three-dimensional analysis of small specimens, (Zhengzong et al., 2011; Rastogi and Hack, 2012; Helm et al., 1996). These are mostly analysed using small stereo angles (θ up to 17°) as this increases the in-plane resolution (Reu, 2013; Ke et al., 2011). Three-dimensional DIC for a wide range of stereo angles and lenses are presented by Ke et al. (2011) and Reu (2013) and deflections and strains are assessed with experimental values, showing the possibility of increasing the stereo angle up to $\theta = 60°$ for large out of plane deformations.

The current research focuses on the assessment of the DIC technique to measure the deformation of foil structures under fluid loading. All of the available parameters (lenses, stereo angle, stand-off distance and speckle pattern) are herein assessed to provide a DIC procedure suitable for a wind tunnel environment. The tested specimen (a curved daggerboard from the NACRA F20 Carbon catamaran) allows the DIC methodology to be assessed in challenging conditions due to its complex geometry and the fact that only small deformations are expected under aerodynamic loading. The presented methodology will be of use not only to high performance foils for catamarans, but also to wind turbine blades (Lin and Lai, 2010, Fedorov et al., 2009, Karaolis et al., 1988, Nicholls-Lee et al., 2009), helicopter rotors (Ganguli and Chopre, 1995; Murugan et al., 2008), propeller blades (Khan et al., 2000; Lee and Lin, 2004), ship rudders (Turnock and Wright, 2000; Molland and Turnock, 2007) and high performance racing cars (Thuwis et al., 2010). At the time of writing, little research has been developed involving Digital Image Correlation (DIC) within a wind tunnel to evaluate a coupled FSI problem. Most