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Experimental study of the steady fluid–structure interaction of flexible hydrofoils

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ABSTRACT

This paper presents results from an experimental study of the hydrodynamic and hydroelastic performance of six different flexible hydrofoils of similar geometry; four metal hydrofoils of stainless steel (SS) and aluminum (AL), and two composite hydrofoils of carbon-fiber reinforced plastic (CFRP). The two CFRP hydrofoils had differing layups, one with fibers at 0° and the other at 30° relative to the spanwise axis of the hydrofoil. All hydrofoil models have the same unswept trapezoidal planform of aspect ratio 3.33. Two section profiles were chosen, a standard NACA0009 (Type I) and a modified NACA0009 (Type II) with a thicker trailing edge for improved manufacture of CFRP hydrofoils. Hydrofoils were tested in a water tunnel mounted from a six-component force balance. Forces and deformations were measured at several chord-based Reynolds numbers up to $Re_c = 1.0 \times 10^6$ and incidences beyond stall. Hysteresis, force fluctuations, and the natural frequency of the hydrofoils in air and in water were also investigated. Pre-stall forces on the metal hydrofoils were observed to be Reynolds number dependent for low values but became independent at 0.8×10^6 and greater. Forces on the CFRP hydrofoils presented an increasing or decreasing lift slope for all Re_c depending on the orientation of the carbon unidirectional layers. The change in loading pattern is due to the coupled bend–twist deformation experienced by the hydrofoils under hydrodynamic loading. Forces and deflections in the Type I hydrofoils were observed to be stable up to stall and non-dimensional tip deflections were found to be independent of incidence and Re_c. Type II metal hydrofoils had a mild Re_c dependence, attributed to the blunt trailing edge, and Type II CFRP hydrofoils had a stronger incidence and Re_c dependence. The natural frequency under stall conditions of all but one of the CFRP hydrofoils was in agreement with added mass and finite element analysis estimates. The disagreement was observed in the CFRP hydrofoil with layers aligned at 30° and is attributed to the complex behavior of the carbon layers and to the coupled bend–twist deformation experienced under hydrodynamic loading of the hydrofoil.

1. Introduction

Hydroelastic tailoring of marine propellers and hydrofoils using composite materials has the potential to improve the hydrodynamic performance of naval ships. In the present context, hydroelastic tailoring is defined as the intentional use of structural and material properties to improve hydrodynamic performance in a broad sense including both static and

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dynamic behavior. Hydrofoils and propellers may be designed to deform under increasing quasi-steady or dynamically varying applied loads to give improved hydrodynamic performance compared with rigid or relatively stiff hydrofoils or propellers. It is envisaged that propellers maybe designed with improved propulsive efficiency as well as reduced unsteady or harmonic force components, vibration and noise emissions. For naval ships, where it is most desirable to reduce vibration and harmonic excitation due to spatial and temporal variations of the inflow to propellers and control surfaces, composites may offer significant advantages over traditional materials.

Traditionally marine propulsion and control equipment have been manufactured in metal particularly using nickel–aluminum bronze or stainless steel. These conventional materials offer the advantages of being homogeneous and isotropic for the purposes of modeling their structural behavior. There is also extensive experience of their design, manufacture and use in the challenging marine environment for both civilian and naval applications (Kerwin, 1986). Composite materials are continuously being developed and are now used extensively in aeronautical applications with limited use to date for ship hull and superstructure applications (Mouritz et al., 2001). Their use for propellers and control surfaces has to date been more limited due to the technical difficulties of designing such devices and the uncertainties over their serviceability and reliability. Nevertheless, composites do offer advantages over traditional materials including reduced weight, corrosion resistance and the potential for hydrodynamic performance improvement through hydroelastic tailoring (Mouritz et al., 2001; Chen et al., 2006; Motley et al., 2009; Miller et al., 2010).

In recent years there has been increased activity focused in computational studies of the fluid–structure interaction (FSI) of deforming hydrofoils and propellers. With increasing sophistication of computational modeling of the turbulent flow about the after-bodies of ships and submarines, the complex nature of the flow in which control surfaces and propellers must operate is being revealed (Fureby, 2007; Andersen et al., 2009; Alin et al., 2010). Several recent studies have presented coupled FSI algorithms and models to study the behavior of composite hydrofoils and propellers in cavitating and sub-cavitating conditions (Young, 2008; Ducoin et al., 2009; Liu and Young, 2009, 2010; Munch et al., 2010; Young et al., 2010; Chae et al., 2013; Akcabay and Young, 2014). Whilst significant progress has been made in this area, comprehensive and detailed experimental data sets are required for further development and validation of computational models.

One of the earliest experiments using flexible hydrofoils was that of Gowing et al. (1998), who reported that the tip deflections helped to delay cavitation inception due to reduced tip loading, while the overall lift and drag coefficients remained unchanged. Ducoin et al. (2009) measured the tip deflection of a hydrofoil made of a plastic material (POM polyacetate) and the results were used to validate a numerical model. The experiments were conducted in a cavitation tunnel with a 192 mm square test section and a hydrofoil with a span of 191 mm. The chord-based Reynolds number ranged from 0.75×10^6 to 1.5×10^6 and incidences from 0° to 6°. The computational results showed that the lift forces exerted on the hydrofoil are strongly coupled with structural deformations. More recently Ducoin et al. (2012b) and Ducoin and Young (2013), using the same foil and experimental setup as previous, showed that for non-cavitating flows the structural response of the hydrofoil depends on the hydrodynamic loading, and that in a transient regime (i.e. transient pitching motion) the tip displacement depends strongly on the pitching velocity.

Given the elastic properties of composite hydrofoils and the documented bending and twisting they experience (Liu and Young, 2009, 2010), it is expected that other forces and moments, particularly the drag force and pitching moment will be significant for validating numerical models and designing flexible hydrofoils and propellers.

To gain basic insight into the FSI problem, particularly as it relates to propellers and control surfaces, experiments of a simple unsteady flow about a flexible three-dimensional hydrofoil have been conceived. The use of a hydrofoil significantly reduces the complexity of models and the experimental setup required compared with that for propellers. An unsteady flow that provides a simplified analogy to spatial and temporal non-uniformity of inflow to propellers or control surfaces is impulsive or periodic variation of incidence. This method eliminates the difficulty of generating unsteadiness in the upstream flow. This arrangement is also compatible with setting up relatively simple computational models. However, it is necessary to first have a baseline knowledge on the hydroelastic behavior of the hydrofoils under steady loading to be able to make meaningful comparisons.

This paper presents the results of an experimental study of the steady hydroelastic behavior of a series of hydrofoil models of nominally identical geometry but of differing materials. In the present context, steady FSI refers to the condition where the structural deformations and flow field are time invariant, as opposed to dynamic FSI where the structural response and flow field vary in time due to either temporal incidence variation or large scale flow fluctuations. This is consistent with the distinctions made by Hodges and Pierce (2011) between static aeroelasticity as an interaction between aerodynamics and elasticity, structural dynamics as an interaction between elasticity and dynamics and dynamic aeroelasticity as an interaction between all three phenomena. The present work is principally concerned with steady deformations in nominally steady flow. Tests were however performed beyond stall where unsteady loads induced unsteady deformations and basic frequency analysis of the hydrofoils were made for completeness.

Models were manufactured in aluminum (AL), stainless steel (SS) and carbon fiber reinforced plastic (CFRP) in two different layups. The use of metal, in addition to CFRP, with predictable material and structural properties provided results that may be compared with the CFRP behavior in both the present experiments and future computational modeling. Measurements were made at several mean chord-based Reynolds numbers up to 10^6 and incidences beyond stall. The results include measurements of lift and drag forces, pitching moments, tip transverse and twisting deformations, and frequency response. This work is limited to steady, non-cavitating flow and is intended as a baseline study for future experiments under oscillating incidence and/or cavitating conditions.