Journal of Fluids and Structures 77 (2018) 58–79

Contents lists available at ScienceDirect

Journal of Fluids and Structures

journal homepage: www.elsevier.com/locate/jfs

Inverse method for hydrodynamic load reconstruction on a flexible surface-piercing hydrofoil in multi-phase flow

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ARTICLE INFO

Article history:
Received 23 May 2017
Received in revised form 24 November 2017
Accepted 1 December 2017

Keywords:
Fluid–structure interaction
Inverse problem
Finite element analysis
Lifting line
Ventilation

ABSTRACT

An inverse method for reconstruction of the *in situ* steady-state hydrodynamic load distribution using limited strain measurements is developed and validated on a rectangular, flexible surface-piercing hydrofoil in fully-wetted (FW) and fully-ventilated (FV) flows. The hydrofoil is used as a canonical proxy to more complex hydrodynamic lifting surfaces such as marine propulsors and turbines. The approach involves using a forward fluid–structure interaction (FSI) model to predict the hydroelastic response for given operating conditions. The inverse problem is solved as an optimization problem to determine unknown operating conditions. The forward FSI model consists of a nonlinear lifting line (LL) fluid solver with considerations for free surface, ventilation, and viscous effects, and a solid finite element method (FEM) solver using 1-D beam elements representing the spanwise bending and twisting deformations.

The coupled FSI model was validated using data collected during towing tank experiments at the University of Michigan. Predictions of the lift and moment coefficients, as well as spanwise bending and twisting deformations agreed well with experimental results in FW and in FV flows.

The inverse problem is formulated as an optimization problem to determine the unknown operating conditions that will minimize the difference between the measured and predicted deformations. To avoid non-uniqueness problems often encountered by inverse problems, a dynamic constraint using the measured wetted natural frequencies was added to help regularize the problem and speed up the solution process. A sequential quadratic programming algorithm was used as the optimizer for the inverse problem. The experimental studies showed that the inverse FSI model accurately determined the unknown operating conditions (angle of attack and immersed aspect ratio) for a given a known flow speed and a limited number of strain measurements in both FW and FV conditions. The converged results were used to reconstruct a 3-D hydrodynamic load distribution on the foil and to predict the cavity shape for FV operating conditions, which were found to agree well with experimental measurements and observations.

1. Introduction

The capability to monitor the full-field loading and structural responses of marine appendages, propulsors and turbines *in situ* for both laboratory studies and in sea operations is highly desirable. Thankfully, advances in computational speed

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https://doi.org/10.1016/j.jfluidstructs.2017.12.001
0889-9746/

and instrumentation have brought this goal closer to reality through the use of inverse methods, *i.e.* using a set of measured system responses (strain, acceleration, *etc.*) to obtain (by inference) the unknown operating conditions and load distribution. When coupled with a suitable physics-based model, such methods can also be used to identify unknown system parameters such as material properties or operating conditions. The desired system response can be measured using various instruments, including but not limited to, micro-electro-mechanical systems (MEMS), piezoelectric materials, strain gages, accelerometers, and optical methods such as digital image correlation (DIC). Unfortunately, the ability to place an adequate number of sensors is limited, if not impossible, in many applications. Hence, inverse methods are typically limited by a solver's ability to reconstruct the full-field load distribution based on a limited number of discrete measurements. Thus, issues arise in uniqueness, stability, and existence of the solution (Chierichetti, 2013; Gherlone et al., 2014; Tessler and Spangler, 2005).

The value of inverse load reconstruction spans across many different disciplines and platforms. For example, engineers in the aerospace (Coates et al., 2005; Nakamura et al., 2012), renewable energy (Pahn et al., 2012), geophysical (Berthet-Rambaud et al., 2008), and biomedical (Bertoglio et al., 2011) fields have investigated the uses of inverse methods for load reconstruction and parameter identification in their respective fields. The possible applications thus extend naturally into the realms of hydrodynamics and hydroelasticity of marine systems. Interest in this application has recently increased, due to the trend towards fabricating marine propulsors and control surfaces from non-metallic materials such as fiber reinforced composites, thermoplastics, and other lightweight materials. The use of advanced construction materials, coupled with the knowledge of real-time load conditions, facilitates the development of active control strategies to improve performance relative to traditional metallic construction and single-point designs in off-design operating conditions and in spatially/temporally varying flow conditions (Motley and Young, 2011; Young et al., 2016). Furthermore, this knowledge can be used for real-time structural health monitoring and to facilitate the development of condition-based maintenance programs.

A relatively simple example application of inverse methods to solve for the unknown net thrust is presented in Pahn et al. (2012). The Moore–Penrose pseudoinverse matrix is used to estimate the net thrust acting on a wind turbine based on acceleration measurements taken from two points on the tower supporting the turbine. While such an approach is sufficient for determining the net thrust, it cannot yield the aerodynamic load distributions on the blades. Predictions were validated using synthetic data generated by the simulation code FAST, but experimental validations were not performed. As shown in Xu et al. (2010), an inverse method was used to reconstruct the full-field pressure distribution acting on a plate due to a nearby explosion using an extended Kalman filter coupled with a finite element model. The model was tested both numerically and experimentally, with the experimental measurements obtained using DIC. Although this approach worked quite well, the effects of fluid–structure interaction (FSI) were not included, which are critical if the structure experiences significant deformation. For cases involving a fluid–solid interface, two-way FSI coupling (*i.e.* when structural deformations affect the loads causing those deformations) is often encountered, and therefore must be included in any inverse model if the deformations and feedback to the loads are significant. The intrinsic limitations of DIC (*e.g.* the necessity of a static reference frame and clear field of view) prohibit application outside of a laboratory setting. Additionally, significant computational effort is necessary to acquire and process the thousands of images necessary to determine the full-field structural response — especially in transient conditions. Hence, it is not practical to use of DIC for real-time load reconstruction.

Reconstructing the in-flight loads on an aircraft wing (Coates et al., 2005) is similar to, and shares some of the challenges with, reconstructing the real-time loads on marine propulsors and control surfaces. In Coates et al. (2005), the aerodynamic load distribution was obtained using limited strain measurements along the span of the wing. The load was estimated using a Fourier series, where the aerodynamic load coefficients were determined using an existing database. This leads to a fast, simplistic model, capable of real-time operation. However, the use of interpolation means that the quality of results is dependent on the accuracy and breadth of the precomputed database. Again, FSI was not included in the study by Coates et al. (2005), which is even more important when examining flexible lifting bodies, where strong two-way FSI coupling exists because fluid loads are highly sensitive to changes in the effective angle of attack and flow-induced vibrations. It should also be noted that reconstructing the load distributions on marine propulsors and control surfaces can be made even more challenging by the presence of a free surface and the susceptibility to cavitation and/or ventilation.

Nakamura et al. (2012) investigated the same problem of reconstructing the aerodynamic loads based on limited strain data using inverse methods. Here, a finite element solid solver was coupled with a fluid solver utilizing 2-D airfoil theory, thus greatly increasing the accuracy of the model by using a physics-based model in place of an empirical regression. The inclusion of a physics-based forward aerodynamic model reduced the size of the optimization problem by effectively constraining the search space to solutions that are physically realizable under the modeling. However, the aerodynamic pressure distribution was assumed to be uniform along the span of the wing — a modeling assumption that is invalid for lifting surfaces of finite span (due to strong 3-D effects) and/or when the load distribution changes due to spanwise-nonuniform twisting that affects the effective angle of attack at each section.

1.1. Objectives

The objectives of this work are to: (1) develop and validate a robust and efficient forward FSI model to predict the dynamic FSI response of a flexible, surface-piercing hydrofoil in both fully wetted (FW) and fully-ventilated (FV) flows, and (2) develop and validate an accurate and efficient inverse FSI model to identify the unknown operating conditions (*e.g.* angle of attack