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Combined particle image velocimetry/digital image correlation for load estimation

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ABSTRACT

Particle image velocimetry (PIV) and digital image correlation (DIC) are widely used experimental techniques in fluid mechanics and structural dynamics, respectively. PIV is capable of resolving detailed velocity fields around structures, from which the hydrodynamic loading can be reconstructed. However, PIV is ill-suited to capturing the structural response, which is critical for a complete understanding of the bidirectional coupling between the fluid flow and the structural dynamics. On the other hand, DIC can accurately quantify local deformation of the structure, but does not afford the precise identification of the hydrodynamic loading due to the ill-posed nature of the inverse load estimation process. Here, we explore the feasibility of a combined PIV/DIC technique for the investigation of fluid-structure interactions. Specifically, we study fluid-structure interactions associated with a flexible cantilever plate immersed in a steady unidirectional flow. We demonstrate that the combination of pressure estimation from PIV and deformation measurement through DIC enables the precise identification of the hydrodynamic loading and structural response. The proposed methodology may help in improving our understanding of a number of fluid-structure interaction problems, such as biomimetic propulsion, aeroelasticity of airfoils, and hydrodynamic impact on marine structures.

1. Introduction

In fully-coupled fluid-structure interaction (FSI) problems, forces imposed on a structure by the fluid flow causes structural deformation, which, in turn, alters the boundary conditions of the fluid, thereby modulating its dynamics. These problems are of fundamental engineering interest, as they arise in a variety of applications, such as energy harvesting [1], animal locomotion [2,3], human speech [4], and vibration of flight structures [5]. Capturing the physics of these interactions requires detailed understanding of both the time-varying fluid loading and the dynamic response of the structure.

The fluid loading generally varies in both time and space, and thus full-field time-resolved velocity measurement is necessary to provide a thorough understanding of the interplay between the fluid and structure. Planar two-dimensional particle image velocimetry (PIV) is a ubiquitous flow measurement technique that resolves two components of a velocity field within a plane [6–10].

In a typical PIV experiment, the fluid is seeded with micron-sized particles that are illuminated by a laser sheet and whose motion is recorded by a camera. Two (or more) images are collected a short time apart and the velocity field is computed by cross-correlating corresponding interrogation regions within sequential images. Among a wide range of FSI problems, PIV has been successfully employed to study the thrust developed by a beam vibrating in a fluid [11], a vortex impinging a deformable plate [12,13], blood flow in a heart [14], and interaction between swimming fish and advected vortices [15].

Several methods have been devised to infer the loading on a structure given knowledge about the velocity field of the encompassing fluid. For example, the loading on flexible plates [11,13], airfoils [16,17], and wind turbine blades [18] has been computed from the surrounding velocity field using a control volume analysis. Alternatively, the full field pressure distribution in the flow can be reconstructed from the velocity data by relating the pressure and velocity fields through Navier–Stokes equations.

Specifically, given an experimentally measured velocity field, the unknown pressure field can be estimated either through direct integration of Navier–Stokes equations, or by taking their divergence of and solving the resulting Poisson equation for pressure [19]. The latter approach was found to be more computationally efficient [20]; however, solving the Poisson equation requires knowledge of pressure or pressure gradient information on all boundaries. In contrast, integration of the Navier–Stokes equations can produce the whole pressure field

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from a single reference point [19]. The accuracy of pressure reconstruction methods has been quantified through error propagation analyses [19], synthesized flow fields [21], and comparisons with theoretical and numerical solutions [22–24]. Pressure reconstruction has been employed in the study of water entry problems [25,26], animal swimming [27,28], vibration of soft active materials in water [29], vortex/plate interactions [30], and rotating bluff bodies [31], to name a few.

The response of solid structures to dynamic fluid loading can be evaluated from direct deformation measurements through the use of displacement sensors and/or high speed cameras. In addition to providing dynamic displacement information, digital image correlation (DIC) yields surface strain measurement in real time [32–35]. Briefly, in DIC, deformation of the surface of a structure is visualized by recording the movement of a natural or applied surface speckle pattern. The two-dimensional displacement and strain fields are then computed by cross-correlating the speckle images recorded before and after deformation [33,34], in a manner similar to PIV. Compared to alternative displacement measurement techniques, such as edge-detection via high speed cameras and point measurement via displacement sensors, DIC affords a higher level of accuracy and spatial resolution.

DIC is pervasive in experimental mechanics [34]. Precise displacement and strain measurements have been demonstrated in the analyses of strain localization in metal [36], crack growth in particulate composites [37], collapse of polymeric foams [38], failure of sandwich structures under blast loading [39,40], delamination of composite laminates [41], stretching of soft tissues [42,43], and compression of bone specimens [44,45].

Deformation data have been combined with various optimization algorithms toward the identification of the external loads active on the structure [46–49]. However, the load identification process is inherently an ill-posed inverse problem, and as such, small perturbations in the measurement data may result in significant errors in the load estimation [47]. Regularization methods, such as Tikhonov regularization [46], that incorporate *a priori* knowledge of the smoothness of the load have been employed to mitigate issues arising from ill-posedness [47–50], but the problem remains.

The objective of this work is to demonstrate the feasibility of a combined PIV/DIC approach for determining the hydrodynamic load and structural deformation in a coupled FSI problem. To this end, we focus on a simple fluid-structure interaction problem, in which a flexible cantilevered plate bends due to a steady fluid flow perpendicular to its undeformed configuration. This archetypal setup brings forward an interesting fluid-structure interaction problem, without experimental confounds that may be associated with multiaxial structural deformations, unsteady phenomena, and free surface flows. The hydrodynamic pressure induced by the water flow on the plate elicits a structural deformation, which, in turn, imposes a change in the boundary of the fluid domain. PIV or DIC alone cannot guarantee accurate measurement of both the hydrodynamic load and the plate deformation. To mitigate this limitation, a combined PIV/DIC experimental setup is employed to capture the fluid dynamics and plate deformation under different flow conditions. The hydrodynamic drag associated with an incoming fluid flow on a rigid plate has been experimentally studied in the literature [51], thereby offering data on which we could benchmark our PIV and DIC load estimation data.

In the literature, combined measurements of the fluid dynamics and structural deformation have improved our understanding of fluid-structure interaction problems. For example, in a study on the sound production mechanism of a saxophone mouthpiece, the velocity field of airflow in the mouthpiece was visualized by PIV and the coupled vibration of the reed was studied through raw PIV images. The analysis revealed a periodic flow velocity fluctuation in accordance with the structural vibration frequency [52]. Similarly, in a study of voice production, the flow field quantified through PIV and the structural vibration measured from high-speed imaging suggested that the rate of closure of the vocal folds is impacted by the intraglottal flow separation [53].

To date, only a few studies have examined the combination of PIV and DIC in fluid-structure interaction problems. More specifically, a combined PIV/DIC technique has facilitated the study of the aerodynamics of a flexible wing [54] and vibration and vortex shedding from an airfoil [55,56]. In these studies, PIV acquisitions have revealed detailed velocity and vorticity morphologies in the vicinity of flexible structures, while DIC measurements allowed for refined measurement of the displacement field of the structure surface. Information gathered from these techniques were used to aid in the study of the coupling between the fluid flow and structural dynamics, but not for the estimation of the hydrodynamic loading. In fact, the hydrodynamic loading on the structure was measured only at a few fixed locations through additional load cells, without fully exploiting the potential of a combined PIV/DIC technique. In this vein, we put forward the integration of PIV and DIC toward a combined measurement of the hydrodynamic load and structural deformation.

Different from previous studies, the present work focuses on the following aspects: (i) demonstrating the feasibility of a combined PIV and DIC system for full-field flow pressure estimation and structural deformation measurement; and (ii) investigating the robustness of the pressure reconstruction with respect to image resolution, field of view, and interrogation window size. We opt for a simple experimental setup to assess the feasibility of a combined PIV/DIC approach and conduct a comprehensive, critical, analysis of its performance, toward laying the foundation of a robust methodology. The proposed experimental framework may facilitate future investigations of novel physical phenomena in fluid-structure interactions. Different from traditional techniques, our experimental approach allows for estimating the structural deformation and fluid loading via two independent measurement methods.

The rest of the paper is organized as follows: experimental details of the combined PIV and DIC system are presented in Section 2; the analysis methods are explained in Section 3; the results of PIV and DIC analyses along with the accuracy assessment of the current methods are presented in Section 4; and conclusions from our major findings are drawn in Section 5.

2. Experimental procedure

In this work, the deformation of an elastic plate due to a steady incoming water flow is studied using PIV and DIC; a schematic of the experimental setup is shown in Fig. 1. Specifically, a flexible plate is clamped at one end and positioned in the center of a water tunnel (Engineering Laboratory Design Inc., Lake City, MN) such that the planar surface of the plate is nominally orthogonal to the incoming flow. The clamped end of the plate is 4.8 cm below the water surface. The water tunnel test section is $0.15 \times 0.15 \times 2.4\ \mathrm{m}^3$ and can generate average flow speeds ranging from 0.5 to 20 cm/s. The depth of the water flow is $H = 11$ cm. A honeycomb flow conditioner is installed 50 cm upstream of the plate to promote a uniform velocity profile in the channel and minimize velocity fluctuations. All experiments are carried out at room temperature, for which the fluid density and viscosity are assumed to be $\rho = 1\ \mathrm{g/cm}^3$ and $\mu = 1$ mPa s, respectively.

Toward eliciting sufficiently large structural deformations, we use a highly compliant material, Polydimethylsiloxane (PDMS), to fabricate the plate. The flexible plates are fabricated by first mixing a SYLGARD 184 Silicone base and curing agent (Sigma–Aldrich, product number 761028) with a 10:1 ratio. The mixture is cast into a rectangular mold and left to polymerize for 2 h at 60 °C, thereby producing a 2.5 mm thick PDMS slab. The PDMS slab is then cut into strips of dimensions $40 \times 62.5 \times 2.5\ \mathrm{mm}^3$ for the experiments.

The Young's modulus of the PDMS is estimated from the fundamental vibration frequency of the plate. The detailed experimental procedure is presented in Appendix A. The effective Young's modulus is

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