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Control design in cyber-physical fluid–structure interaction experiments

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A B S T R A C T

Cyber-physical fluid dynamics is a hybrid experimental–computational approach to study fluid–structure interaction (FSI). It enables on-the-fly changes to structure inertia, damping, stiffness, and even kinematic constraints by replacing traditional elastically-mounted structures with actuators and a controller. The control design plays a central role in matching the closed-loop dynamics of the cyber-physical structure (CPS) to those of the desired structure. Control designs based on traditional proportional–integral–derivative (PID) and post-modern H_∞ control are presented. The controllers are synthesized to match the linearized desired structural dynamics (or the input–output response) but no assumption of linearity is levied on the fluid behavior. To quantify the matching of input–output response, a CPS deviation index is defined based on H_∞ norms. To evaluate and compare the performance of the control designs, two well-known FSI instabilities are considered, galloping and aeroelastic flutter. These FSI instabilities represent convenient test cases because they can be analyzed with linear aerodynamic models. Comparing the critical instability flow velocity and oscillation frequency of the CPS with different control designs and the desired mechanical structure demonstrates that the internal structure of the controller is crucial to fully matching the response of the desired structure. H_∞ model-matching control with admittance causality is found to be the most adept control design for the CPS.

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1. Introduction

In recent years, a hybrid experimental–computational approach known as cyber-physical fluid dynamics (CPFD) has been adopted by several researchers to study a broad range of fluid–structure interaction (FSI) phenomena (Fagley et al., 2016; Gowda et al., 2017; Hover et al., 1998, 1997; Ji et al., 2018; Lee et al., 2011; Mackowski and Williamson, 2015, 2011; Mandre et al., 2014; Onoue et al., 2015; Onoue and Breuer, 2016; Sun et al., 2017, 2015; Zhang et al., 2018). CPFD replaces traditional elastically mounted wind or water tunnel models with a cyber-physical structure (CPS) as shown in Fig. 1. A CPS integrates active actuation, sensing, and control algorithms to physically replicate the inertia, stiffness, damping, and kinematic constraints of a desired structure while interacting with a physical environment.

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Nomenclature

b	Half-chord length
C_y	Coefficient of normal force
c	Coefficient of viscous damping
F_X	Force due to X component or interaction
h	Heave position
${}^{\bar{O}}_{X}\vec{h}_Y$	Angular momentum with $\bar{O}$-frame velocity w.r.t X and moment arm w.r.t Y
I_X	Inertia about point X
K	Torque or force constant
k_d	Derivative gain
k_i	Integral gain
k_p	Proportional gain
L	Aerodynamic lift
M^*	Mass or Inertia ratio
M	Moment
m, M_X	Mass. X is identifier
N	Derivative control filter coefficient
$\vec{r}_{i/X}$	Position of i w.r.t X
U	Flow velocity
${}^{\bar{O}}\vec{v}_{i/X}$	Velocity of i w.r.t X in $\bar{O}$-frame
W_u	Controller-output weight
α	Angle of attack
θ	Pitch angle (mechanical system)
ς	Damping ratio
$\vec{\tau}_X$	Torque about point X
φ	Pitch angle (CPS)
ω	Circular frequency

Subscripts

act	Actuator
clp	Closed loop
f	Flutter instability
g	Galloping instability
h	Heave
L	Linear actuator
θ	Pitch
φ	Rotational actuator

In a purely computational approach to study fluid–structure interaction (FSI), both the structural and the fluid dynamics are solved using a digital computer. In the cyber-physical fluid dynamics (CPFD) approach to study FSI, the digital computer only solves the structural dynamics, which are then implemented in hardware with a controller. The Navier–Stokes equations and the discretized flow field are replaced with real fluid flow (Mackowski and Williamson, 2011). As a result, the fluid non-linearities are not part of the cyber-physical structure (CPS) design or development. CPS is advantageous because the mechanical properties of the CPS can be precisely set as with computational methods, but unlike mechanical structures, can be readily altered in software. In addition, the use of real fluid flow provides physically valid flow behaviors and infinite spatial resolution. The CPS in this work are used solely to emulate the dynamics of the desired structure.

Despite the adoption of the CPFD approach by several researchers, concerns remain regarding the time-lag associated with digitally processing the inputs and outputs of the controller. Some researchers have attempted to quantify this lag; for instance, the VIV test facility at MIT is reported to have a phase lag of 5° to 12° (Hover et al., 1997, 1998). Addressing these concerns would further enable a more widespread and meaningful use of this research methodology. Also, the implications of control design on CPS performance remain unexplored. The typical method of CPS validation consists of comparing historical and CPS experiment data (Mackowski and Williamson, 2011), or by comparing either the impulse, step, or free response of the CPS with a theoretical model (Fagley et al., 2016; Gowda, 2016; Onoue et al., 2015). However, a comparison with previous experiments is limiting as historical data may not always be available for each parameter setting. In addition, there are two implicit assumptions in this validation methodology. First, a CPS which performs adequately for one set of parameters will do so for any set of parameters under constant or scheduled controller gains. Second, a mechanical structure and CPS will undergo flow-induced instability at the same velocity and with the same frequency. Both assumptions remain unproven. Matching flow-induced instability characteristics is necessary for using a CPS in instability driven applications

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