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Active vortex-induced vibration control of a circular cylinder at low Reynolds numbers using an adaptive fuzzy sliding mode controller

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An adaptive fuzzy sliding mode control (AFSMC) scheme is applied to actively suppress the two-dimensional vortex-induced vibrations (VIV) of an elastically mounted circular cylinder, free to move in in-line and cross-flow directions. Laminar flow regime at Re = 90, low non-dimensional mass with equal natural frequencies in both directions, and zero structural damping coefficients, are considered. The natural oscillator frequency is matched with the vortex shedding frequency of a stationary cylinder at Re = 100. The strongly coupled unsteady fluid/cylinder interactions are captured by implementing the moving mesh technology through integration of an in-house developed User Define Function (UDF) into the main code of the commercial CFD solver Fluent. The AFSMC approach comprises of a fuzzy system designed to mimic an ideal sliding-mode controller, and a robust controller intended to compensate for the difference between the fuzzy controller and the ideal one. The fuzzy system parameters as well as the uncertainty bound of the robust controller are adaptively tuned online. A collaborative simulation scheme is realized by coupling the control model implemented in Matlab/Simulink to the plant model constructed in Fluent, aiming at determination of the transverse control force required for complete suppression of the cylinder streamwise and cross-flow oscillations. The simulation results demonstrate the high performance and effectiveness of the adopted control algorithm in attenuating the 2D-VIV of the elastic cylinder over a certain flow velocity range. Also, the enhanced transient performance of the AFSM control strategy in comparison with a conventional PID control law is demonstrated. Furthermore, the effect of control action on the time evolution of vortex shedding from the cylinder is discussed. In particular, it is observed that the coalesced vortices in the far wake region of the uncontrolled cylinder, featuring the C(2S)-type vortex shedding characteristic mode, are ultimately forced to switch to the classical von Kármán vortex street of 2S-type mode, displaying wake vortices of moderately weaker strengths very similar to those of the stationary cylinder. Lastly, robustness of AFSMC is verified against relatively large structural uncertainties as well as with respect to a moderate deviation in the uniform inlet flow velocity.

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1. Introduction

Vortex-induced vibration (VIV) is a fundamental phenomenon frequently encountered in many practical engineering applications and physical sciences where an external fluid flow dynamically excites and interacts with a freely mounted bluff solid or flexible structure (Griffin and Ramberg, 1982; Blake, 1986; Williamson and Govardhan, 2008; Bearman, 2011; Païdoussis et al., 2011; Wu et al., 2012). The unsteady flow force, generated by the alternate vortex shedding, affects the structural vibration, while the oscillating structure will in turn influence the flow field, giving rise to a complex nonlinear coupled fluid–structure interaction (FSI) problem (Blevins, 1990). This may result in noise, strain the fatigue life of structures, and even lead to disastrous structural damage. Consequently, suppression of vortex-induced structural vibration through modification of wake vortex dynamics has attracted great attention in the literature (Bearman, 1967, 1984; Williamson and Roshko, 1988; Mittal and Kumar, 2001; Sarpkaya, 2004). Existing control strategies may be categorized into two main groups: flow control (which targets only vortex shedding to suppress vortex-induced vibration), and structural vibration control (which directly controls the structural vibration). Most existing research involve flow control; a wide variety of techniques have been set out, among them are passive control (Zdravkovich, 1981;Owen et al., 2001; Quadrante and Nishi, 2014), acoustic excitation (Ffowcs Williams and Zhao, 1989), oscillating or rotating cylinders (Berger, 1967; Fujisawa et al., 2001), surface blowing or suction (Min and Choi, 1999; Winkel et al., 2004; Chen et al., 2013), electromagnetic forcing (Chen et al., 2005; Zhang et al., 2014), and cylinder shape control (Xu et al., 2014). With the introduction of fast digital processing and state-of-the-art actuators, active control of VIV has recently gained increased consideration (Muddada and Patnaik, 2010; Meliga et al., 2011; Mehmood et al., 2012). It implicates the direct input of energies by means of actuators driven by external sources through a controller to bring about desirable changes to the flow structure system. Active schemes can be either open-loop (which uses independent external disturbance) or closed-loop (which relies on a feedback signal from the system). The open-loop control is very effective in suppressing vortex shedding and structural vibration only when the actuating signal is properly tuned in terms of frequency. Furthermore, to achieve the best performance, the open-loop control requires reasonably large actuator perturbation amplitudes, and the perturbation frequency must be in a certain small range. In what follows, an exhaustive review of the subject is avoided, and essentially a brief overview on the key recent contributions regarding the active VIV control of freely suspended slender cylindrical structures is presented.

Berger (1967) was perhaps the first to introduce the concept of feedback control to suppress vortex shedding from a bimorph cylinder at a low Reynolds number. Baz and Ro (1991) investigated the use of a simple velocity feedback controller, based on its operation on an internally mounted electromagnetic actuator and hot wire flow measurement, to monitor and actively attenuate vortex-induced vibrations of a flexible circular cylinder. The method was shown to be very effective in attenuating the vibration of a single vibration mode in the synchronization regime by using a single collocated sensor/actuator pair. Venkatraman and Narayanan (1993) studied the active control of vortex-induced oscillations of circular cylinders and galloping vibrations of a square prism modeled as a single dof linear damped oscillator, by using the so-called disturbance accommodating control (DAC) philosophy. Baz and Kim (1993) used an independent modal space controller utilizing collocated piezoelectric actuators and sensors bonded to the root of a flexible cantilevered cylinder to suppress the vortex-induced vibrations of the dominant modes in crossflow. Consequently, the amplitude of vibration was reduced by 40% over a $5500 < \mathrm{Re} < 7500$ range. Poh and Baz (1996) used a robust adaptive feedforward Least Mean Square (LMS) algorithm to control low amplitude vortex-induced vibrations of flexible cylinders. It was shown that the adopted algorithm provides an excellent means of rejecting the effect of the periodic vortex-induced excitations which act persistently on the flexible cylinders. Warui and Fujisawa (1996) used a velocity feedback control system using electromagnetic actuators installed at both ends of the cylinder and hot-wire flow measurements to effectively reduced the vortex strength at a moderate Reynolds number of 6700. Gattulli and Ghanem (1999) developed an adaptive control technique based on feedback linearization and the sliding mode concepts that permits the control of the motion of offshore structures undergoing two dimensional vortex-induced vibrations. Carbonell et al. (2003) formulated a control algorithm with three different schemes for suppression of flow-induced vibration (FIV) of fluid–structure interaction systems with bounded disturbance and variable parameters. The classical model of a uniform flow past an elastically supported rigid cylinder was considered to simplify the illustration. Cheng et al. (2003) proposed a novel perturbation technique involving curved surface-embedded piezoceramic actuators (THUNDER) to modify the interactions between synchronizing vortex shedding and structural vibration of a flexibly supported bluff body (square cylinder) in cross flow. However, their open-loop control technique (i.e., lacking the feedback of either flow or structural vibration information), suffered from two main shortcomings; namely, a relatively narrow perturbation frequency range to achieve the desired performance near the resonance region, and a relatively large required perturbation amplitude (i.e., about 25% of the cylinder vibration amplitude). The performance of the latter control system was greatly enhanced by Zhang et al. (2004) with the deployment of a closed-loop control system perturbing the cylinder surface using piezo-ceramic actuators activated by a feedback hot-wire signal via a proportional-integral-derivative (PID) controller. It was demonstrated that the best performance can be achieved in terms of both suppressing vortex shedding and FIV of the flexibly supported square cylinder provided that feedback signal is properly chosen. Chen and Aubry (2005) developed a closed-loop control algorithm by application of arrays of Lorentz force actuators for suppressing one-degree-of-freedom vortex-induced vibration of a circular cylinder in cross-flow direction at $\mathrm{Re}=100$ and 200. Li et al. (2007) using surface-embedded PZT micro-actuators to experimentally control vortex-induced vibration of two side-by-side circular cylinders in a cross flow. Wu et al. (2007) proposed a multi-high-frequency perturbation controller with a feedback closed-loop system for FIV control of an elastically mounted square