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Computational fluid dynamics-based transonic flutter suppression with control delay

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ABSTRACT

This work investigates the effects of control input time delay on closed-loop transonic computational aeroelastic analysis. Control input time delays are becoming critical as the demand for high frequency control actions is increasing. The flow in transonic conditions exhibits strong nonlinearities which require accurate physical modeling techniques, in turn resulting in large dimensional systems that are computationally costly to solve. A unified framework is demonstrated for the robust and efficient generation of reduced order models. Once generated, the reduced order model is employed for the flutter boundary search, and excellent agreement with the large order coupled model is demonstrated. The aero-servo-elastic reduced order model is then exploited to design a feedback control law, which is implemented in the fully coupled computational fluid/structural dynamics solver. As expected, the controller effectiveness is found to degrade for increasing time delay, up to a critical value where the controller fails to suppress flutter. It is shown that a controller for a time-delay system may be designed using the same aero-servo-elastic reduced order model, incurring in no extra costs or complications. The new controller is found to achieve excellent flutter suppression characteristics. The aero-servo-elastic reduced order model may also be used to identify, for a given feedback controller, the critical value of control input time delay at which the closed-loop aero-servo-elastic system loses its stability. The test cases are for a two-dimensional pitch-plunge aerofoil section and the AGARD 445.6 wing modified with a trailing-edge control surface.

1. Introduction

Flutter is a dynamic instability phenomenon caused by the interaction of aerodynamic, elastic and inertial forces. At flutter, a catastrophic failure of the airframe will normally occur. To control or suppress flutter ensuring the structural integrity of the aircraft structural components, several active and passive control strategies have been investigated

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(Da Ronch et al., 2013b; Marzocca et al., 2012; Papatheou et al., 2013). In this work, in particular, the interest is on active control strategies that are relevant to industrial aircraft design, extending the operational flight envelope and ensuring safety. Among active control techniques, a large body of work using feedback strategies has been reported, see for example Da Ronch et al. (2013b) and Tantaroudas et al. (2015). Adaptive and nonlinear feedback control has been investigated, for example, in Tantaroudas et al. (2014) where a numerical study for gust loads alleviation of various aeroelastic models was presented, and Da Ronch et al. (2014), Fichera et al. (2014) and Papatheou et al. (2013) demonstrated the suppression of limit cycle oscillations (LCOs) for a nonlinear aeroelastic wind tunnel model. On the other hand, feedforward control strategies have the advantage that there is no time delay between the disturbance measurement and the control action. Whereas a number of numerical investigations (Wang et al., 2014, 2015) showed promising results compared to feedback control, the measurement of the disturbance is challenging in an experimental setting, particularly to detect atmospheric turbulence in flight.

Several classic and modern control theories have been applied to design active feedback control laws, such as linear quadratic regulator (LQR) and optimal controllers. However, these control strategies may be ineffective if the aeroelastic system has a control delay. Time delays in control loops are inevitable when digital controllers and hydraulic actuators are modeled (Liu and Hu, 2010), and may arise from measuring and filtering the system states, computing the control outputs, and transmitting control outputs to actuators. Time delays become particularly critical when the control effort demands large control forces or high frequencies. Time delay introduces a phase shift, which deteriorates the controller performance and may drive the system to instability. In most previous studies in aero-servo-elasticity, time delays in control feedback loops have been neglected. In some cases, a suitable control delay was found to improve the system stability (Zhao, 2009; Zhao and Xu, 2007). By Olgac and Holm-Hansen (1994), a delayed feedback control was investigated. The technique offers a number of attractive advantages in eliminating oscillations of the primary system, such as real time tunability, wide range of frequency, and simplicity of the control. For a suitable delay in the control feedback loop system, the delay feedback control may expand the system's stability region (Zhao, 2009). Zhao (2009, 2011) presented a systematic study on aeroelastic stability of a two-dimensional (2D) aerofoil in incompressible flow with single or multiple time delays in the feedback control loops. It was found that a small time delay in the feedback control can stabilize the aeroelastic system, which is initially unstable under delay-free control.

Stability analysis and control of time delayed systems have been widely studied in recent years (Chen and Xu, 2013; Dai et al., 2014c, 2015; Hu et al., 1998a, 1998b). In the field of aero-servo-elasticity, for example, Yuan et al. (2004) and Xu et al. (2014) investigated the effects of the time-delayed feedback control on the flutter instability boundary of a 2D supersonic lifting surface. Librescu et al. (2005) presented the effects of time delay on the stability of a 2D aeroelastic system in incompressible flow and designed a delayed feedback controller to stabilize the system. Previous studies have mainly focused on a 2D aeroelastic system, with few cases looking at three-dimensional (3D) aeroelastic models. For example Huang et al. (2012, 2015b) presented numerical and experimental studies on the active flutter suppression (AFS) of a 3D wing model involving a control delay. A high-dimensional multiple-actuated-wing was established in their work as a test case to validate the control method.

Generally, aero-servo-elastic studies have used low-fidelity linear aerodynamic models, including lifting surface theory (Yuan et al., 2004), piston theory (Xu et al., 2014), quasi-steady aerodynamics (Zhao, 2009, 2011), and the doublet-lattice method (Huang et al., 2012, 2015b). The assumption of linear aerodynamics is adequate to treat subsonic and supersonic flow regimes (Xie et al., 2014a). In transonic conditions, which are relevant for passengers' transport aircraft jets, the flow is dominated by nonlinear effects and exhibits complex interactions between shock waves and boundary layer (Alder, 2015; Dai et al., 2014a, 2014b). Take-off and landing conditions are equally critical phases of flight, in particular when in presence of cross-winds. Computational fluid dynamics (CFD) solvers are needed for realistic predictions in transonic conditions. From the available literature, it is apparent that the effects of time delay and delayed feedback control designed for transonic aeroelastic models have been rarely studied.

With the previous paragraphs as background, this paper aims at investigating time delay effects in transonic aeroelastic models, and developing control strategies for the transonic flutter suppression. High-fidelity aeroelastic modeling, based on coupling a research CFD solver with a computational structural dynamics (CSD) solver, is used for accurate time marching. Two considerations are worth noting about the application of coupled CFD/CSD methods for AFS problems: first, the computational cost of coupled simulations for 3D configurations is today unrealistic for practical applications despite the availability of high performance computing (HPC) facilities[1]; second, a low-dimensional state space model is needed for the control design synthesis. To find a compromise between these two contrasting requirements, model reduction techniques aim at balancing high fidelity and low cost/dimensionality. Various techniques exist, but these are generally limited to linear or weakly-nonlinear systems (Ghoreyshi et al., 2013; Lucia et al., 2004). Among nonlinear ROMs, the harmonic balance (Da Ronch et al., 2013a) and the nonlinear model projection (Da Ronch et al., 2012, 2013c; Timme et al., 2013) have been applied to a variety of test cases and models. The latter method, in particular, is well suited to control synthesis design for gust loads alleviation. Alternative methods based on proper orthogonal decomposition (POD) (Xie et al., 2014b) have also been used to generate CFD-based ROMs. Chen et al. (2012b, 2014), respectively, performed AFS and control design for gust loads

[1] The University of Southampton hosts two HPC facilities, Iridis4 and Lyceum. Iridis4, in particular, is ranked the most powerful academic supercomputer in the UK with 12,320 Intel® Xeon® E5-2670 processor cores, a petabyte of disc space, and 50 terabytes of memory.