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Brief paper

Adaptive boundary control of store induced oscillations in a flexible aircraft wing☆

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ABSTRACT

An adaptive boundary control strategy is developed for the suppression of store induced oscillations in the bending and twisting deflections of an uncertain flexible aircraft wing. A Lyapunov-based stability analysis is used to show that the total energy in the system, and hence the distributed states of the system, remains bounded and decays asymptotically to zero. Simulation results illustrate the performance of the developed controller.

1. Introduction

Store induced oscillations commonly described as Limit Cycle Oscillations (LCO) occur on current high performance fighter aircraft and are expected to remain an issue for next generation aircraft (Beran, Strganac, Kim, & Nichkawde, 2004). Store induced oscillations are characterized by antisymmetric, non-divergent periodic motion of the wings. Asymmetry in the wing oscillations cause a lateral motion in the fuselage that hinders a pilot's ability to read cockpit instruments and heads-up display which can lead to the premature termination of the mission or avoidance of a region of the flight envelope crucial to combat survivability. Furthermore, questions have been raised regarding the safe release of wing stores, the target acquisition of smart munitions, and the accuracy of unguided ordnance (Bunton & Denegri, 2000). These concerns necessitate the development of a control strategy designed to suppress store induced oscillations.

In a wide range of Mach numbers (Sheta, Harrand, Thompson, & Strganac, 2002), store induced oscillations are prominent. Store induced oscillations in the subsonic range provide additional acceleration and result in additional force on the aircraft, which affects its performance. Experimental investigations of oscillation of nonlinear aeroelastic systems in the subsonic airflow region are found in Platanitis and Strganac (2004), Sheta et al. (2002) and Strganac, Ko, Thompson, and Kurdila (2000). Experimental results in Sheta et al. (2002) indicate the importance of addressing oscillations in the subsonic airflow region.

Previously developed control strategies have focused on suppressing oscillation behavior in a two-dimensional airfoil system. Several of these control strategies require knowledge of the system dynamics, including linear–quadratic regulator (Block & Strganac, 1999; Prime, Cazzolato, Doolan, & Strganac, 2010; Zhang & Ye, 2007), feedback linearization (Ko, Strganac, & Kurdila, 1998), linear reduced order model-based control approaches (Danowsky et al., 2010; Thompson et al., 2011), a Nissim aerodynamic energy-based control approach (Cavagna, Ricci, & Scotti, 2009), and state-dependent Riccati equation and sliding mode control approaches (Elhami & Narab, 2012). Many adaptive control strategies have been developed for uncertainties in the torsional stiffness model such as adaptive feedback control for linear-in-the-parameter uncertainties (Ko, Strganac, & Kurdila, 1999; Strganac et al., 2000). Most recently, a RISE control structure was used to ensure asymptotic tracking of a two-dimensional airfoil section with modeling uncertainties in the structural and aerodynamic properties (Bialy, Pasiliao, Dinh, & Dixon, 2012), and then extended to compensate for actuator saturation (Bialy, Andrews, Curtis, & Dixon, 2013).

Previously, research on control strategies for the suppression of oscillation has been concerned with a two-dimensional airfoil section rather than a full flexible aircraft wing. This work develops an adaptive boundary controller for the suppression of store induced oscillations in a full three-dimensional flexible aircraft

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wing. The dynamics of a flexible aircraft wing can be modeled, using Hamilton's principle (Hodges & Dowell, 1974; Hodges & Ormiston, 1976; Martins, Mohamed, Tokhi, Sá da Costa, & Botto, 2003; Morita et al., 2002; Zhang, Xu, Nair, & Chellaboina, 2005; Ziabari & Ghadiri, 2010), as a set of partial differential equations (PDEs) and associated boundary conditions.

There are two boundary control methodologies that have been developed for a system described by a set of PDEs. The first method approximates the PDE system with a finite number of ordinary differential equations (ODE) using operator theoretic tools (Bucci & Lasiecka, 2010; Byrnes, Laukó, Gilliam, & Shubov, 2000; Luo, 1993; Luo & Guo, 1995) or Galerkin and Rayleigh–Ritz methods (Christofides & Daoutidis, 1997; Meirovitch, 1967; Shawky, Ordys, & Grimble, 2002). A boundary controller is then designed using the resulting reduced-order model. The primary concern with using a reduced-order model for the control design is the potential for spillover instabilities (Balas, 1978; Meirovitch & Baruh, 1983), in which the controller excites higher-order modes that were neglected in the approximation. In special cases, the placement of actuators and sensors can guarantee the neglected modes are not excited (Balas, 1982). Specifically, placing actuators at known zero locations of the higher-order modes will alleviate spillover instabilities; however, this can conflict with the desire to place actuators away from the zeros of the controlled modes.

The alternative approach is to design the controller based on the full PDE system where model reduction techniques are only required for implementation purposes. A PDE backstepping strategy, described in Krstic and Smyshlyaev (2008), constructs a state transformation using an invertible Volterra integral. The transformation maps the original system to an exponentially stable target system. Due to the invertibility of the transform, stability of the target system translates to stability of the closed-loop system consisting of the original PDE and boundary feedback control. While this method avoids spillover instabilities, it is limited to linear PDEs and nonlinear PDEs of a particular form. The boundary control strategy described in de Queiroz, Dawson, Nagarkatti, and Zhang (2000) and de Queiroz and Rahn (2002) uses Lyapunov-based design and analysis arguments to stabilize PDE systems. The essence of the analysis is the assumption that for a real physical system, if the energy of the system is bounded, then the states that compose the energy are also bounded. Based on this assumption, a Lyapunov-based stability analysis is used to show that the energy in the closed-loop system remains bounded. A PDE-based boundary control approach has been previously used to stabilize fluid flow through a channel (Vazquez & Krstic, 2007), maneuver flexible robotic arms (de Queiroz, Dawson, Agarwal, & Zhang, 1999), control the bending in an Euler beam (Fard & Sagatun, 2001; He, Ge, How, Choo, & Hong, 2011; Siranosian, Krstic, Smyshlyaev, & Bement, 2011), regulate a flexible rotor system (de Queiroz & Rahn, 2002; Nagarkatti, Dawson, de Queiroz, & Costic, 2001), and track the net aerodynamic force or moment of a flapping wing aircraft (Paranjape, Guan, Chung, & Krstic, 2013).

Many PDE-based and ODE-based control strategies have been developed to stabilize the bending of a flexible beam such as Fard and Sagatun (2001), Luo (1993), Luo and Guo (1995) and Siranosian et al. (2011); however, this collection of work is focused on structural beams and robotic arms and therefore do not encounter the closed-loop interactions between the structural dynamics and aerodynamics intrinsic to aircraft systems. Recently, the work in Paranjape et al. (2013) used the PDE-backstepping method described in Krstic and Smyshlyaev (2008) to track the net aerodynamic forces on a flapping wing UAV whose dynamics are represented by linear PDEs. The control objective in Paranjape et al. (2013) was not concerned with the performance of the distributed states, rather it focused on controlling the spatial integral of the state variables.

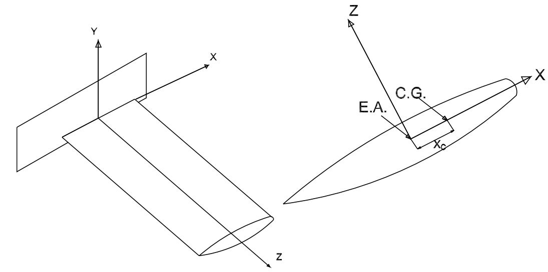

Fig. 1. Schematic of the wing section., where E.A. denotes the elastic axis and C.G. denotes the center of gravity.

The focus of the current work is the design of a controller to suppress store induced oscillations in an aircraft wing described by uncertain coupled nonlinear PDEs via regulation of the state variables. An adaptive boundary controller is designed to ensure the distributed states of the flexible wing are regulated asymptotically. The challenge in this problem is that the uncertain nonlinear PDE cannot be transformed into an exponentially stable target system using the Voltera integral strategy in Krstic and Smyshlyaev (2008). As a result, the controller is developed through a Lyapunov-based analysis. The Lyapunov analysis is facilitated by examining the energy in the aircraft wing and through the development of novel auxiliary terms introduced to yield favorable outcomes from the derivative of the wing energy. Simulation results demonstrate the open-loop oscillation and how the controller is applied to damp out the oscillation.

2. Flexible aircraft wing model

Consider a flexible wing of length $l \in \mathbb{R}$, mass per unit span of $\rho \in \mathbb{R}$, moment of inertia per unit length of $I_w \in \mathbb{R}$, and bending and torsional stiffnesses of $EI \in \mathbb{R}$ and $GJ \in \mathbb{R}$, respectively, with a store of mass $m_s \in \mathbb{R}$ and moment of inertia $J_s \in \mathbb{R}$ attached at the wing tip. The bending and twisting dynamics of the flexible wing are described by the following PDE system[1]

$$\begin{aligned}\bar{L}_w\varphi(y,t) &= \rho\omega_{tt}(y,t) - \rho x_c \sin\left(\varphi(y,t)\right)\varphi_t^2(y,t) \\ &\quad + \rho x_c \cos\left(\varphi(y,t)\right)\varphi_{tt}(y,t) + EI\omega_{yyyy}(y,t), \qquad (1)\end{aligned}$$

$$\begin{aligned}\bar{M}_w\varphi(y,t) &= \left(I_w + \rho x_c^2\right)\varphi_{tt}(y,t) \\ &\quad + \rho x_c \cos\left(\varphi(y,t)\right)\omega_{tt}(y,t) - GJ\varphi_{yy}(y,t), \qquad (2)\end{aligned}$$

where $\omega : \mathbb{R}\times\mathbb{R} \to \mathbb{R}$ and $\varphi : \mathbb{R}\times\mathbb{R} \to \mathbb{R}$ denote the bending and twisting displacements, respectively, $y \in [0, l]$ denotes spanwise location on the wing, $x_c \in \mathbb{R}$ represents the distance from the wing elastic axis to the wing center of gravity (as shown in Fig. 1), and $\bar{L}_w \in \mathbb{R}$ and $\bar{M}_w \in \mathbb{R}$ denote aerodynamic lift and moment coefficients, respectively.

Remark 1. *EI*, *GJ* and other wing parameters are considered to be spatially invariant, although this work may be extended to include spatially varying wing parameters by incorporating a similar approach as in Ishihara and Nguyen (2014).

In (1) and (2), the subscripts t and y denote partial derivatives with respect to time or the spanwise position along a wing. The boundary conditions for tip-based control are

$$\omega(0,t) = \omega_y(0,t) = \omega_{yy}(l,t) = \varphi(0,t) = 0, \qquad (3)$$

$$L_{tip}(t) = m_s\omega_{tt}(l,t) - m_s x_s \sin\left(\varphi(l,t)\right)\varphi_t^2(l,t)$$

[1] Damping terms (e.g., Kelvin–Voigt damping Kangsheng & Zhuangyi, 1998) could be added to the model; however, the subsequent development illustrates how to mitigate the oscillation through the closed-loop control.