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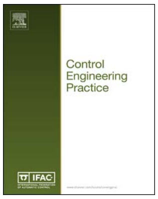

Fractional-order integral resonant control of collocated smart structures

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ABSTRACT

This paper proposes a fractional-order integral controller, FI, which is a simple, robust and well-performing technique for vibration control in smart structures with collocated sensors and actuators. This new methodology is compared with the most relevant controllers for smart structures. It is demonstrated that the proposed controller improves the robustness of the closed-loop system to changes in the mass of the payload at the tip. The previous controllers are robust in the sense of being insensitive to spillover and maintaining the closed-loop stability when changes occur in the plant parameters. However, the phase margin of such closed-loop systems (and, therefore, their damping) may change significantly as a result of these parameter variations. In this paper the possibility of increasing the phase margin robustness by using a fractional-order controller with a very simple structure is explored. This controller has been applied to an experimental smart structure, and simulations and experiments have shown the improvement attained with this new technique in the removal of the vibration in the structure when the mass of the payload at the tip changes.

1. Introduction

There are many industrial and scientific applications for which very lightweight mechanical structures are needed. These are built from lightweight materials with a small cross section. However, the performance of these structures may be impaired because they are prone to undamped vibrations and noises; see for example (Moheimani & Fleming, 2005), Vepa (2010). Smart structures, or structures with integrated sensors and actuators, are a technical solution which efficiently damps mechanical vibrations in applications in which passive techniques are either insufficient or impractical. Examples of these smart structures are nanopositioning devices in scanning probe microscopes (Fleming, Aphale, & Moheimani, 2010), large telescopes (Preumont, Bastaits, & Rodrigues, 2009), active noise cancellation systems in vibroacoustics (Tokhi & Veres, 2002), precision machines (Quintana & Ciurana, 2011) or fluid-flexible structure systems like the one resulting from the coupling of the deflection of a plane wing and the sloshing of the fuel inside the wing's tank (Robu, Baudouin, & Prieur, 2009).

The most common class of smart structures are those with integrated piezoelectric actuators and sensors. Their small volume, low weight and ease of structural integration, signify that piezoelectric sensors and actuators are very often used as transducers in smart structures. It is well known that there are a number of difficulties associated with the control of flexible structures, the foremost being: variable resonance frequencies; high system order – which implies the risk of destabilizing systems with high-frequency dynamics (spillover effect), and highly resonant dynamics (Aphale, Fleming, & Moheimani, 2007). Traditional control system design techniques such as LQG, H_2 and H_∞ have been applied to control these structures; see for example Banks, Smith, and Wang (1996); Ghosh, Sahu, and Bhattacharya (2015); Halim and Moheimani (2002a); Halim and Moheimani (2002b); Petersen and Pota (2003); Zhu, Liu, Huang, and Gao (2009). Unfortunately, the direct application of such techniques has the tendency to produce control systems of a high order and possibly poor stability margins. Other techniques address Lyapunov based techniques (Preumont, 2011) in order to guarantee stability, or flatness based control (Meurer, Thull, & Kugi, 2008) for trajectory tracking that is robust to spillover effects. There are also some techniques based on Luenberger-type observers whose asymptotic stability and insensitivity to spillover are guaranteed by Lyapunov based control design strategies, e.g. (Meurer & Kugi, 2011) and (Schröck, Meurer, & Kugi, 2011) for different configurations of stacks of piezoelectrics in the beam.

A different approach is that of attempting to take advantage of the properties of collocated resonant mechanical systems in order to design robust control systems. The most useful characteristic of

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a collocated system is the interlacing of poles and zeros up the $j\omega$ axis (IPZ property). This results in a phase response that lies continuously between 0° and 180°. Some control techniques have been developed that exploit this property, yielding controllers with significantly more robust properties while having simpler structures than those mentioned previously. In particular, some of these controllers make it possible to address the spillover problem in a quite straightforward manner. Our research has therefore been focused on this class of controllers. The most relevant controllers for smart structures that use the IPZ property are presented as follows.

Positive position feedback (PPF) is one of the control techniques to use the IPZ property and to have found a practical application. This technique was first introduced in Goh and Caughey (1985). PPF is essentially a second-order filter, which has proven to be an effective vibration control method for flexible systems embedded with smart materials (Fanson & Caughey, 1990; Chu & Cui, 2015). PPF controllers are stable in the presence of uncontrolled in-bandwidth modes, and roll off quickly at higher frequencies, thus reducing the risk of spillover. A modification of this controller, denoted as the MPPF controller, was proposed in Mahmoodi and Ahmadian (2009) in order to improve the active damping. An adaptive version of the MPPF was later proposed in Mahmoodi, Ahmadian, and Inman (2010). Another control technique is Velocity feedback (VF). Bar-Kana, Fischl, and Kalata (1991) proved that this technique could remove vibrations even in the case of totally undamped structures and Omidi, Mahmoodi, and Shepard (2015) is a recent example of a practical application. VF attempts to introduce damping in the system. However, one drawback of the controller involved is that its high-frequency gain must be attenuated so as to avoid noise amplification and destabilization owing to unmodeled or non-collocated dynamics. Two additional poles must therefore be added to the controller, which often yield a relatively low performance and a poor phase margin. Another approach is the resonant control (RC), which guarantees closed-loop stability in the presence of uncontrolled out-of-band modes of the structure. This has been successfully applied to collocated resonant systems (Pota, Moheimani, & Smith, 2002), but the high-pass nature of the controller may impede its use in certain applications. An improvement to this technique is the integral resonant control (IRC). This controller significantly augments the damping provided by the RC while maintaining the rolling off feature at higher frequencies.

The previous controllers are robust in the sense of being insensitive to spillover and maintaining the closed-loop stability when changes occur in the plant parameters. However, the phase margin of these closed-loop systems (and, therefore, their damping) may change significantly with these parameter variations. In this paper, the possibility of increasing the phase margin robustness by using a fractional-order controller with a very simple structure is explored.

The previous work carried out on the control of flexible structures and robots showed the increase in robustness that can be achieved by using fractional-order controllers. For example, a fractional-order proportional-derivative controller was proposed by Manabe (2002) for a flexible spacecraft attitude control; controllers that include a proportional term plus two fractional-order derivative terms of different orders were designed by Valerio (2005) to control a planar two degrees of freedom flexible robot; a fractional-order proportional-derivative controller was also used by Monje, Ramos, Feliu, and Vinagre (2007) for the control robust to payload changes of a single link flexible robot, while an analog device denoted as a “fractor” was proposed by Bohannan (2008) to control a flexible link using a fractional-order proportional-integral controller. Despite the fact that fractional-order controllers can improve the robustness of control systems, none of the previous controllers guarantee robustness to spillover effects. Several methods should also be mentioned with which to tune fractional-order controllers with simple structures that already exist. Fractional-order *PI* controllers that achieve nominal phase margin and gain crossover frequency specifications or nominal gain margin and phase crossover frequency specifications, together with local robustness to plant gain changes were proposed by Monje, Calderon, Vinagre, Chen, and Feliu (2004). Phase-lead and phase-lag compensators that achieved nominal phase margin and gain crossover frequency specifications, together with local robustness to plant gain changes and low and high frequency disturbance rejection were also developed by Monje, Vinagre, Feliu, and Chen (2008). Padula and Visioli (2012) proposed tuning rules so as to optimize certain integral control performance indexes applied to integral and unstable processes. More recently, Tavazoei and Tavakoli-Kakhki (2014) developed some conditions for the simultaneous achievement of desired phase and gain margins with fractional-order compensators. It should be stated that all these methods – and others that also exist in scientific literature – are not well suited to controlling systems as that studied in this work, which consists of an infinite dimensional system with very lowly damped vibration modes.

This paper therefore presents the development of a new control scheme for collocated smart structures, which achieves higher robustness by using a fractional-order controller. The robustness is achieved in the phase margin and, equivalently, in the damping of the closed-loop system. In order to assess the advantages attained by this controller, its performance is compared with the performances achieved by three techniques that simultaneously share the following features: (1) they propose controllers that are robust to spillover effects, (2) they have robust stability to large parametric variations, (3) the controllers yielded are linear and the methodology used in their design is relatively simple, and (4) they are highly recognized works in the smart material structures scientific community, and are considered as reference methods with which to control beam structures with piezoelectrics. These three techniques are the aforementioned IRC, PPF and MPPF control schemes.

This paper is organized as follows. Section 2 describes the experimental setup. Section 3 develops the dynamic modeling and identification of the platform. Section 4 presents the three well-known techniques with which to control collocated smart structures, Section 5 develops our new fractional-order controller. Section 6 presents simulated and experimental results using the four proposed controllers and Section 7 outlines some conclusions.

2. Experimental system

The experimental smart structure consists of a flexible aluminium cantilevered beam which is clamped at one end (the base of the beam) and is free at the other end (the tip of the beam). It should be mentioned that the clamped end is attached to a DC motor that is not used in the experiments shown in this paper. This DC motor is braked. It is therefore assumed that the clamped end of the beam is quiet. This structure is shown in Fig. 1 and is composed of:

- The uniform flexible beam.
- Strain gauges placed at the base of the beam to measure the torque at that point of the structure.
- Piezoelectric actuators placed at the base of the beam (hereafter denoted as PEA), whose purpose is to apply torque to the structure in order to remove existing mechanical vibrations.
- A Polytec LDV (model OFV-5000) with a sensor head of model “OFV-534 Compact Sensor Head” which measures the

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