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Fractional-order positive position feedback compensator for active vibration control of a smart composite plate

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ABSTRACT

In this paper, Active Vibration Control (AVC) of a rectangular carbon fibre composite plate with free edges is presented. The plate is subjected to out-of-plane excitation by a modal vibration exciter and controlled by Macro Fibre Composite (MFC) transducers. Vibration measurements are performed by using a Laser Doppler Vibrometer (LDV) system. A fractional-order Positive Position Feedback (PPF) compensator is proposed, implemented and compared to the standard integer-order PPF. MFC actuator and sensor are positioned on the plate based on maximal modal strain criterion, so as to control the second natural mode of the plate. Both integer and fractional-order PPF allowed for the effective control of the second mode of vibration. However, the newly proposed fractional-order controller is found to be more efficient in achieving the same performance with less actuation voltage. Moreover, it shows promising performance in reducing spillover effect due to uncontrolled modes.

1. Introduction

In the past decades research on Active Vibration Control (AVC) has found increasing interest in control of flexible thin-walled structures, mainly made of new advanced materials such as carbon fibre composites. These type of composite structures combine high stiffness with good flexibility in achieving complex shapes, and are mostly used in automotive and aerospace applications where they are often subjected to undesirable vibrations. In the field of AVC, a new type of sensor and actuator have become popular by using the so-called *smart materials*, such as piezoelectric materials, shape-memory alloys and electroactive polymers. These materials are called smart because they are inherently capable of detecting or responding to changes in their environment, making them very suitable both for sensing and actuation purposes. Given their distributed nature, they can be easily mounted on different types of structures, thus making them *smart structures*.

Piezoelectric transducers are often selected as sensors and actuators for the active control of smart flexible structures because of their unique properties including low cost, low mass, ease of integration and wide frequency range of control. In 1996 NASA invented a specific type of transducer called Macro Fibre Composite (MFC) which provides high performance, durability and a very good flexibility, making these transducers a preferred option in the case they shall be adapted to different structure geometries. Piezoelectric transducers in general, when used as sensors, measure strain which is proportional to the physical displacement. In fact, control schemes specifically designed to use position as feedback signal have been extensively studied

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and applied in this context.

The main objective of the controller is to provide active damping to the structure (plant), which results in an attenuation of the resonance peak in the dynamic amplification. The dynamics of flexible structures have very interesting properties: because of their flexibility, they have a large number of elastic modes resulting in very high order transfer functions that are rather difficult to control. Controllers are designed to target specific vibration modes in a restricted bandwidth of interest, and the fact that transfer functions are of high order means that there are out-of-bandwidth modes which are neglected, but whose effect might influence the closed-loop response. The effect of the uncontrolled, or out-of-bandwidth modes, is known in the literature as *spillover* [1]. Another important aspect regarding the controller is that, apart from being able to reduce structural vibrations, it should ensure robustness and closed-loop stability for the controlled system. In this sense, careful positioning of sensors and actuators can have a great influence. The majority of the controllers studied in literature use a *collocated* configuration, where sensors and actuators are related to the same Degree of Freedom (DOF) of the structure. The phase of the open-loop collocated transfer function is always between 0° and −180°, meaning that poles and zeros interlace on the imaginary axis, where zeros and poles correspond to anti-resonances and resonances of the frequency response, respectively. Collocated systems have the property of being always closed-loop stable with respect to out-of-bandwidth dynamics [2] and that is why most of the research involves collocation.

One of the most popular collocated modal control schemes is Positive Position Feedback (PPF), which has been first proposed in 1985 by Goh and Caughey [3] to overcome the instability associated with finite actuator dynamics. This controller was applied for the first time in 1987 by Fanson [4] to experimentally suppress vibrations in large space structures. PPF is effective if tuned to suppress a chosen frequency and mode. It is a second order low-pass filter which rolls off quickly at high frequencies, making it very appealing against possible instability or performance losses due to out-of-bandwidth dynamics.

Applications of PPF with smart structures are also extensively studied in literature. Kwak and Heo [5] applied a Multi-Input Multi-Output (MIMO) PPF to control vibrations of a smart grid structure equipped with piezoelectric transducers. They proposed a new technique to control a higher number of modes than the number of actuators and sensors. Zippo et al. [6] applied PPF for active vibration control of a composite sandwich plate using MFC transducers. Ferrari and Amabili [7], as a continuation of the work of Zippo, applied non-collocated PPF both in Single-Input Single-Output (SISO) and MIMO.

Direct Velocity Feedback (DVF), Resonant Control (RC) and Integral Resonant Control (IRC) are also collocated control techniques which are popular in literature. However, the DVF and RC [8] use velocity and acceleration as their feedback, respectively and thus they present limitations when used with piezoelectric transducers. Moreover, compared to PPF, IRC is a position feedback control with less suppression of higher order modes due to its first order filter behaviour [9]. In the field of AVC in general, apart from the aforementioned methods, many other different control strategies have been applied for several types of applications. Fractional-order calculus has been found to be an effective tool in control (see e.g. Refs. [10–15]), however, it has rarely found room in the context of AVC [16,17] and little research is present [18–20].

Fractional-control has never been experimentally applied before in the field of AVC of smart structures, and it is for the first time presented in this paper. A fractional-order versions of the PPF compensator is proposed, and compared to the standard integer-order PPF. Controllers are then implemented to control the 2nd mode of a carbon fibre/epoxy composite plate equipped with MFC actuator and sensor. A similar setup to the one used by Alijani and Amabili for similar studies [21,22] is built to test and control the plate with all edge free boundary conditions. These type of boundary conditions reduce the influence of temperature variations and other non-ideal boundary conditions which are generally associated with relevant changes in natural frequencies due to thermal stress. Therefore, completely free boundary conditions have been chosen to perform experimental modal analysis on the composite plate. In the next section, integer and fractional-order PPF compensators are elaborated and compared. In section 4 the experimental dynamics setup and complete AVC setup are described in detail. In section 5 results are presented, whereas final remarks and conclusions follow in section 6.

2. Problem definition

2.1. Direct velocity feedback

Direct Velocity Feedback of a 1-DOF system is defined as follows:

$$\ddot{\xi} + 2\zeta\omega\dot{\xi} + \omega^2\xi = \omega^2 f \tag{1}$$

where ξ, ω, ζ are modal coordinate, natural frequency and modal damping of the structure, respectively; $f = -g\dot{\xi}$ is the modal control force and g is the feedback gain. Equation (1) can be rewritten in the following form:

$$\ddot{\xi} + (2\zeta\omega + g\omega^2)\dot{\xi} + \omega^2\xi = 0 \tag{2}$$

It can be noted that active damping in this case is achieved through direct velocity feedback signal with gain g. DVF does not prevent the occurrence of spillover effect, but unconditional closed-loop stability is guaranteed nevertheless for $g > 0$ [8]. Despite its stability properties, DVF shows important limitations that do not make it an appealing control scheme in the context of active control with piezoelectric transducers. First of all, piezoelectric sensors measure strain of the structure, which can be considered as a displacement signal that would need to be differentiated before being fedback to the velocity controller. Therefore, in using DVF a differentiator is required, but generally not preferred. Secondly, in order to make sure that the compensator rolls-of at high frequencies, extra dynamics needs to be added to it although this could potentially cause instability ([8]). Furthermore