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Multimodal suppression of vibration in smart flexible beam using piezoelectric electrode-based switching control☆

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ABSTRACT

This paper describes an active vibration control system combining a piezoelectric electrode configured with a novel switching control system to achieve multimodal vibration suppression in smart flexible structures embedded with only a single piezoelectric actuator. The fact that high-frequency vibrations attenuate more rapidly than do low frequency vibrations motivated the development of a novel scheme in which the resonant excitation of coupled bending and lateral vibrations is applied to a cantilever beam. Switching times are determined using time-frequency analysis of modal responses. A smoothing function was applied to alleviate the effects of high-frequency oscillations during the switching control transition in order to facilitate the suppression of bending mode vibrations. Algorithms for proportional derivative (PD) control and positive position feedback (PPF) control can be tailored specifically for the target vibration modes and implemented in a variety of switching control schemes. The vibration responses induced by various switching control schemes was analyzed in order to derive appropriate control parameters for the development of an efficient switching control system aimed at suppressing multimodal vibrations. Experiment results demonstrate the effectiveness of the proposed piezoelectric electrode configuration in suppressing lateral mode vibrations. The proposed switching control system also proved highly satisfactory in suppressing vibrations in a system subject to simultaneous bending mode excitation.

1. Introduction

Piezoelectric sensors and actuators are widely applied in smart materials and structures for active vibration control, thanks to their compactness, responsiveness, high electromechanical efficiency, and high precision [1]. The core concept behind this type of mechatronic system is the integration of structures, actuators, and sensors as a feedback control system. Suitable control inputs are calculated using vibration control algorithms with the aim of suppressing the occurrence of unwanted vibrations in flexible structure systems [2–5].

From the perspective of mechatronics, previous research related to the active vibration control of flexible structures using piezoelectric materials falls into two general categories: (1) control algorithm development [6–13] and (2) the optimal placement of sensors and actuators [14–18]. The first category includes the proportional-derivative (PD) and positive-position-feedback (PPF) control methods in smart structures [6–8]. Advanced control methods, such as robust and adaptive controls, are used to compensate for uncertainties in modeling and high-frequency dynamics in various systems involving a flexible structure [9–13]. When a structure is suitable for the placement of piezoelectric actuators at a fixed end, such as cantilever beams and I-beams [6,9–13], the first category of methods can be used to control low-frequency modes. When a structure involves a complex combination of mode shapes or when the primary focus is suppressing vibrations pertaining to high frequency modes, the second category of methods can be used to determine the optimal placement of sensors and actuators using theoretical finite element modal analysis and/or through experimental investigations into the vibration characteristics of the structures [14–18]. Both of these are well-accepted approaches to promoting the efficiency of actuators and suppressing vibrations.

Flexible structures are infinite-dimensional low-damped mechanical systems with vibration responses comprising multiple vibration modes, including bending modes, torsional modes, lateral modes, and longitudinal modes [19,20]. The bending modes that dominate low-frequency vibrations and most other non-bending vibration modes fall within the category of high-frequency modes. Applying an electric field to the surface of a standard piezoelectric actuator causes a contraction in the active layer and expansion in the other layer [21–23], i.e., the piezoelectric actuator bends. A piezoelectric actuator with this configuration presents the highest excitation efficiency in bending modes. The

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inherent operating principle behind the use of a single piezoelectric actuator limits their applicability to the suppression of bending mode vibrations in flexible structures. This makes it necessary to employ algorithms to control coupled vibrations that include non-bending modes [24,25]. One common strategy for the suppression of multi mode vibrations in smart flexible structures involves applying multiple pairs of actuators and sensors to achieve active vibration control [26–28].

The core concept behind this approach is the same as that of the second category mentioned above; i.e., the proper placement of actuators to achieve optimal vibration suppression performance. Finite element method can be used to analyze the distribution of strain in structures associated with various vibration modes. It can also be used to facilitate the placement of multiple actuators/sensors in order to suppress specific vibration responses [29,30]. This is a feasible strategy when seeking to suppress vibrations in high-frequency modes; however, the need to formulate a multi-input/multi-output control system [31–35] that involves cross coupled dynamics and uncertainty modeling [36,37] can greatly hinder the development of affordable vibration suppression system. It may also be difficult to predict specific vibration modes when using multiple actuators and sensors, due to the indeterminate effects of glue on the mass of the structures and stiffness of the system. Thus, the current study focuses on the suppression of multimodal vibration in smart flexible structures using a single piezoelectric actuator.

The problem of suppressing non-bending mode vibrations using a single piezoelectric actuator has been dealt with by adjusting the configuration of surface electrodes to control the efficiency of mode excitation [38]. Previous studies [39,40] have investigated the vibration characteristics of thin piezoelectric resonators, and applied the dynamic electromechanical coupling factor to evaluate the efficiency of four electrode configurations. Modal excitation experiments have revealed improvements in the efficiency of mode excitation when using well-designed electrode configurations and revealed the potential benefits that could be garnered by increasing the mode excitation efficiency of non-bending modes using a single piezoelectric actuator. In [38], the authors first used electrode configuration to suppress lateral mode vibrations in a smart cantilever beam. Their experiment results demonstrated that an appropriate electrode configuration within an active vibration control system can improve mode excitation efficiency in the first lateral mode. They also showed that PD and PPF control algorithms could improve control over the suppression of lateral vibration. However, the vibration control method proposed in [38] is applicable only to suppressing modal vibrations corresponding to the electrode configuration (i.e., lateral mode vibrations); i.e., it is inapplicable to the suppression of bending mode vibrations and complex coupled vibrations.

This paper presents an active control method for multimodal vibrations in which the electrode configurations and corresponding control algorithms are controlled using a novel switching control system. Finite element software is first used to analyze the distribution of strain in a cantilever beam in order to obtain an electrode configuration capable of controlling the second bending mode and the first lateral mode of the structure. To enable fast transient responses, the switching time is determined using time-frequency analysis of modal responses, and a smoothing function is applied to reduce the effects of high frequency oscillations during the transition. The system design includes the control parameters of the PD and PPF algorithms for the target vibration modes. The results of multimodal vibration suppression were evaluated using the proposed switching control system with numerous variations in design parameters. Experiments demonstrate the efficacy of the proposed switching control system in suppressing coupled bending and lateral vibrations in a flexible structure. The contributions of this work are summarized in the following.

(1) We developed a piezoelectric electrode configuration with a novel time-based switching control system for the suppression of multimodal vibrations.
(2) We derived a mathematical model for smart flexible beams integrated with a piezoelectric actuator in an electrode configuration with the aim of suppressing lateral mode vibrations.
(3) We conducted a series of experiments to analyze the design parameters and evaluate the proposed switching control scheme in terms of vibration suppression performance.

The remainder of this paper is organized as follows. Section 2 details the vibration mode shapes described above as well as the placement of piezoelectric actuators and sensors based on our analysis of active vibration control in a cantilever beam. Section 3 reviews the theories used to guide the configuration of electrodes in piezoelectric resonators, and describes the electrode configurations applied in this study to control the coupled vibration modes based on finite element modal analysis. Section 4 presents the apparatus used for electrode switching control with a detailed discussion on selecting design parameters. That section also presents a performance comparison in the suppression of multimodal vibration, which was conducted using a range of experiments. Finally, concluding remarks and future directions in the formulation of electrode configurations for multimodal active vibration control designs are described at the end of the paper.

2. Smart flexible beam

This section first describes the use of finite element-based modal analysis to guide the placement of piezoelectric sensors and actuators along a flexible beam fixed at one end. A dynamic model of the piezoelectric beam [41] is presented before discussing the electrode configuration in order to facilitate subsequent analysis of the proposed electrode switching control system.

2.1. Modal analysis in placement of piezoelectric sensors and actuators

Modal analysis was conducted using finite element software, ANSYS, to identify the appropriate locations for the placement of piezoelectric sensors and actuators [14]. The rule of thumb here is to examine the distribution of nodal lines and strain throughout the structure. The beam in this study was aluminum, with a length of 450 mm, width of 45 mm, and thickness of 1 mm. In all theoretical analysis and finite element calculations, the material property were as follows: density of 2714 kg/m^3, Young's modulus of 71.41 GPa, and Poisson's ratio of 0.359. The mode shapes of a flexible structure generally comprise various vibration modes. For illustration purposes, Fig. 1 presents the mode shapes and vibration-displacement contours of the four vibration modes: first bending mode, second bending mode, first torsional mode, and first lateral mode. The solid lines indicate the contours of displacements along the y-axis, and the regions on both sides of the solid lines represent anti-phased (convex and concave) displacements. The boldest solid lines indicate the “nodal lines” mentioned above as the region with zero displacement. In the case of the bending modes in Fig. 1(a) and (b), deformation occurred along y-axis and is denoted as w_y. Fig. 1(c) presents the first torsional mode of the beam that vibrated harmonically as the twist angle ϕ_x. The deflection of the first lateral mode is along the z-axis as shown in Fig. 1(d) and is denoted as w_z (i.e., “laterally bending mode” along the x-y plane). The principle of piezoelectric sensors [42] implies that more strain produces more electric energy as an output signal. The nodal lines in the strain field are the same as those in the displacement field on the center line of the minor axis (boldest solid lines in Fig. 1(c) and (d)). This means that placing sensors in regions distal to the nodal lines is suitable for the feedback control of these four modes in smart structures. Thus, Fig. 1(a) and (b) indicate that vibration signals of the bending modes are accessible in all regions except in areas of minimum strain, i.e., free end of the beam. In cases of non-bending modes (Fig. 1(c) and (d)), clear nodal lines are concentrated in the central section of the beam. To obtain reliable