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A fuzzy robust control scheme for vibration suppression of a nonlinear electromagnetic-actuated flexible system

A.R. Tavakolpour-Saleh*, M.A. Haddad

Department of Mechanical and Aerospace Engineering, Shiraz University of Technology, Shiraz, Iran

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ABSTRACT

In this paper, a novel robust vibration control scheme, namely, one degree-of-freedom fuzzy active force control (1DOF-FAFC) is applied to a nonlinear electromagnetic-actuated flexible plate system. First, the flexible plate with clamped-free-clamped-free (CFCF) boundary conditions is modeled and simulated. Then, the validity of the simulation platform is evaluated through experiment. A nonlinear electromagnetic actuator is developed and experimentally modeled through a parametric system identification scheme. Next, the obtained nonlinear model of the actuator is applied to the simulation platform and performance of the proposed control technique in suppressing unwanted vibrations is investigated via simulation. A fuzzy controller is applied to the robust 1DOF control scheme to tune the controller gain using acceleration feedback. Consequently, an intelligent self-tuning vibration control strategy based on an inexpensive acceleration sensor is proposed in the paper. Furthermore, it is demonstrated that the proposed acceleration-based control technique owns the benefits of the conventional velocity feedback controllers. Finally, an experimental rig is developed to investigate the effectiveness of the 1DOF-FAFC scheme. It is found that the first, second, and third resonant modes of the flexible system are attenuated up to 74%, 81%, and 90% respectively through which the effectiveness of the proposed control scheme is affirmed.

1. Introduction

The flexible plate structures have received many attentions from the designers owing to their extensive applications in mechanical systems such as aircraft and submarine. However, such flexible plates can be more easily affected by unwanted vibrations. Indeed, the amplitude of unwanted vibrations in the flexible structures should be controlled so that the flexible systems do not experience performance degradation or structural damage. Accordingly, vibration control of the flexible plates is a significant task.

The Vibrations of flexible plate structures can be attenuated by either passive or active vibration control techniques. The passive control method consists of mounting passive material on the structure in order to change its dynamic characteristics such as stiffness and damping coefficient. This method is efficient at high frequencies, but expensive and bulky at low frequencies [1,2]. Moreover, passive vibration control usually leads to an increase in the overall weight of the structure. On the other hand, active vibration control (AVC) is a technique to electronically generate an additional vibration field to cancel out the unwanted vibrations at an observation point. Lueg [3] was among the first researchers who introduced the concept of active noise control in pipes, which was later extended to active vibration control problems as well. Generally, there are two well-defined AVC approaches for the flexible

* Corresponding author.
E-mail addresses: tavakolpour@sutech.ac.ir, alitavakolpur@yahoo.com (A.R. Tavakolpour-Saleh).

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plates namely feedforward and feedback control schemes [4]. In designing the feedforward vibration controllers, it is assumed that a reference signal representing the primary source of vibration is observable. However, a suitable reference signal is not available in many cases. Besides, the feedforward AVC scheme mostly attenuates the unwanted vibrations in the flexible plates locally. On the other hand, in the feedback AVC schemes, an error signal is fed into the controller and then, the feedback controller generates a control signal to drive the error signal to zero. It is important to note that the stability is assured in the feedback AVC systems containing collocated actuator/sensor pairs [4]. Furthermore, overall vibration attenuation can be found in the flexible plate system using the feedback controllers. Hence, a novel feedback controller was considered in this paper. However, in the digital implementation of the feedback control algorithms, the bandwidth of the control system is usually dependent on the sampling frequency. One should keep in mind that the sampling frequency of a feedback AVC system is restricted by different parameters such as hardware and software limitations. The software limitation is usually the dominant factor. Thus, the increase of sampling frequency results in the increase of bandwidth in the feedback controllers [4]. Obviously, a simple feedback control algorithm helps to reduce the processing time, which leads to a higher sampling frequency. Accordingly, the bandwidth of the control system can be modified. As a result, the simple feedback AVC schemes have a better chance to cope with the high-frequency vibrations. In contrast, more complicated control algorithms are not usually effective for controlling the high-frequency vibrations. Thus, another objective of the paper is to consider the simplicity of the feedback control algorithm because of the mentioned benefits.

In general, three observation signals, including displacement, velocity, and acceleration can be employed in the feedback AVC systems [5]. The main drawback of both displacement and acceleration feedbacks is due to the phase shift between the observation signal and the actuating force, which considerably affects the performance of the feedback controller. Whereas, in the velocity feedback AVC systems, the observation signal is in-phase with the actuating force through which the control system performance is improved. Hence, the velocity feedback control is known as the most effective control strategy for suppressing vibrations of the flexible plate structures. However, the velocity sensors, which are the key elements of the velocity feedback controllers, are often massive and expensive compared to the conventional acceleration sensors. Consequently, the next objective of the paper is to present an AVC algorithm based on the acceleration feedback, but with the benefits of the velocity feedback controllers.

Many researchers proposed different feedback controllers to suppress unwanted vibrations of the flexible structures. Qiu et al. [6] presented an acceleration sensor-based modal identification and active vibration control methods to suppress the first two bending and the first two torsional modes of vibration of a cantilever plate. Three acceleration sensors and piezoelectric actuator patches were mounted on the structure at optimal locations to decouple the bending and torsional vibrations in sensing and actuating actions. Two acceleration-based control approaches, including the acceleration proportional feedback and a nonlinear control scheme, were proposed and experimentally compared. Finally, effective vibration suppression was found based on the acceleration-based control algorithms. Previdi et al. [7] reported another work on the acceleration feedback AVC. They applied a single acceleration sensor collocated with a piezoelectric actuator to a kitchen hood to reduce the unwanted vibrations in the system. Two different minimum variance control laws were considered. The first controller operated without the information about the hood motor velocity while the second one required the velocity information. Vibration reductions of about 85% and 75% were found for the first and second controllers respectively. An et al. [8] applied a time-delayed acceleration feedback controller to a flexible structure. Due to the introduction of time delay into the controller with acceleration feedback, the presented control system had the feature of not only changing the mass property but also altering the damping property of the controlled system. Thus, the control system behavior was improved considerably with this feature. The proposed controller was applied to a flexible beam and its performance in comparison with a pure acceleration feedback controller was experimentally evaluated. Enríquez-Zárate et al. [9] applied positive acceleration feedback (PAF) and multiple positive acceleration feedback (MPAF) controllers to suppress vibrations of a building-like structure. The experimental results revealed a relatively acceptable performance of the proposed feedback controllers in suppressing the first three dominant modes of vibration of the structure.

Jenifene [10] proposed a simple position feedback controller for AVC of a single-link flexible manipulator. A delayed position feedback signal was used to actively control the vibration of the flexible structure. This method was found to be acceptable in lightly damped dynamic systems. Tavakolpour-Saleh et al. [2] proposed a self-learning control technique with displacement feedback for active control of a rectangular flexible plate with clamped edges. Iterative learning algorithm along with the collocated piezoelectric actuator and laser displacement sensor were considered in this investigation. It was demonstrated that the proposed control system effectively suppressed the unwanted vibrations. Gosiewski and Koszewnik [11] investigated the performance of the proportional-derivative (PD) controller to attenuate vibrations of a 3D space truss. They considered Eddy current displacement sensor as the sensing element of the feedback controller. The effectiveness of the proposed active vibration damping system was demonstrated via simulation and experiment. Khorshidi et al. [12] studied active vibration control of a circular plate coupled with piezoelectric layers on both sides using simulation. They proposed linear quadratic regulator (LQR) and fuzzy logic controller (FLC) to control the transverse displacement of a circular plate, which was excited by sound pressure waves. The simulation results revealed the effectiveness of the proposed control techniques.

Wu et al. [13] applied independent modal control approach based on negative velocity feedback to a highly flexible beam. They used Hamilton's principle to model the beam dynamics. Piezoelectric patches were mounted on the hosted beam and the first three modes of vibration of the flexible system were investigated. The simulation and experimental results revealed the effectiveness of the proposed control method in suppressing the unwanted vibration. Gupta et al. [14] proposed a negative velocity feedback to control the first mode of vibration of a smart plate at different temperatures. The simulation results showed an effective vibration suppression of the smart plate. However, no experimental results were given to validate the simulation outcomes.

Active force control (AFC) is a well-known disturbance rejection technique that was proposed in a compact form by Hewit and Burdess [15] in 1816 for robotic applications. The conventional AFC scheme consisted of two feedback loops that formed a 2 degree-