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Self-learning active vibration control of a flexible plate structure with piezoelectric actuator

Ali Reza Tavakolpour [a], Musa Mailah [a,*], Intan Z. Mat Darus [a], Osman Tokhi [b]

[a] Department of Applied Mechanics, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia (UTM), Johor Bahru, Malaysia
[b] Department of Automatic Control and System Engineering, University of Sheffield, United Kingdom

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ABSTRACT

In this paper, an active vibration control (AVC) incorporating active piezoelectric actuator and self-learning control for a flexible plate structure is presented. The flexible plate system is first modelled and simulated via a finite difference (FD) method. Then, the validity of the obtained model is investigated by comparing the plate natural frequencies predicted by the model with the reported values obtained from literature. After validating the model, a proportional or P-type iterative learning (IL) algorithm combined with a feedback controller is applied to the plate dynamics via the FD simulation platform. The algorithms were then coded in MATLAB to evaluate the performance of the control system. An optimized value of the learning parameter and an appropriate stopping criterion for the IL algorithm were also proposed. Different types of disturbances were employed to excite the plate system at different excitation points and the controller ability to attenuate the vibration of observation point was investigated. The simulation results clearly demonstrate an effective vibration suppression capability that can be achieved using piezoelectric actuator with the incorporated self-learning feedback controller.

1. Introduction

The quest to reduce the amount of material that is used in mechanical structures has prompted many designers to employ lightweight materials with smaller cross sectional dimensions. Weight reduction, decrease of wind resistance and energy requirement and increase of acceleration are the major benefits of using lightweight materials with small cross section. However, a significant drawback of employing lightweight materials is that the structures tend to become more flexible. Flexible structures are more susceptible to the detrimental effects of unwanted vibration, particularly when they operate at or near their natural frequencies.

Thin plates are known to be the most commonly used flexible element in mechanical structures and machines such as aircrafts, ships and submarines. The stability of such flexible elements is usually caused and contributed by the dynamic forces and random cyclic loads. There exist a large number of discrete frequencies at which a flexible plate will experience large amplitude vibration through sustained time varying forces of matching frequencies. Thus, the possibility of large displacement and stresses due to this type of excitation must be taken into account. The methods used to tackle the problems arising from unwanted structural vibrations include passive and active control. The mechanical 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 tend to be expensive and bulky at low frequencies [11,13,30].

* Corresponding author. Tel.: +60 177717777; fax: +60 75566159.
E-mail address: musa@fkm.utm.my (M. Mailah).

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The type of control technique usually leads to an increase in the overall weight of structure, which makes it less attractive especially for space applications [13]. However, the passive vibration control can also be implemented using piezoelectric patches bounded to the structure and connected to resonant passive electric circuits [2,10]. Although this recent type of passive control strategy is known to be light and appropriate for aeronautic and space applications, it cannot be used for a broad range of frequency control. Active vibration control can be defined as artificially generating sources that absorb the energy caused by the unwanted vibrations in order to cancel or reduce their effect on the overall system [30]. Lueg [18] is among the first who used AVC in order to cancel out the vibrations. Since then, a large number of researchers have concentrated on developing methodologies for the design and implementation of AVC systems.

The AVC problem of flexible structures such as plates and beams has attracted considerable attention during the last two decades. Many researchers proposed different control strategies for the purpose of AVC of flexible structures. A simple position control system was proposed by Jenifene [13] for the AVC of a single link flexible manipulator. A delayed position feedback signal was used to actively control the vibrations of the flexible structure and then, the stability of the controller was investigated. This method was found to be acceptable in lightly damped dynamic systems. Hu et al. [12] applied LMI (Linear Matrix Inequality)-based H_∞ robust control for AVC of a flexible plate structure. They used specific transformations of Lyapunov variable with appropriate linearizing transformations of the controller variables, which give rise to a tractable and practical LMI formulation of the vibration control problem. Based on LMI, a H_∞ output feedback controller was designed to suppress the low-frequency vibrations caused by external disturbances. The simulation results showed that the proposed robust active control method is efficient for active vibration suppression. Other research on the effectiveness of the robust H_∞ control for AVC of the flexible structures has been addressed in [15,32].

Madkour and co-workers [20] investigated the performance of different intelligent AVC strategies for suppressing the unwanted vibration in a flexible beam structure. They proposed FD methods to model and simulate the flexible beam system. They then employed different learning algorithms including genetic algorithm (GA), artificial neural network (ANN) and adaptive neuro-fuzzy inference system to develop the mechanisms of an AVC system. Comparative studies were carried out and the effectiveness of each technique was investigated.

Tokhi and Hossain [30] proposed an active control mechanism for vibration suppression of a flexible beam within an adaptive control framework. A control mechanism was designed within a feedforward control structure on the basis of optimum cancellation at an observation point. The design relations were formulated such that it allows on-line design and implementation and thus results in a self-tuning control algorithm. They employed a FD method to simulate the flexible system. The simulation results confirmed the performance of the proposed algorithm. Later, Mat Darus [22] applied a similar intelligent adaptive control strategy to a square flexible thin plate structure. She modeled the flexible plate system using a FD approach. Then, a feedforward self-tuning adaptive controller was applied to compensate the unwanted vibration of the plate system. The efficiency of the control technique was demonstrated through a simulation study using the FD simulation.

The concept of IL control (sometimes also called repetitive control) was first presented by Arimoto et al. [1] in 1984. Since then, many researchers employed the IL for different control problems such as robot motion control. However, a few papers can be found about the application of the IL for AVC of the flexible structures. Felio et al. [7] utilized IL control for active vibration suppression of a single link flexible manipulator. They showed the effectiveness of IL in attenuating the vibration of the flexible linkage through simulation studies. Zain et al. [23] applied IL control with acceleration feedback for control of vibration of a flexible manipulator system. They employed GAs to find the optimized learning parameters of the PD (proportional-derivative)-type IL controller. They reported that the proposed control strategy considerably reduced the level of vibration.

Based on the previously outlined literature, there is no published report in which the IL is used for the purpose of intelligent AVC of a flexible plate system. In this research, a self-learning control strategy with the displacement feedback based on an IL algorithm is applied to the problem of AVC of a rectangular flexible thin plate with clamped edges. First, the flexible plate system is modeled using the FD method and the validity of the obtained model is investigated. Then, the proposed IL algorithm is implemented within the FD simulation platform using collocated sensor and piezoelectric actuator. The best value of the learning parameter as well as the appropriate stopping criterion for the mentioned IL scheme is proposed through a rigorous simulation study. Finally, the performance of the self-learning control system to compensate the unwanted vibrations due to different types of disturbances is evaluated.

2. Modelling of the flexible plate system

2.1. Dynamic equation of the thin plate

The governing equation of a flexible thin plate can be formulated as a partial differential equation (PDE) together with the corresponding boundary conditions. The plate is assumed to undergo a small lateral deflection. Using Kirchhoff's plate theory, this yields [29]:

$$\frac{\partial^4 w(x,y,t)}{\partial x^4} + 2\frac{\partial^4 w(x,y,t)}{\partial x^2 \partial y^2} + \frac{\partial^4 w(x,y,t)}{\partial y^4} + \frac{\rho h}{D}\frac{\partial^2 w(x,y,t)}{\partial t^2} = \frac{q(x,y,t)}{D} \tag{1}$$