Mechatronics 33 (2016) 23–33

Contents lists available at ScienceDirect

Mechatronics

journal homepage: www.elsevier.com/locate/mechatronics

Multi positive feedback control method for active vibration suppression in flexible structures

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ARTICLE INFO

Article history:
Received 27 May 2015
Accepted 6 December 2015
Available online 30 December 2015

Keywords:
Active vibration control
Collocated system
$\mathcal{H}_2$ and $\mathcal{H}_\infty$ norms
Multi-input multi-output system
Piezoelectric actuator

ABSTRACT

This paper presents a novel controller for active vibration reduction in piezoelectric-actuated flexible structures. The new Multi Positive Feedback (MPF) control consists of two sections where each operates using a set of actuators. One section uses position and the other uses velocity feedback to perform real-time vibration control. The 90° phase difference between the feedbacks leads to non-zero resultant control output. This property results in a more effective operation of the available actuators. Sections of the MPF controller are designed based on the concept of the Modified Positive Position Feedback (MPPF) control approach, where the damping of the control system is increased by addition of a first-order term parallel to a second-order compensator. The controller is designed to simultaneously control single or multi resonant frequency vibrations. Due to the high influence of gain values on the control performance, $\mathcal{H}_2$ and $\mathcal{H}_\infty$ norms are used to optimize these gains. For validation purposes, the controller is verified here numerically and experimentally for vibration control of a clamped–clamped beam and a cantilever at resonance. According to the results, the MPF controller has a superior performance compared to the MPPF controller, in addition to effective suppression on both vibration displacement and velocity. Using the MPF controller in multimode and by utilizing the $\mathcal{H}_\infty$ gain optimization method, vibration displacement amplitudes were reduced to 19.4% of the uncontrolled state for the beam.

1. Introduction

Active vibration control using piezoelectric actuators is one of the most popular and practical approaches to reduce the amplitude of unwanted vibrations in flexible structures. This popularity is due to the light weight of the actuating elements, the lack of moving mechanical parts, the relatively easy fabrication process, and the low cost and low power consumption. Piezoelectric materials have been used as ceramics and PVDFs for actuation and sensing in studies and for various purposes [1–4]. This broad usage of piezoelectric materials and their special application in vibration control at both micro and macro scales requires effective and compatible controllers. As a matter of fact, performance of an active vibration control setup could be highly improved by modifications in the control system software; similar to other systems that the controllers play very important roles [5–7]. This improvement in efficiency provides the chance of using smaller and fewer numbers of piezoelectric actuators and sensors, which results in a lower implementation cost.

There are several reasons for applying active vibration to structures. One is to increase the precision of machines, such as in spacecraft [8]. Another reason is to prevent the damaging effects of resonant vibrations in spatial structures [9,10] or to reduce the generated noise [11,12]. In flexible structures, large deformations or deflections case geometric nonlinearities due to nonlinear curvatures [13]. In these cases, the vibration controller should also account for the nonlinearities and methods such as multiple scales are required to obtain the modulation equation [14,15]. Even if the vibration amplitude does not exceed the allowable level, transverse resonant vibrations may eventually lead to fatigue failure. Suitable controllers have been proposed and utilized for each of the purposes mentioned above. Just a few examples of these controllers include: positive position feedback (PPF) [16], filtered dynamic inversion [17], Hybrid Positive Feedback (HPF) [18], state-switched method [19], sliding mode control (SMC) [20], $\mathcal{H}_\infty$ static-output feedback control [21], and delayed position feedback [22]. Recently, a set of network-based vibration control methods have been proposed, where consensus PPF method is the leading example [23]. Although vibration amplitude reduces to a lower level using the PPF controller, the resulting closed-loop system is more flexible and consequently, the steady-state error is large [24]. It has been shown in Ref. [25] that the performance of the PPF controller improves when a first-order term is used parallel to the second-order compensator. This increases the damping of the system and results in lower steady-state error compared to the conventional method,

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http://dx.doi.org/10.1016/j.mechatronics.2015.12.003
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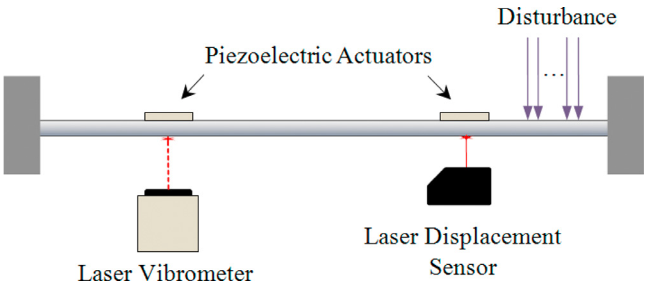

Fig. 1. Clamped–clamped beam with the implemented actuators and sensors.

which is the basic of Modified Positive Position Feedback (MPPF) control [26,27].

According to the concept of transverse vibrations in continuous systems, all points on the structure cross their considered neutral axes at the same time. If the positive feedback controller uses just one type of feedback i.e. displacement, velocity or acceleration, the net control output of all actuators would have infinite zero points while the vibration is still in progress. Harmonic vibration displacement phase lags velocity by 90°. Therefore, utilization of both displacement and velocity feedbacks will result in a non-zero overall control output. This is the main contribution of the current work in comparison to aforementioned methods.

In this paper, the Multi Positive Feedback (MPF) controller is presented as a new method for active vibration suppression in smart structures. In this method, the vibration control system is divided into two sections where one uses the vibration position and the other uses the vibration velocity for positive feedback control. This concurrent implementation of displacement and velocity feedback under two separate modified second-order PPF compensators provides a high-level suppression using the non-zero overall control output. Another advantage of the MPF approach is in suppression of both vibration displacement and velocity to lower levels in multimode control. Since in vibration control systems magnitude of the acquired feedback is compared to the zero reference of the same type, that specific vibration signal is suppressed to a lower level compared to the other signals. This is due to the fact that each resonant mode has a different contribution to the aggregate vibration displacement, velocity or acceleration. For instance, typically first mode contributes to the vibration displacement more that velocity, and second mode to velocity more than displacement. Hence, when both displacement and velocity feedbacks are implemented, resonant modes gain the required feedback amplitude and consequently control effort for both vibration displacement and velocity. The MPF always senses the high amplitude vibrations in the structure in either form of displacement or velocity, and implements the control effort toward suppression of both of them.

The system model is considered linear, and the MPF is naturally a multi-input multi-output (MIMO) control system due to its requirement for more than one input/output. Additionally, since the MPF controller is a collocated control system, it is resilient to the destabilizing effect of spillover, which is the result of channeled control energy to higher modes [28]. To achieve a high level of vibration suppression for a wide range of disturbances, it is essential to perform multimode control rather than single-mode control [27]. As it has been shown in [27], vibration suppression under multimode conditions has its own challenges. The performance of the controller in suppression of each mode is not only sensitive to the assigned values in the gain vectors of that mode, but also to the gain values of the other modes. This cross-sensitivity is due to the limited available control power by the actuators. In addition, there are too many gain values to be found by trial and error for an effective performance. The MPF controller has two gains for each mode on each actuation/sensing patch. Hence, efficient gain optimization methods have to be utilized to guarantee the optimal level of suppression in the system. Here, $\mathcal{H}_2$ and $\mathcal{H}_\infty$ norms of the closed-loop system have been used for controller performance optimization using the gain vectors. Stability criterion of the closed-loop system is also extracted and the

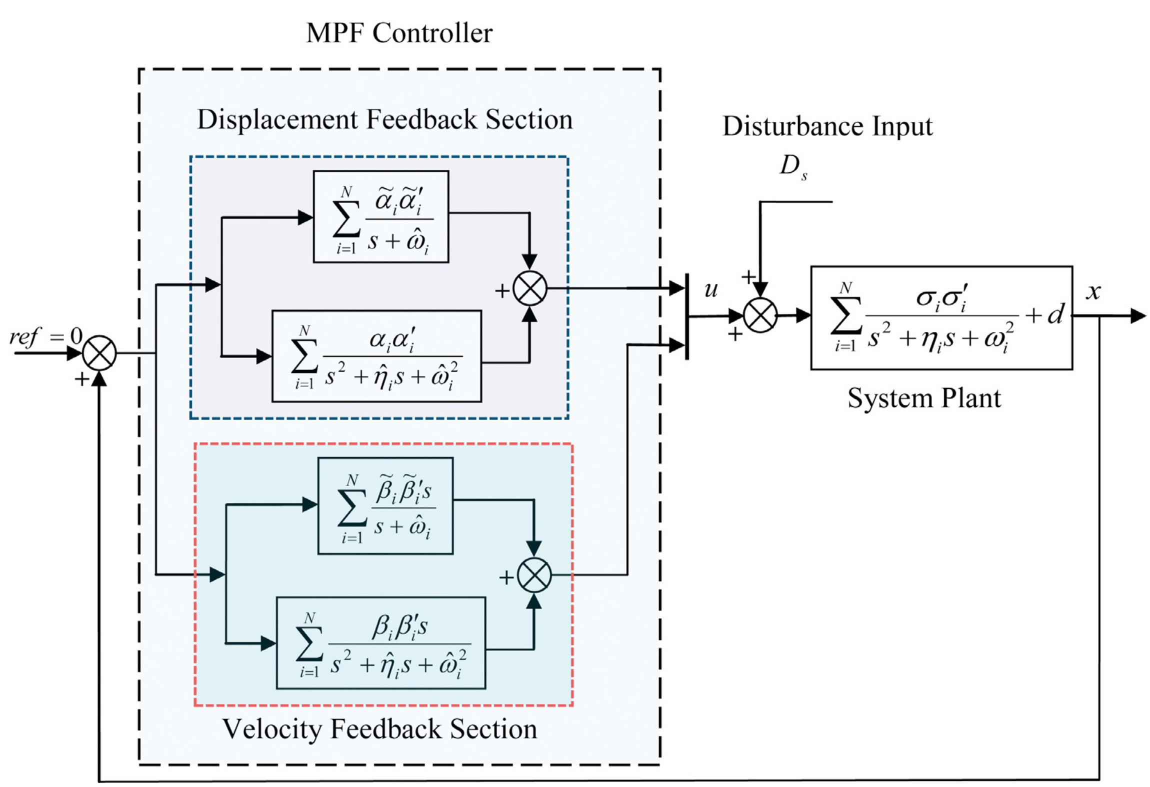

Fig. 2. Block diagram of closed-loop control system.