Mechanical Systems and Signal Processing 114 (2019) 644–657

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Microvibration isolation by adaptive feedforward control with asymmetric hysteresis compensation

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ARTICLE INFO

Article history:
Received 16 January 2018
Received in revised form 28 April 2018
Accepted 2 May 2018

Keywords:
Microvibration isolation
Hysteresis nonlinearity
Magnetostrictive actuator
Adaptive control
Filtered-x normalized least mean square (FxNLMS)

ABSTRACT

This paper proposes an improved adaptive filtered-x normalized least-mean-square (FxNLMS) algorithm to achieve active microvibration isolation. Physically, microvibration disturbance is attenuated by a custom-developed magnetostrictive-actuated device. Whereas, magnetostrictive materials characterize hysteresis. Particularly, when the amplitude of the input current is large, the hysteresis loop describes strong asymmetry and nonlinearity. To avoid this phenomenon, in some studies, the actuators are limited to move over a small range, and thus the potential range of the isolated microvibration is restrictive. Then Jiles-Atherton model and Bouc-Wen model are utilized to compensate hysteresis, however these models are non-analytical with certain approximation. In order to compensate hysteresis more accurately, Preisach model, a popular operator-based model, is presented. However, due to the double integrals in this model, the hysteresis identification and inversion process is complicated. Therefore, we reduce hysteresis based on a modified Prandtl-Ishlinskii (PI) model which is more simple but effective. This model utilizes the polynomial operators to describe hysteresis asymmetry and nonlinearity. The inverse hysteresis is then applied to compensate the magnetostrictive-induced hysteresis and to alleviate microvibration combining with the conventional FxNLMS algorithm. An experimental setup is fabricated and some experimental investigations are conducted. Experimental results show that the improved FxNLMS algorithm enhances the performance of microvibration isolation effectively—in the presence of single-tone (4 Hz at amplitude of 250 μm) and double tone (2 Hz mixed with 6 Hz at amplitude of 250 μm) excited microvibration, the isolation ratios of the improved FxNLMS controller are 20.79 dB and 15.32 dB respectively, while those of the conventional FxNLMS controller are 13.83 dB and 10.65 dB respectively.

1. Introduction

In the field of aerospace, precision engineering, etc., many ultra-high-precision equipment and instruments, such as space telescope [1], space camera [2], and semiconductor manufacturing machines [3], are sensitive to environmental microvibration disturbance. In order to prevent them from microvibration, various types of isolation techniques have been employed. According to whether and how energy is introduced into the isolation apparatus, the isolation techniques can be divided into

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https://doi.org/10.1016/j.ymssp.2018.05.013
0888-3270/

four categories: passive [4], active [5], semi-active [6] and passive-active hybrid [7]. Typically, high-frequency microvibration is isolated by passive methods while the low-frequency is suppressed by the active.

Since the active vibration isolation technique utilizes the electronic device and automation algorithm, it possesses flexibility and offers better performance in some circumstances compared to the passive isolation technique. Like many other automation strategies, feedback and feedforward control have been implemented to achieve microvibration suppression. The popular feedback control approaches include PID control [8,9], conventional output (e.g., acceleration [10], velocity [11], displacement [12], force [13]) feedback control, positive position feedback control (PPF) [14], anti-phase feedback control (APF) [14], etc. To address the issues of complicated dynamics and nonlinearity in the vibration isolation system, some advanced control techniques are also studied, for instance, fuzzy logic control [15], adaptive control [16], neural network control [17], sliding mode control [18] and robust control [19,20]. However, for feedback control, only the disturbance-induced response is detected to update the control law. If the external disturbance can be observed and treated as the reference signal, a more effective feedforward controller can be designed. Considering the excitation signal and the model of the disturbance propagating path often vary, in the real applications, the adaptive filter-based feedforward control methods [21] have been widely exploited, e.g., filtered-x least-mean-square (FxLMS) [22,23] control and filtered-u least-mean-square (FuLMS) [24] control. Based on the FxLMS algorithms, we present an improved adaptive control algorithm to isolate microvibration.

Micro-scale excited vibration poses a special requirement for the actuator which needs to exactly provide active force to counterbalance vibration. The primary concern of actuator selection is whether it can generate desired displacement/force. In general, traditional actuators (e.g., hydraulic, electro-magnetic) cannot perform micro-scale motion effectively because of their complex mechanical structures. However, based on the principle of direct energy conversion, for example, from electric or magnetic to mechanical, smart-material-based actuators possess satisfied stroke (typically a few ten micrometers) and accuracy (typically sub-micrometer). Among them, piezoelectric [25,26] and magnetostrictive [13,15] based actuators have been widely applied for microvibration isolation. In this article, we implement the proposed microvibration control strategy on a custom-developed magnetostrictive-actuated isolation device.

Although the magnetostrictive material can be utilized to suppress microvibration, its output vs. input relationship characterizes nonlinear hysteresis, which is a main issue to affect control accuracy. The nonlinear degree of hysteresis depends on the amplitude of the input signal. Particularly, it can be regarded as approximately linear if the input amplitude is moderate. Based on this assumption, some linear controllers are implemented to isolate microvibration [13,27]. However, the actuators are limited to move over a small range and the potential range of the isolated microvibration is restrictive. To overcome this drawback, the amplitude of the input signal should preform its maximum ability, even if the hysteresis loop describes strong asymmetry and nonlinearity [28–31]. A few techniques have been proposed to address the issue of strong hysteresis nonlinearity. Robust feedback control was utilized, which the hysteresis was treated as disturbance [32]. Nevertheless, it is complicated to realize vibration isolation in the presence of external disturbance together with hysteresis-induced pseudo disturbance. Furthermore, it is difficult to obtain the accurate bound of the pseudo disturbance when designing the robust controller. In other literature, integrated with conventional vibration controller, inversion-based hysteresis compensator is applied for microvibration isolation. For instance, a nonlinear constitutive model (physical-based model) [33] and a Bouc-Wen model (differential-based model) [26] were utilized to compensate the hysteresis. The former and latter compensators were implemented with least-quadratic-regulator (LQR) and the sky-hook feedback to attenuate microvibration, respectively. However, since there is no effective methods to achieve exact hysteresis inversion, model approximation is applied for the practical implementation of these hysteresis compensators. The Preisach model is one of the operator-based models which can characterize hysteresis more exactly compared against the physical-based model and differential-based model. It has been exploited with the FxLMS algorithm in application of the piezoceramic-actuated microvibration isolator [34]. Specifically, the single-frequency reference signal in the traditional FxLMS controller is premultiplicated by the Presaich model of the piezoceramic stack. Since the Preisach model is not analytically invertible, the compensator that integrates the FxLMS is actually the direct nonlinear model rather than the inverse. It acts as a harmonic generator to only isolate the single-tone disturbance. Moreover, the modeling process is complicated due to the existence of double integrals in Preisach model. Therefore, we apply a more practical operator-based model, Prandtl-Ishlinskii model (PI), with FxLMS-like algorithm synthesized, to isolate not only the single-tone but the dual-tone and band-limited sweep disturbances in this article.

PI model, as a subset of the Presaich model, possesses a more simplified form and more importantly, can achieve inverse hysteresis analytically, applying extensively to model hysteresis recently [35]. Considering the hysteresis asymmetry and saturation, the conventional PI model modified by the weighted dead-zone operators [31], or by the piecewise tangent envelop function (called general PI model) [36,37] were proposed. Although the theories and experiments verified the effectiveness of these techniques, some more simple mathematical models can be exploited to describe the hysteresis asymmetry. Therefore, in this paper, we utilize the polynomial series to modify the conventional PI approach according to other studies [30,38].

The main contribution of this work is that an improved filtered-x nomalized-least-mean-square (FxNLMS) algorithm is implemented to isolate microvibration both theoretically and experimentally. The improved control method integrates asymmetric hysteresis compensation with the conventional FxNLMS algorithm. The remainder of this paper starts by introducing the concept of the modified FxNLMS controller in Section 2. Then in Section 3, the details of controller design are described, which comprises two parts: a conventional FxNLMS controller and a modified PI based hysteresis compensator.