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Robust adaptive controller for semi-active control of uncertain structures using a magnetorheological elastomer-based isolator

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ABSTRACT

The isolator based on magnetorheological elastomers (MREs) that is used with semi-active controllers has emerged as a kind of smart devices that could potentially improve vibration control in traditional systems. The nonlinear damping characteristics of the isolator make the controller design more difficult. Generally, the command current/voltage is determined according to the relative responses in conventional semi-active controllers. However, these controllers may exhibit unsatisfactory isolation performance and even cause instability owing to significant excitations or nonlinear effects. In this study, the design of the new semi-active controller for an MRE-based isolator was investigated to overcome the drawbacks of traditional controllers from two perspectives. Firstly, an inverse model is designed for the isolator so that it can be used to predict an appropriate electric current supplied to the electromagnet based on the desired control force. Secondly, a robust adaptive controller for semi-active control is proposed for a nonlinear system with unknown dynamic parameters. The control scheme consists of three parts: a standard adaptive linearizing controller, an adaptive sliding mode controller, and a single robust controller. The proposed method guarantees zero convergence of the displacement response and provides robust stability. In addition, the singularity problem that usually appears in standard adaptive control is eliminated. Simulations demonstrate that the proposed controller exceeds the performance of the passive system as assessed in the protection of a two-story shear building during seismic events.

1. Introduction

A magnetorheological elastomer (MRE) is a smart material that is mainly characterized by a magnetic field-dependent variable stiffness. MREs also possess fast response features in applications of vibration control. Recently, MREs have been used effectively for base isolation of structures in the effort to reduce system responses [1–3]. The MRE-based isolator has the ability to govern the vibration transmissibility by adjusting its properties, such as damping and stiffness. Owing to their great

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potential in vibration applications, many researchers have been interested in the development of the isolator integrated with semi-active control schemes.

There are various semi-active algorithms developed for MRE-based isolators. The on-off algorithm [4,5] has been extensively used in MRE devices. In these cases, the stiffness is adjusted to either a high or a low value according to the measured relative displacements. The clipping control algorithm for MRE-based isolators [6] is divided into two stages: an ideal active controller and a passive controller in which the control variable is switched by a “clipped on-off” algorithm. The Lyapunov control algorithm [7] determines the control voltage to minimize the derivative of the Lyapunov function. The Bang—Bang controller [8] is introduced for use with an MR damper to dissipate energy in the structure. In these algorithms, the applied command current/voltage is set at either the minimum or the maximum value states. Consequently, chattering will be caused that could inversely affect the system's quality. However, the current/voltage associated with a suitable command may lie between the maximum and minimum values. The semi-active fuzzy control algorithm [9–11] can generate a continuous control output. The controller overcomes the chattering and effectively reduces the structural response of the buildings.

In the algorithms mentioned above, the command current/voltage is determined based only on the measured relative displacement and velocity responses without considering the dynamical behavior of the system. Moreover, uncertainties may exist in the structural parameters, such as the material inhomogeneity, nonlinearity components, changing load environment, and disturbances [12]. Consequently, these controllers may exhibit unsatisfactory isolation performance, and even cause instability. To overcome these drawbacks, the design of a robust controller for the nonlinear dynamic system is necessary. Till date, only a few robust control algorithms have been presented for semi-active control. A robust H_∞ controller [13] was designed for use with a smart damper to mitigate vibrations in the cable stayed bridge with structural uncertainties. Consistent control results could be obtained in the nominal case when the perturbed dynamic behavior is considered in the system. More recently, the adaptive sliding mode controller [14,15], and the adaptive fuzzy sliding mode controller [16,17], have been used as the newer methods in vibration control technology. The robust control approach is thought to be an effective algorithm for achieving system stability. However, the bounds of uncertainties and disturbance must be known in advance, and the bands should be narrow. In the case of a broad uncertainty bound, the controller requires a considerable control effort, and the requirement may exceed the loading capacity of the isolator. Furthermore, a singularity problem usually appears in adaptive control based on which the system may lose its controllability. Therefore, while maintaining these advantages, the controller design that overcomes the listed drawbacks in robust control is still anticipated.

In this study, an inverse dynamic model is firstly designed based on the dynamic model of MRE, and the model is used to convert the desired force into the appropriate electric current to drive the electromagnet. Because the MRE-based isolator is the semi-active device, the force generated in the device depends on displacement of the device and the applied current. The isolator cannot always afford to track the desired force from active controller. Therefore, an appropriate active controller for semi-active control is proposed in this study. The proposed controller is expected to be sufficiently compatible with the properties of MRE-based isolator in which a standard adaptive linearizing controller is combined with a sliding mode controller for an uncertain nonlinear system. The controller can estimate the unknown nonlinear parameters of the dynamic model. By using a smooth switching algorithm, the denominator part in the adaptive control formula is adjusted to be nonzero so that the singularity problem is eliminated. In addition, a single robust controller is introduced that compensates for the external disturbance added to the controller to guarantee stability. By using the proposed controller, the displacement response asymptotically converges to zero, and the control output value can be significantly reduced near the singularity condition. Numerical simulations are carried out to illustrate the validity of the proposed controller design.

2. Inverse dynamics model of an MRE-based isolator

2.1. Dynamic model of MRE-based isolator

In this section, our previous studies on MRE properties and MRE model are overviewed [3,10]. The elastomer properties of MRE was investigated comprehensively for an anisotropic MRE sample ($25 \times 25 \times 10$ mm and iron content of 40 vol%). The equivalent stiffness and damping were defined by $K = F_0/x_0$ and $D = \Delta E/(F_0 x_0)$, respectively, where F_0 is the force amplitude, x_0 is the displacement amplitude, and ΔE is the energy loss calculated by the area of force-displacement hysteresis loop. The stiffness and damping are strongly nonlinear functions of displacement amplitude, frequency, and magnetic flux density. In the amplitude dependence, the stiffness has the high value at the small amplitude and decreases when the excitation amplitude increases. Furthermore, the hysteresis loops remain constant as nominal viscosity even though the excitation frequencies are very low. These properties are similar to fictional behaviors. With respect to the frequency dependency, the equivalent stiffness coefficient increases monotonically and the hysteresis loops become more elliptical with the increase in frequency. It is the fundamental characteristic of the viscoelastic material. The equivalent stiffness increases significantly for the magnetic field ranging from 0 mT (0 A) to 218 mT (4 A) and saturates when the magnetic field reaches 316 mT (6 A). The increasing stiffness is the consequence of magnetic induced properties.

In order to capture the dynamic properties of the MRE deforming in shear direction, a dynamic system was modeled. The model consists of a standard linear solid model, a stiffness variable spring, and a smooth Coulomb friction as shown in Fig. 1. The total force F generated by the MRE is expressed as the sum of the three components as follows,