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ADAPTIVE SEMI-ACTIVE VIBRATION CONTROL IN CASE WITH UNCERTAINTIES IN MR DAMPER AND STRUCTURE

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Abstract

A new fully adaptive control scheme is proposed for vibration isolation using a semi-active MR damper installed between ground and first floor, which is composed of two adaptive controllers. One is an adaptive inverse controller which can give necessary input voltage to MR damper so as to generate specified reference damping force acted on a controlled structure. The other is an adaptive reference controller which can match the dynamics of the first floor of structure to a reference dynamics. The proposed fully adaptive approach can cope with both uncertainties in models of MR damper and structure. Experimental results are also shown to validate its effectiveness.

INTRODUCTION

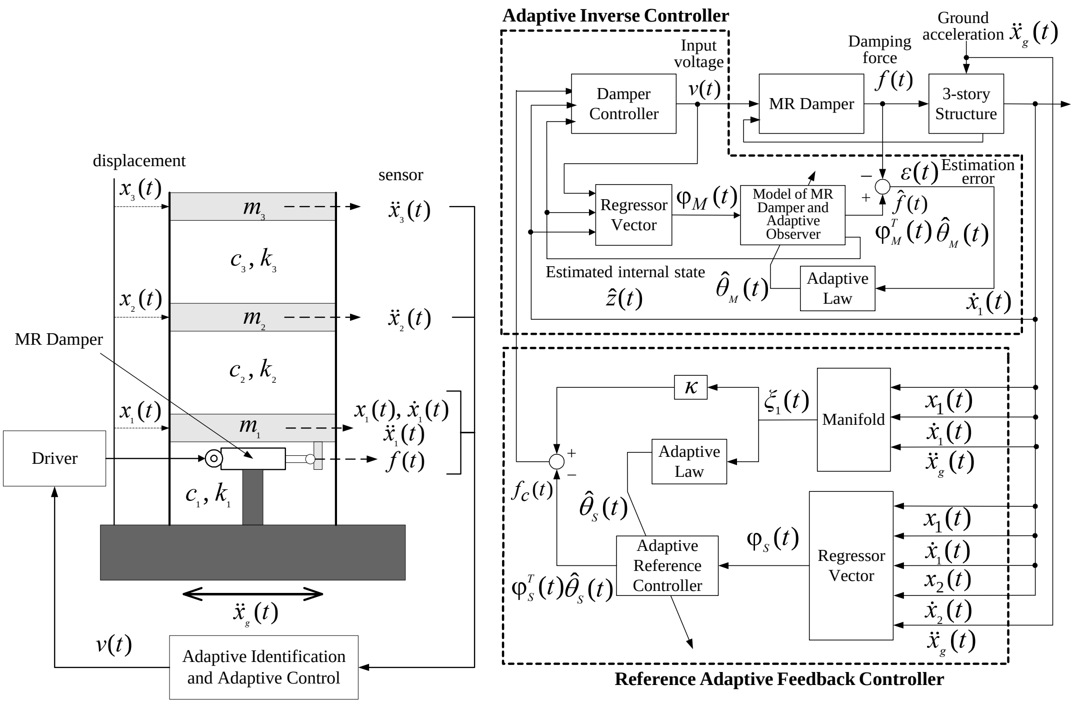
In order to efficiently use the MR (magnetorheological) damper for attenuating vibrations, we should clarify a dynamical model for deciding the necessary input voltage to the MR damper to generate the required damping force. The MR damper has inherently has hysteresis characteristics in nonlinear friction mechanism, and many efforts have been devoted to the modeling of nonlinear behavior from static and dynamic points of view [13][12]. Static models for MR damper can express nonlinear mapping from velocity to damping force, by adopting piecewise linearization, combination of hyperbolic functions, polynomial models and others [13][9][3][7]. However, it seems rather hard to express its hysteresis curves by using a small number of model parameters from actual nonstationary seismic input-output data. Dynamic model can better describe nonlinear dynamic behavior, and so many works have been done, for instance, the Bouc-Wen model [13][12], LuGre model [1][5] and their modifications [10] have been discussed. The Bouc-Wen model can simulate the nonlinear hysteresis behavior of MR dampers, however it has a complicated structure which includes too many model parameters to be identified in real-time manner. The LuGre model has a rather simple structure and the number of model parameters can also be reduced and modified to enable real-time design of an inverse controller [10].

Control strategies for vibration isolation depend on modeling of MR damper. Several approaches to determination of the input voltage of MR damper have been proposed. The voltage input is decided so that the damping force of the MR damper can track a desired command damping force which can be given by the LQG control or clipped-optimal control [4][6]. Inverse modeling approach is also proposed based on neural network [2] to decide the voltage input generating the command damping force. By regarding the total system including the MR damper and linear structure as a nonlinear controlled system, nonlinear control design methods can also be applied, such as sliding mode control [6], gain scheduled control [8], adaptive control [14], integration of adaptive control and bilinear H_∞ control [11].

The purpose of the present paper is to give a fully adaptive control approach which can cope with uncertainties included in both MR damper model and structure model. The proposed control approach consists of two adaptive controllers: One is an adaptive inverse control for compensating the nonlinear hysteresis dynamics of the MR damper, and the other is an adaptive reference feedback control which can match the dynamics of the first floor of the structure to a specified reference dynamics.

PROPOSED TOTAL VIBRATION CONTROL SYSTEM

Isolation of structures from earthquakes can be attained by a semi-active MR damper installed between the ground level and the first floor as illustrated in Fig.1(a). Fig.1(b) shows a schematic diagram of the proposed fully adaptive vibration isolation system for a three-story



(a) Three story structure with MR damper (b) Fully adaptive semi-active vibration control

Fig.1 Fully adaptive vibration isolation algorithm for 3 story structure with MR damper structure. In the paper, we first propose a simple mathematical model for the MR damper, which can express hysteresis characteristics in nonlinear friction dynamics, and give an analytical method for deciding the necessary input voltage $v(t)$ to the MR damper so as to generate the required command damping force $f_c(t)$. If the adaptive inverse controller is perfectly designed so that the linearization from the command damping force $f_c(t)$ to the actual damping force $f(t)$ acting on the structure, that is, $f_c(t) = f(t)$, we can realize almost active control. When the linearization can be attained, we can design a feedback controller in a feedback loop to control vibration of the structure as if it is an active control.

However, since the MR damper is actually a nonlinear semi-active device, it is difficult to make it play as an active device, and it needs very fine and complicated tuning of the inverse controller in adaptive manner. Straightforward use of the optimal LQG control in the feedback loop cannot attain good performance. Therefore, in order to realize a almost active control using the MR damper, we should construct a precise MR damper model and a corresponding inverse controller, and further design a new adaptive feedback controller compensating uncertainties of the structure. The main purpose of the paper is to realize a fully adaptive vibration control using the MR damper, which consists of two controllers: One is the adaptive inverse controller which can give a required input voltage $v(t)$ so that the MR damper can give a desired command damping force $f_c(t)$, and the other is the adaptive reference controller which can give the command damping force matching the structural dynamics to and compensate for uncertainty in the structural parameters.

ADAPTIVE INVERSE CONTROL FOR MR DAMPER UNCERTAINTY

Adaptive Identification of MR Damper

MR damper is a semi-active device in which the viscosity of the fluid is controllable by the input voltage, and has hysteresis effects in its nonlinear friction mechanism. As stated, a variety of approaches have been taken to modeling of the nonlinear behavior of the MR damper. Compared to the Bouc-Wen model [13][12], the LuGre model has simpler structure and smaller number of parameters needed for expression of its behavior [5]. We have also modified the LuGre model so that a necessary input voltage can be analytically calculated to produce the specified command damping force $f_c(t)$ [10].

The damping force $f(t)$ is expressed by

$$f = \sigma_a z + \sigma_0 z v + \sigma_1 \dot{z} + \sigma_2 \dot{x} + \sigma_b \dot{x} v \tag{1}$$

$$\dot{z} = \dot{x} - a_0 |\dot{x}| z \tag{2}$$

where $z(t)$ is an internal state variable (m), $\dot{x}$ velocity of structure attached with MR damper (m/s), σ_0 stiffness of $z(t)$ influenced by $v(t)$ (N/(m $\cdot$ V)), σ_1 damping coefficient of $z(t)$ (N $\cdot$ s/m), σ_2 viscous damping coefficient (N $\cdot$ s/m), σ_a stiffness of $z(t)$ (N/m), σ_b viscous damping coefficient influenced by $v(t)$ (N $\cdot$ s/(m $\cdot$ V)), and a_0 constant value (V/N).

Substituting (2) into (1), we obtain the nonlinear input-output relation as

$$f = \sigma_a z + \sigma_0 z v - \sigma_1 a_0 |\dot{x}| z + (\sigma_1 + \sigma_2)\dot{x} + \sigma_b \dot{x} v = \theta_M^T \varphi_M \tag{3}$$

where $\theta_M = (\sigma_a, \sigma_0, \sigma_1 a_0, \sigma_1 + \sigma_2, \sigma_b)^T = (\theta_1, \theta_2, \theta_3, \theta_4, \theta_5)^T$ and $\varphi_M = (z, zv, -|\dot{x}|z, \dot{x}, \dot{x}v)^T$.

Let the identified parameter vector $\hat{\theta}_M$ be denoted by $\hat{\theta}_M = (\hat{\theta}_1, \hat{\theta}_2, \hat{\theta}_3, \hat{\theta}_4, \hat{\theta}_5)^T$. Since the internal state z of the MR damper model cannot be measured, the regressor vector φ_M should be replaced with its estimate $\hat{\varphi}_M$ as $\hat{\varphi}_M = (\hat{z}, \hat{z}v, -|\dot{x}|\hat{z}, \dot{x}, \dot{x}v)^T$, where the estimate $\hat{z}$ is given later by using the updated model parameters. The output of the identification model is now described as $\hat{f} = \hat{\theta}_M^T \hat{\varphi}_M$. By using the damping force estimation error defined by $\varepsilon \equiv \hat{f} - f$, and the identified parameter $\hat{a}_0$, the estimate $\hat{z}$ of the internal state can be calculated as

$$\dot{\hat{z}} = \dot{x} - \hat{a}_0 |\dot{x}| \hat{z} - L\varepsilon \tag{4}$$

where L is an observer gain such that $0 \le L \le 1/\hat{\sigma}_{1,\max}$, and the upper bound is decided by the stability of the adaptive observer.

To assure the stability of the adaptive identification algorithm, we introduce the normalizing signal as $N = (\rho + \hat{\varphi}_M^T \hat{\varphi}_M)^{1/2}, \rho > 0$. By dividing the signals and errors by N as $\varphi_{MN} = \varphi_M / N$, $\hat{\varphi}_{MN} = \hat{\varphi}_M / N$, and $\varepsilon_N \equiv \hat{f}_N - f_N$, where $f_N = f / N$ and $\hat{f}_N = \hat{\theta}_M^T \hat{\varphi}_{MN}$, we can give the adaptive law with a variable gain for updating the model parameters as

$$\dot{\hat{\boldsymbol{\theta}}}_M = -\boldsymbol{\Gamma} \hat{\boldsymbol{\varphi}}_{MN} \varepsilon_N \tag{5}$$

$$\dot{\boldsymbol{\Gamma}} = \lambda_1 \boldsymbol{\Gamma} - \lambda_2 \boldsymbol{\Gamma} \hat{\boldsymbol{\varphi}}_{MN} \hat{\boldsymbol{\varphi}}_{MN}^T \boldsymbol{\Gamma} \tag{6}$$

where λ_1, λ_2 and $\boldsymbol{\Gamma}(0)$ have to satisfy the following constraints: $\lambda_1 \ge 0, 0 \le \lambda_2 < 2$, $\boldsymbol{\Gamma}(0) = \boldsymbol{\Gamma}^T(0) > 0$. For practical implementation, $\boldsymbol{\Gamma}(t)$ is chosen constant. Thus, the physical model parameters can be calculated from the relation (3).

Design of Inverse Controller

The role of the adaptive inverse controller shown in Fig.1(b) is to decide the control input voltage v to the MR damper so that the actual damping force f may coincide with the specified command damping force f_c, even in the presence of uncertainty in the MR damper model. The input voltage giving f_c can be analytically calculated by taking an inverse model of the proposed mathematical model of MR damper (3). Actually using the identified model parameters, the input voltage v is given from (1) and (2) as

$$v = \mathrm{SAT}(v_c, V_{\max}), \quad \text{where} \quad v_c = [f_c - \{\hat{\sigma}_a \hat{z} - \sigma_1 \hat{a}_0 |\dot{x}| \hat{z} + (\sigma_1 + \hat{\sigma}_2)\dot{x}_1 - L\varepsilon\}] / d_\rho \tag{7}$$

where $\mathrm{SAT}(v_c, V_{\max})$ is a saturation function which takes 0 for $v_c \le 0$, v_c for $0 < v_c \le V_{\max}$, and $V_{\max}$ for $v_c > V_{\max}$. d_ρ is defined by $d_\rho = \delta$ for $|\rho| < \delta$ and $d_\rho = \rho$ for $|\rho| > \delta$, where δ is introduced to avoid division by zero, and $\rho = \hat{\sigma}_0 \hat{z} + \hat{\sigma}_b \dot{x}$. f_c is the specified command damping force, which will be given in the next section.

ADAPTIVE REFERENCE CONTROL

We consider a three-story structure installed with the semi-active MR damper as shown in Fig.1(a). The purpose of the MR damper is to isolate the structure from vibrations due to earthquake. We first derive the adaptive reference feedback controller in Fig.1(b) separately by considering that the damping force f can be generated in an active manner. Next, we replace it with the command damping force f_c. Let the structure dynamics be expressed by

$$\boldsymbol{M}\ddot{\boldsymbol{x}} + \boldsymbol{C}\dot{\boldsymbol{x}} + \boldsymbol{K}\boldsymbol{x} = \boldsymbol{\gamma} f - \boldsymbol{M}\boldsymbol{\lambda}\ddot{\boldsymbol{x}}_g \tag{8}$$

where $\boldsymbol{M}$ is a mass matrix defined by $\boldsymbol{M} = \mathrm{Diag}[m_1, m_2, m_3]$, and $\boldsymbol{C}$ a damping matrix by

$$\boldsymbol{C} = \begin{bmatrix} c_1 + c_2 & -c_2 & 0 \\ -c_2 & c_2 + c_3 & -c_3 \\ 0 & -c_3 & c_3 \end{bmatrix}$$

and $\boldsymbol{K}$ a stiffness matrix which has a similar matrix expression as $\boldsymbol{C}$. We consider that the physical parameters in $\boldsymbol{M}$, $\boldsymbol{C}$ and $\boldsymbol{K}$ have uncertainties, and λ is a vector with 1 in all entries, and γ is a location vector defined by $\gamma = (-1, 0, 0)^T$ when the MR damper is installed between the ground and first floor.

We introduce a reference model for desirable dynamic behavior of the first floor to be realized along the idea of adaptive skyhook control [14] as

$$\ddot{x}_1 + 2\zeta\omega\dot{x}_1 + \omega^2 x_1 = -\ddot{x}_g \tag{9}$$

It follows from (8) that the dynamic equation of the first floor is expressed by

$$m_1\ddot{x}_1 + (c_1 + c_2)\dot{x}_1 - c_2\dot{x}_2 + (k_1 + k_2)x_1 - k_2 x_2 = -f - m_1\ddot{x}_g \tag{10}$$

Then let the reference error ξ_1 be defined from (9) as

$$\xi_1 = \dot{x}_1 + (s + 2\zeta\omega)^{-1}(\omega^2 x_1 + \ddot{x}_g) \tag{11}$$

Let the unknown parameter vector $\boldsymbol{\theta}_S$ and regressor signal vector $\boldsymbol{\varphi}_S(t)$ be denoted by

$$\boldsymbol{\theta}_S = (k_1 + k_2, -k_2, c_1 + c_2, -c_2, m_1)^T$$
$$\boldsymbol{\varphi}_S(t) = \left(x_1, x_2, \dot{x}_1, \dot{x}_2, \ddot{x}_g, -\frac{s}{s + 2\zeta\omega}(\omega^2 x_1 + \ddot{x}_g) \right)$$

where $\hat{\boldsymbol{\theta}}_S(t)$ denotes an adjustable parameter vector for $\boldsymbol{\theta}_S$. It should be noticed that we need to measure the displacements and velocities of two layers x_1 and x_2, $\dot{x}_1$ and $\dot{x}_2$, and the ground acceleration $\ddot{x}_g$ to construct the regressor vectors for any story-structure.

From the stability point of view, we can give the adaptive damper force $f(t)$ and the adaptive adjusting law for $\hat{\boldsymbol{\theta}}_S(t)$ as

$$f(t) = \kappa\,\xi_1(t) - \boldsymbol{\varphi}_S(t)^T\,\hat{\boldsymbol{\theta}}_S(t) \tag{12}$$

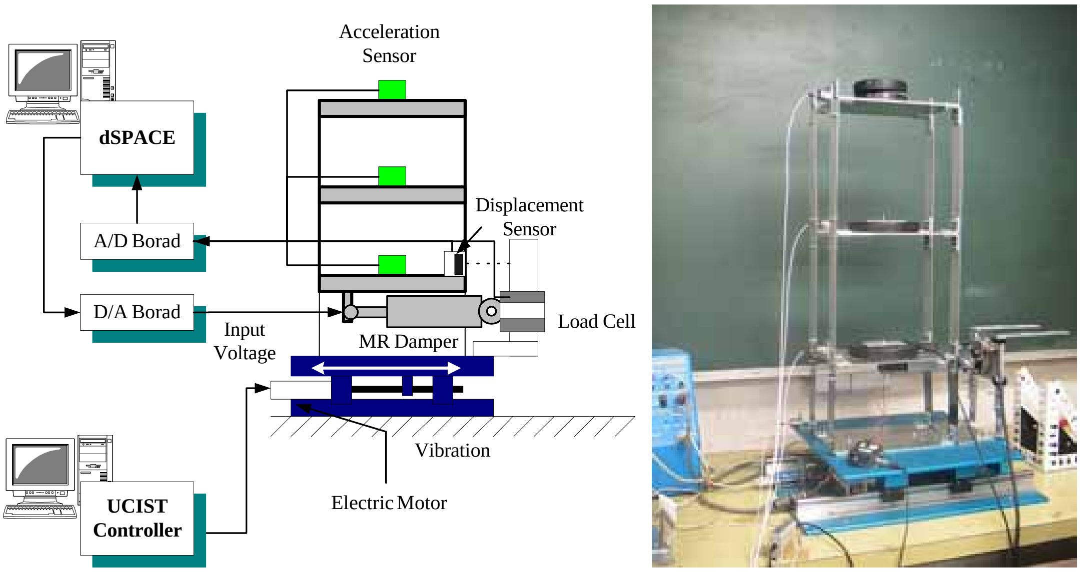
$$\dot{\hat{\boldsymbol{\theta}}}_S(t) = -\boldsymbol{P}\,\boldsymbol{\varphi}_S(t)\xi_1(t) \tag{13}$$

where κ is a positive constant larger than a specific value to assure the stability of the overall uncertain system, while $\kappa > 0$ can be arbitrarily chosen in a simple situation [14]. It can be proved that the desired reference dynamics of the first floor in (9) can be attained even in the presence of uncertainties in any structural parameters.

Thus, the fully adaptive control scheme in Fig.1(b) can be obtained by substituting $f(t)$ in (12) into $f_c(t)$ in (7).

EXPERIMENTAL RESULTS

We constructed a 3-story structure shown in Fig.2, in which the random input and the NS component of the 1940 El Centro seismic data were used as the ground acceleration $\ddot{x}_g$ which is reproduced according to the scale of the shaker table. As the semi-active device, the MR

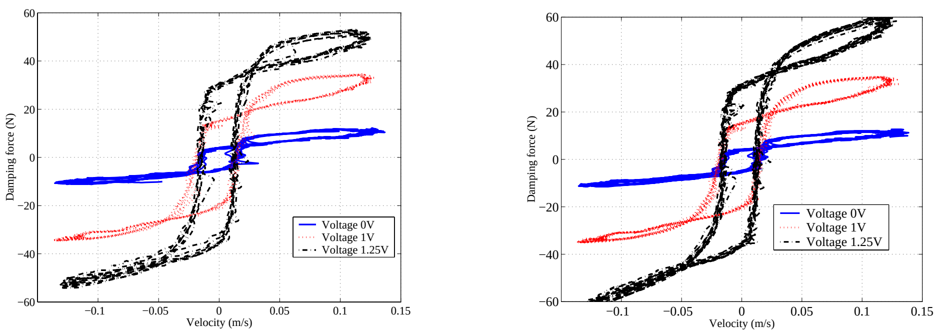


(a) Experimental setup (b) Structure with MR damper

Fig.2 Experimental setup for semi-active vibration control by MR damper

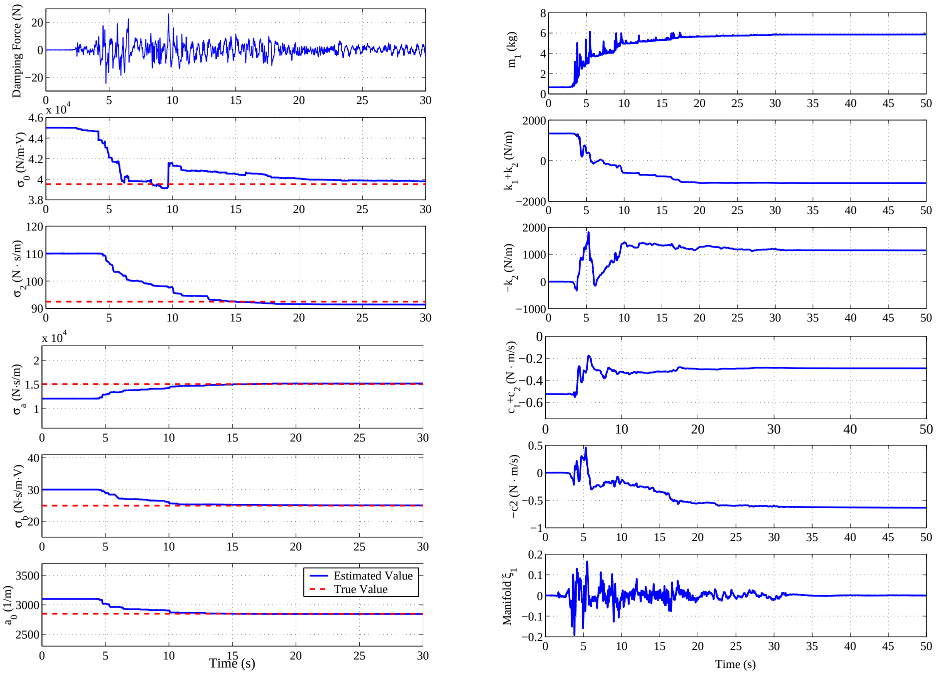
damper (RD-1097-01) provided by Lord Corporation was adopted to isolate the first floor from the ground acceleration. A laser displacement sensor was placed to measure the displacement x_1 of the piston rod of the MR damper. A strain sensor was also installed in series with the damper to measure the damping force f . The MR damper model parameters were identified by (4) to (6), and convergence of all the parameters to constants were attained within two seconds [9]. The identified model parameters are obtained as: $\hat{\sigma}_0 = 39.5\times10^3$ [N/(mV)], $\hat{\sigma}_1 = 0.131$ [Ns/m], $\hat{\sigma}_2 = 92.5$ [Ns/m], $\hat{\sigma}_a = 15.1\times10^3$ [N/m], $\hat{\sigma}_b = 24.9$ [Ns/(mV)] and $\hat{a}_0$ $= 2.85\times10^3$ [V/N].

The proposed model and adaptive identification algorithm can be validated by observing the hysteresis characteristics of the MR damper when sinusoidal movements with amplitude of 1.5[cm] were applied for constant voltages 0, 1 and 1.25 [V]. The measurement results show that the MR damper has the hysteresis behavior between the velocity $\dot{x}$ and damper force f as shown in Fig.3(a). On the other hand, Figs.3 (b) show the hysteresis properties, which were obtained by the proposed adaptive identification of the model parameters with the adaptive



(a) Measured force-velocity hysteresis (b) Predicted hysteresis by adaptive identification

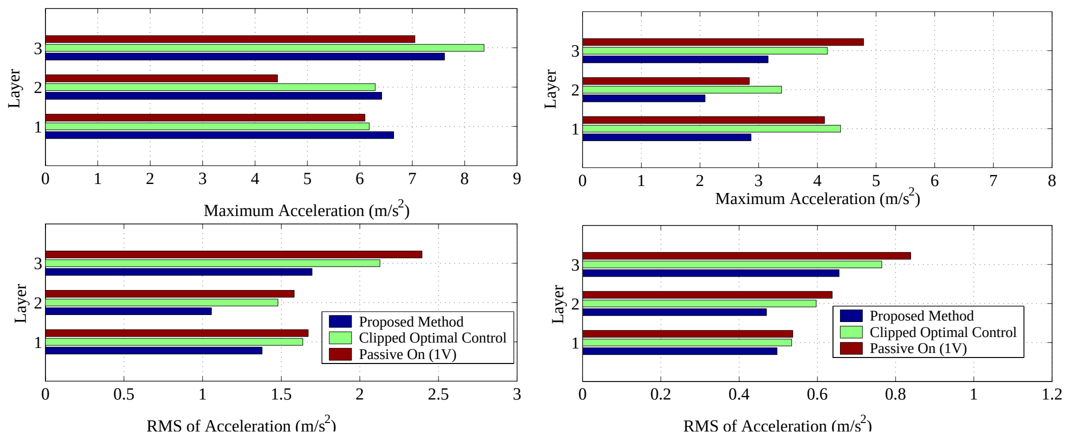
Fig.3 Comparison of measured hysteresis and estimated hysteresis by adaptive observer



(a) Parameters of MR damper (b) Parameters of structure

Fig.4 Parameter convergence of of MR damper model and adaptive reference feedback controller

observer in (4) and (5). It is verified that the hysteresis dynamics can be almost perfectly expressed by the proposed model and adaptive identification algorithm. We consider two kinds of ground acceleration to be applied to the shaker, one is stationary band-limited white noise, and the other is scaled El Centro seismic data. Prior to control experiments by the proposed method, we identified the structure model and the physical story parameters, by adopting the subspace method and parameter fitting in the frequency domain.



(a) Random acceleration (b) El-Centro earthquake

Fig. 5 Comparison of proposed method with other conventional schemes

In the case of stationary random ground acceleration, Fig.5(a) gives comparisons of the maximum and RMS values of the controlled acceleration of three floors obtained by the proposed method with the results obtained by the MR damper with fixed voltages 1.0[V] and the clipped optimal control [4][6]. By adaptively controlling the voltage input to the MR damper by the proposed method, the accelerations can be nicely suppressed. The peak accelerations of all floors can also be improved. In case of the El Centro seismic data shown in Fig.5(b), the acceleration of the RMS and the peak acceleration can also be suppressed by the proposed fully adaptive control compared to fixed voltage input to the MR damper.

CONCLUSIONS

We have presented the fully adaptive vibration isolation system which consists of the adaptive inverse controller compensating for nonlinear friction dynamics of MR damper, and the adaptive reference controller matching the dynamics of the first floor of structure to a reference dynamics. The effectiveness of the proposed approach has been validated in the structural control experiment and in stability analysis of the total system.

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