2005 American Control Conference
June 8-10, 2005. Portland, OR, USA

Fully Adaptive Vibration Control for Uncertain Structure Installed with MR Damper

Takashi Terasawa and Akira Sano
Department of System Design Engineering, Keio University
3-14-1 Hiyoshi, Kohoku-ku, Yokohama 223-8522, Japan
terasawa@contr.sd.keio.ac.jp, sano@sd.keio.ac.jp

***Abstract*— This paper is concerned with a new fully adaptive control scheme for vibration isolation using a semi-active MR damper. A simple mathematical model is presented to express its hysteresis behavior of nonlinear dynamic friction mechanism of the MR fluid. The model parameters are identified by using an adaptive observer, and the identified model is effectively used to synthesize an adaptive inverse controller to attain linearization of the nonlinear behavior of the MR damper, which generates the necessary voltage input to the MR damper so that the desirable damping force can be added to the structure. The desired damping force can also be designed so that the behavior of the structure may coincide with a desired reference dynamics even when the structure model involves uncertain parameters. Hence the proposed fully adaptive algorithm can deal with the uncertainty in the MR model as well as the uncertainty of the structure. Simulation results validate the proposed fully adaptive control algorithm.**

I. 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 [1][2]. 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 [1][3]-[6]. 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 [1][2], LuGre model [7][8] and their modifications [9] 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 [8], however, it is not adequate for real-time design of an inverse controller.

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 [10][11]. Inverse modeling approach is also proposed based on neural network [12] 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 [11], gain scheduled control [13], adaptive control [14], nonlinear H_∞ control.

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 which decides the input voltage to MR damper to generate the command damping force. 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 even in the presence of uncertainties in the structure model. Simulation results revealed that the proposed fully adaptive algorithm can reduce the command damping force compared to LQG control scheme using true structure parameters, and thus the linearization from the command damping force to the actual damping force acting on the structure can better be attained. Finally stability conditions of the total control system are analyzed on some feasible assumptions, since the overall algorithm and system configuration is rather complicated.

II. 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. Fig.2 shows a schematic diagram of the proposed fully adaptive vibration isolation system for a three-story 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

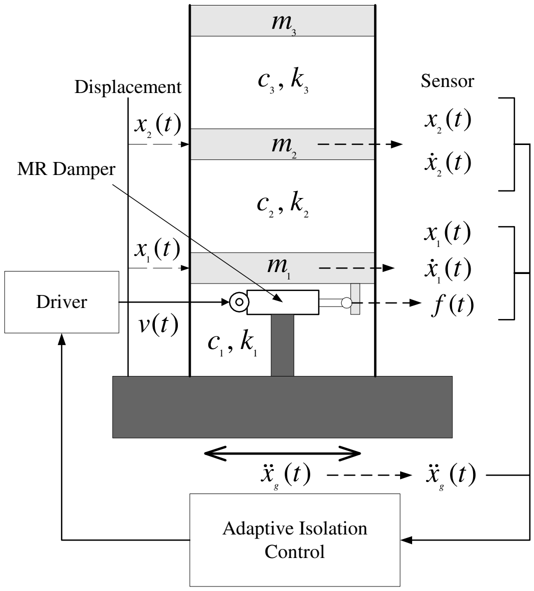


Fig. 1. Schematic diagram of 3 story structure with MR Damper

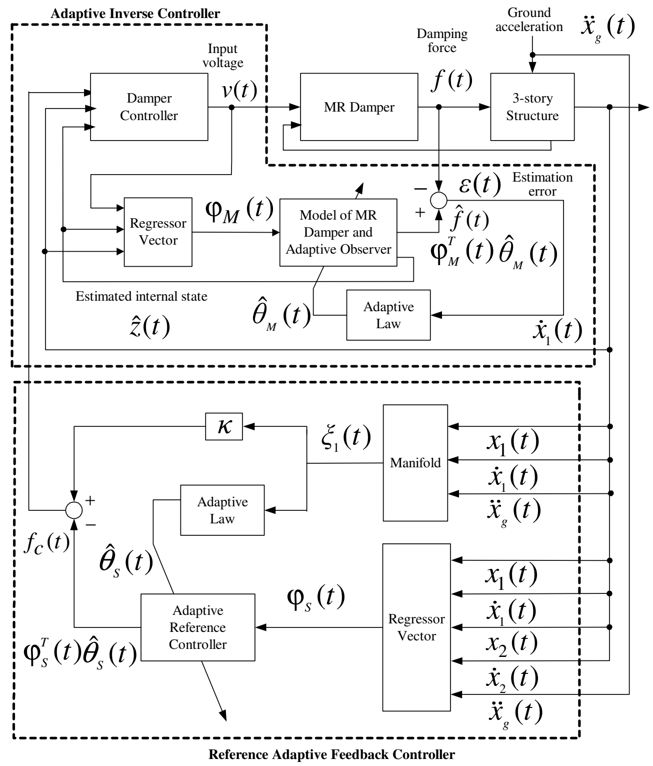


Fig. 2. Proposed fully adaptive vibration isolation control system

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 so that the MR damper can give a desired command damping force f_c, 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.

III. Adaptive Inverse Controller for MR Damper Uncertainty

A. Modeling of MR Damper

The MR damper is a semi-active device in which the viscosity of the fluid is controllable by the input voltage. Experimentally it has been observed that the MR damper has hysteresis effects in its nonlinear friction mechanism. A variety of approaches have been taken to modeling of the nonlinear behavior of the MR damper. The Bouc-Wen model and its variations can express its nonlinear input-output dynamic relation by a set of nonlinear differential equations [1][2]. However they include too many model parameters to be identified. Modeling based on the LuGre model has also been studied to express the nonlinear behavior from a friction point of view [7][8]. The friction mechanism is a phenomenon in which two surfaces make contact at a number of asperities at the microscopic level. In the modified LuGre friction model, this mechanism is expressed by the average behavior of the bristles. The model has simpler structure with small number of model parameters. However, it is difficult for this model to calculate optimal voltage input which produces desired damping force due to its complicated dynamics, that is, an inverse model can hardly be created.

One of the aims of this paper is to give a simple model which can analytically create an inverse model as well as express dynamic friction characteristics and hysteresis effect. In the proposed model, the damping force f is expressed by

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

$$\dot{z} = \dot{x} - \sigma_0 a_0 |\dot{x}| z \tag{2}$$

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

(V/N).

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

$$f = \sigma_a z + \sigma_0 z v - \sigma_0\sigma_1 a_0 |\dot{x}| z + (\sigma_1 + \sigma_2)\,\dot{x} + \sigma_b \dot{x} v \quad (3)$$

Let the parameter vector $\boldsymbol{\theta}_M$ and the regressor vector $\boldsymbol{\varphi}_M$ be defined as

$$\begin{aligned}\boldsymbol{\theta}_M &= (\ \sigma_a \quad \sigma_0 \quad \sigma_0\sigma_1 a_0 \quad \sigma_1+\sigma_2 \quad \sigma_b\ )^T \\ &= (\ \theta_1 \quad \theta_2 \quad \theta_3 \quad \theta_4 \quad \theta_5\ )^T \qquad (4)\\ \boldsymbol{\varphi}_M &= (\ z \quad zv \quad -|\dot{x}|z \quad \dot{x} \quad \dot{x}v\ )^T. \qquad (5)\end{aligned}$$

Then, (3) can be rewritten into a compact form as

$$f = \boldsymbol{\theta}_M^T \boldsymbol{\varphi}_M. \quad (6)$$

Let the identified parameter vector $\hat{\boldsymbol{\theta}}_M$ be denoted by

$$\begin{aligned}\hat{\boldsymbol{\theta}}_M &= (\ \hat{\sigma}_a \quad \hat{\sigma}_0 \quad \widehat{\sigma_0\sigma_1 a_0} \quad \hat{\sigma}_1+\sigma_2 \quad \hat{\sigma}_b\ )^T \\ &= (\ \hat{\theta}_1 \quad \hat{\theta}_2 \quad \hat{\theta}_3 \quad \hat{\theta}_4 \quad \hat{\theta}_5\ )^T. \qquad (7)\end{aligned}$$

Then the following assumptions are made: (i) The value of σ_2 is known, but it is not so restrictive as stated later; (ii) In order to assure that $\hat{z} \in L_\infty$ where $\hat{z}$ is an estimate of the internal state z which is given later, an upper bound $\hat{g}_{\max}$ on $\hat{g} \equiv 1/\widehat{\sigma_0 a_0} = (\hat{\theta}_4 - \sigma_2)/\hat{\theta}_3$ is known, *i.e.*, both lower bounds $\hat{\sigma}_{0\min}$ and $\hat{a}_{0\min}$ are known; (iii) In order to design a stable adaptive observer for $\hat{z}$ and decide the observer gain L, an upper bound $\hat{\sigma}_{1\max}$ on $\hat{\sigma}_1$ is known.

Since the internal state z of the MR damper model cannot be measured, the regressor vector $\boldsymbol{\varphi}_M$ should be replaced with its estimate $\hat{\boldsymbol{\varphi}}_M$ as $\hat{\boldsymbol{\varphi}}_M = (\hat{z},\ \hat{z}v,\ -|\dot{x}|\hat{z},\ \dot{x},\ \dot{x}v)$, where the estimate $\hat{z}$ is given later by using the updated model parameters. The output of the identification model is now described by $\hat{f} = \hat{\boldsymbol{\theta}}_M^T \hat{\boldsymbol{\varphi}}_M$.

B. Adaptive Identification of Model Parameters

Let the estimation error be defined by

$$\varepsilon \equiv \hat{f} - f. \quad (8)$$

Then by using the updated parameter $\widehat{\sigma_0 a_0}$ and the estimation error ε, the estimate $\hat{z}$ of the internal state can be calculated as

$$\dot{\hat{z}} = \dot{x} - \widehat{\sigma_0 a_0}|\dot{x}|\hat{z} - L\varepsilon, \quad (9)$$

where L is an observer gain such that $0 \le L \le /\hat{\sigma}_{1\max}$.

Next, we introduce the normalizing signal defined as

$$N = \left(\rho + \hat{\boldsymbol{\varphi}}_M^T \hat{\boldsymbol{\varphi}}_M\right)^{\frac{1}{2}}, \quad \rho > 0, \quad (10)$$

and the signals divided by N are defined as $\boldsymbol{\varphi}_{MN} = \boldsymbol{\varphi}_M/N$ and $\hat{\boldsymbol{\varphi}}_{MN} = \hat{\boldsymbol{\varphi}}_M/N$, where, by using the assumption (ii), it can be proved that $z \in L_\infty$ and $\hat{z} \in L_\infty$. Then, it also holds that $v \in L_\infty$ and $\dot{x} \in L_\infty$, when v and $\dot{x}$ are bounded inputs. By using the normalizing signal N, it is given that $\boldsymbol{\varphi}_{MN} \in L_\infty$ and $\hat{\boldsymbol{\varphi}}_{MN} \in L_\infty$. Then, by using (8) and (10), it leads to the normalized estimation error expression:

$$\varepsilon_N = \hat{f}_N - f_N, \quad (11)$$

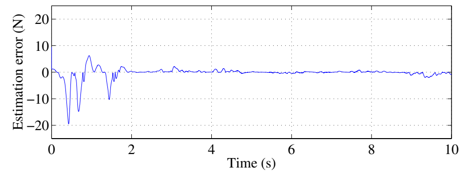


Fig. 3. Experimental result: Estimation error $\epsilon = \hat{f} - f$

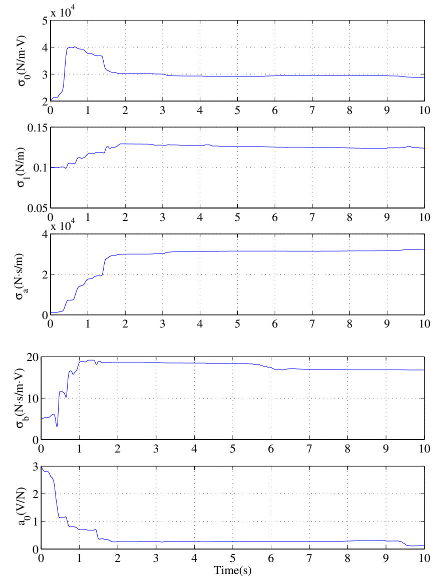


Fig. 4. Experimental result: Convergence profiles of identified model parameters

where $f_N = f/N$ and $\hat{f}_N = \hat{\boldsymbol{\theta}}^T \hat{\boldsymbol{\varphi}}_{MN}$.

By using ε_N and $\hat{\boldsymbol{\varphi}}_{MN}$, we can give the adaptive law with a variable gain for updating the model parameters as

$$\dot{\hat{\boldsymbol{\theta}}}_M = -\boldsymbol{\Gamma}\hat{\boldsymbol{\varphi}}_{MN}\varepsilon_N \quad (12)$$

$$\dot{\boldsymbol{\Gamma}} = \lambda_1\boldsymbol{\Gamma} - \lambda_2\boldsymbol{\Gamma}\hat{\boldsymbol{\varphi}}_{MN}\hat{\boldsymbol{\varphi}}_{MN}^T\boldsymbol{\Gamma} \quad (13)$$

where λ_1, λ_2 and $\boldsymbol{\Gamma}(0)$ have to satisfy the following constraints: $\lambda_1 \ge 0$, $0 \le \lambda_2 < 2$, $\boldsymbol{\Gamma}(0) = \boldsymbol{\Gamma}^T(0) > 0$.

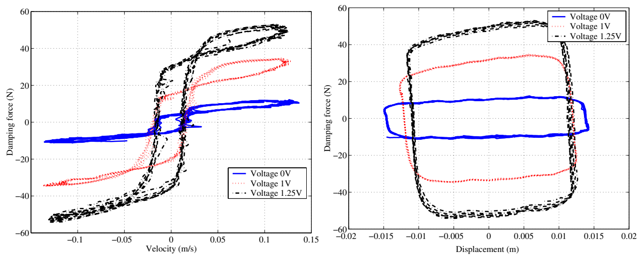
Now the physical model parameters can be calculated from $\hat{\boldsymbol{\theta}}_M$ by using (7).

In the above, we assumed that the model parameter σ_2 is known. Otherwise, we should estimate its nominal value prior to the adaptive identification, or update the estimates of $\boldsymbol{\theta}_M$ and σ_2 iteratively.

C. Model Validation in Experimental Results

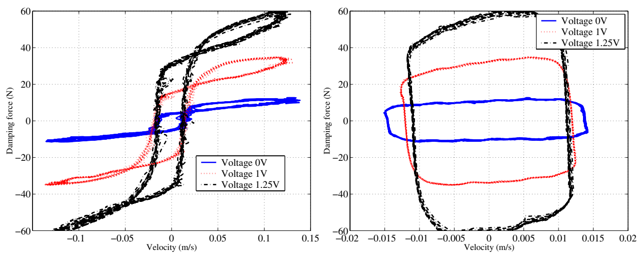
The proposed model was examined via adaptive identification experiments in which the MR damper (RD-1097-01) provided by Lord Corporation was adopted. A laser displacement sensor was placed to measure the displacement x of the piston rod of the MR damper, and a strain sensor was installed in series with the damper to measure the output force f. The signals x and f are sampled at the rate 10 kHz. The identified model has two inputs of velocity $\dot{x}$ and voltage v and one output f. As for the input velocity $\dot{x}$, we used the NS component of the 1940 El Centro seismic data, and the input voltage v was chosen a random signal.

Fig.3 gives a convergence profile of the estimation error $\varepsilon = \hat{f} - f$ in (8). It is shown that the error decreased within



(a) Measured force-velocity hysteresis loop (b) Measured force-displacement hysteresis loop

Fig. 5. Measured hysiteresis characteristics of MR damper



(a) Estimated force-velocity hysteresis loop (b) Estimated force-displacement hysteresis loop

Fig. 6. Estimated hysiteresis characteristicss of MR damper obtained by the proposed adaptive identification method with adaptive observer

about two seconds. The time profiles of the MR damper model parameters are also given in Fig.4, in which quick convergence is also attained within two seconds.

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 1.5cm 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.5(a), and the hysteresis property between f and x shown in Fig.5(b). On the other hand, Figs.6(a)(b) show the hysteresis properties, which were obtained by the proposed adaptive identification of the model with the adaptive observer. The hysteresis dynamics can be almost perfectly expressed by the proposed model and adaptive identification algorithm.

D. Design of Inverse Controller

The role of the adaptive inverse controller shown in Fig.2 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

$$\beta = \hat{\sigma}_0 \hat{z} + \hat{\sigma}_b \dot{x}$$

$$d_\beta = \left\{ \begin{array}{ll} \beta & \text{for} \ \ \beta < -\delta, \ \ \delta < \beta \\ \delta & \text{for} \ \ -\delta \le \beta \le \delta \end{array} \right.$$

$$v_c = \frac{f_c - \{\hat{\sigma}_a \hat{z} - \sigma_1 \hat{a}_0 |\dot{x}_1| \hat{z} + (\sigma_1 + \hat{\sigma}_2)\dot{x}_1 - L\varepsilon\}}{d_\beta}$$

$$v = \left\{ \begin{array}{ll} 0 & \text{for} \ \ v_c \le 0 \\ v_c & \text{for} \ \ 0 < v_c \le V_{\max} \\ V_{\max} & \text{for} \ \ V_{\max} < v_c \end{array} \right. \tag{14}$$

where f_c is the specified command damping force, which will be given in the next section. v is assumed to be fixed near $\beta = 0$.

IV. Adaptive Reference Feedback Controller for Structure Uncertainty

A. Structure and Reference Dynamics

We consider a three-story structure installed with the semi-active MR damper as shown in Fig.1. 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.2 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

$$\boldsymbol{M}\ddot{\boldsymbol{x}} + \boldsymbol{C}\dot{\boldsymbol{x}} + \boldsymbol{K}\boldsymbol{x} = \boldsymbol{\gamma} f - \boldsymbol{M}\boldsymbol{\lambda}\ddot{x}_g, \tag{15}$$

where $\boldsymbol{M}$ is a mass matrix defined by $\boldsymbol{M} = diag\,[m_1,\ m_2,\ m_3]$, and $\boldsymbol{C}$ a damping matrix and $\boldsymbol{K}$ a stiffness matrix, both of which has a similar matrix expression as

$$\boldsymbol{C} = \left[\begin{array}{ccc} c_1 + c_2 & -c_2 & 0 \\ -c_2 & c_2 + c_3 & -c_3 \\ 0 & -c_3 & c_3 \end{array} \right]$$

$$\boldsymbol{K} = \left[\begin{array}{ccc} k_1 + k_2 & -k_2 & 0 \\ -k_2 & k_2 + k_3 & -k_3 \\ 0 & -k_3 & k_3 \end{array} \right]$$

We assume that the physical parameters in $\boldsymbol{M}$, $\boldsymbol{C}$ and $\boldsymbol{K}$ have uncertainties and that there is only horizontal displacement but torsions and vertical displacements are not considered. $\boldsymbol{\lambda}$ is a vector with 1 in all entries, and $\boldsymbol{\gamma}$ is a location vector defined by $\boldsymbol{\gamma} = (-1,\ 0,\ 0)^T$ when the MR damper is installed between the ground and first floor.

Next, we consider a reference model for dynamic behavior of the first floor which is to be realized as

$$\ddot{x}_1 + 2\zeta\omega\dot{x}_1 + \omega^2 x_1 = -\ddot{x}_g \tag{16}$$

B. Adaptive Reference Feedback Controller

It follows from (15) that the dynamic equation of the first floor is expressed by

$$m_1\ddot{x}_1 + (c_1 + c_2)\dot{x}_1 - c_2\dot{x}_2 + (k_1 + k_2)x_1 - k_2 x_2 = -f - m_1\ddot{x}_g \tag{17}$$

Then we consider the manifold surface ξ_1 defined as

$$\xi_1 = \dot{x}_1 + (s + 2\zeta\omega)^{-1}(\omega^2 x_1 + \ddot{x}_g) \tag{18}$$

Let a candidate of the Lyapunov function be given by

$$V_S = \frac{1}{2} m_1 \xi_1^2(t) + \frac{1}{2}\tilde{\boldsymbol{\theta}}_S(t)^T \boldsymbol{P}^{-1}\tilde{\boldsymbol{\theta}}_S(t) \tag{19}$$

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

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

where $\tilde{\boldsymbol{\theta}}_S(t) = \hat{\boldsymbol{\theta}}_S(t) - \boldsymbol{\theta}_S$. $\hat{\boldsymbol{\theta}}_S(t)$ is a 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.

We now take a time derivative of $V_S(t)$ as

$$\begin{aligned}\dot{V}_S &= m_1\xi_1(t)\dot{\xi}_1(t) + \dot{\tilde{\boldsymbol{\theta}}}_S(t)^T \boldsymbol{P}^{-1}\tilde{\boldsymbol{\theta}}_S(t)\\ &= m_1\xi_1(t)\left\{\ddot{x}_1 + \frac{s}{s+2\zeta\omega}(\omega^2 x_1 + \ddot{x}_g)\right\}\\ &\quad + \dot{\tilde{\boldsymbol{\theta}}}_S(t)^T \boldsymbol{P}^{-1}\tilde{\boldsymbol{\theta}}_S(t)\\ &= \xi_1(t)\{-(c_1+c_2)\dot{x}_1 + c_2\dot{x}_2 - (k_1+k_2)x_1 + k_2 x_2\\ &\quad - f - m_1\{\ddot{x}_g - \frac{s}{s+2\zeta\omega}(\omega^2 x_1 + \ddot{x}_g)\}\}\\ &\quad + \dot{\tilde{\boldsymbol{\theta}}}_S(t)^T \boldsymbol{P}^{-1}\tilde{\boldsymbol{\theta}}_S(t) \end{aligned} \tag{20}$$

By using the notation of $\boldsymbol{\varphi}_S(t)$ and $\tilde{\boldsymbol{\theta}}_S(t)$ in (20), we have

$$\dot{V}_S = \xi_1(t)\{-f - \boldsymbol{\varphi}_S(t)^T\boldsymbol{\theta}_S\} + \dot{\tilde{\boldsymbol{\theta}}}_S(t)^T \boldsymbol{P}^{-1}\tilde{\boldsymbol{\theta}}_S(t) \tag{21}$$

Therefore, we can give the adaptive damper force $f(t)$ as

$$f = \kappa\xi_1(t) - \boldsymbol{\varphi}_S(t)^T\hat{\boldsymbol{\theta}}_S(t) \tag{22}$$

and the adaptation law as

$$\dot{\hat{\boldsymbol{\theta}}}_S(t) = \dot{\tilde{\boldsymbol{\theta}}}_S(t) = -\boldsymbol{P}\boldsymbol{\varphi}_S(t)\xi_1(t) \tag{23}$$

Then substituting the above into (21), we have

$$\dot{V}_S = -\kappa\xi_1^2(t) \le 0 \tag{24}$$

Thus it leads to that

$$\lim_{t\to\infty}\xi_1(t) = 0 \tag{25}$$

then the desired reference dynamics of the first floor in (16) can be attained even in the presence of uncertainties in any story structure.

Now as shown in Fig.2, we combine the two adaptive controllers (14) and (22) to construct the fully adaptive algorithm, in which the desired damping force $f_c(t)$ is generated as

$$f_c(t) = \kappa\xi_1(t) - \boldsymbol{\varphi}_S(t)^T\hat{\boldsymbol{\theta}}_S(t) \tag{26}$$

V. Simulation Results

A. Setup of MR Damper and Structure

It is assumed that the MR damper is installed between the ground and first floor to isolate a three-story structure from earthquakes, where the structural parameters are specified as follows: The mass of each floor is $m_i = 98.3$ [Kg] for $i = 1,\ 2,\ 3$, the damping factors are $c_1 = 125$, $c_i = 50$ [N $\cdot$ s], and the stiffness parameters are $k_1 = 5.26 \times 10^5$, $k_i = 6.84 \times 10^5$ [N/m] for $i = 2,\ 3$. It is assumed that the measurable signals are the displacements of the first and second floors, $x_1,\ x_2$, and the velocities of the first and second floors, $\dot{x}_1,\ \dot{x}_2$, and the ground acceleration $\ddot{x}_g$ due to earthquakes. The reference dynamics of the first floor is given in (16), where the natural frequency and damping factor are specified as $\omega = 0.5$ and $\zeta = 0.7$, as if the upper part of the structure is floating.

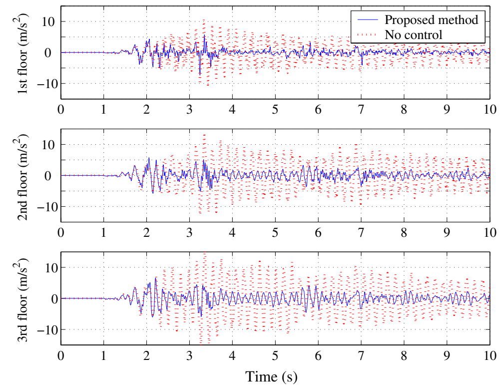


Fig. 7. Acceleration of each floor: Comparison with no damper

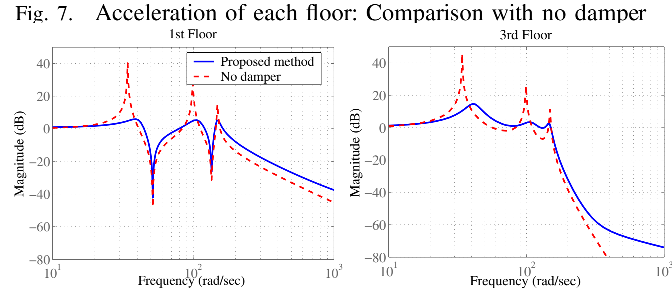


Fig. 8. Frequency response of the structure of 1st and 3rd floors (Comparison with a case without MR damper)

B. Control Results

The accelerations of three floors controlled by the proposed fully adaptive algorithm are illustrated in Fig.7, in which the effectiveness of the isolation control is clearly indicated, compared to a case without any damper. Fig.8 gives the effectiveness of the MR damper based isolation control in the frequency domain. Two figures plot the frequency responses from ground acceleration to acceleration of first and three floors. It is confirmed that all of the resonance peaks can be sufficiently suppressed, even when both models of MR damper and structure include uncertain parameters and no prior information on the model parameters.

Fig.9 shows the convergence behavior of the identified model parameters of the MR damper in (12) and (13), and these parameters are used in the construction of the adaptive inverse controller in (14). All of the parameters converge to true parameters within about 1.5 seconds after the control start at 1 second. Fig.10 show the convergence of the adjustable parameters in the adaptive reference feedback

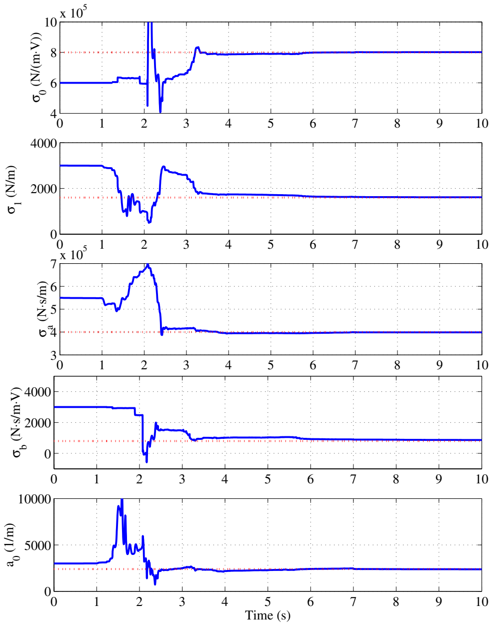


Fig. 9. Parameter convergence of MR damper model

controller in (22) and (23). Although initial values for all the controller parameters are set at zeros, they converge in stable manner and the control error ξ can also be kept within a small range.

C. Comparison with LQG Controller

The LQG control schemes are widely applied to structural vibration control, and its effectiveness is also validated in a case in which the structural model parameters are correctly given. However, careful parameter estimation of a multi-degree-of-freedom structure model and fine tuning of the controller gains are actually needed, since model parameter errors sometimes causes large degradation of control performance The proposed approach can cope with parametric uncertainties in both MR damper model and structure model in a real time manner.

If the adaptive inverse controller can achieve perfect linearization from f_c to f in Fig.2 and the parameters of the structure are precisely known, the adaptive reference controller in the feedback loop may be designed via the well-known LQG control for the known linear structure. We compare the results obtained by the proposed fully adaptive approach in a case with unknown MR damper and structure and the results obtained by replacing the adaptive reference feedback control with the optimal LQG control for the known linear structure.

Figs.11(a) and (b) illustrate the profiles of the desired command damping forces $f_c(t)$ calculated by the proposed fully adaptive algorithm and the optimal LQG control with perfect knowledge on the structure respectively. To make the difference clear we plotted the relationship between $f(t)$ and $f_c(t)$ on the $(f_c(t),\ f(t))$-plane. It should be noticed that the proposed algorithm provides much smaller magnitude of the command damping force f_c compared

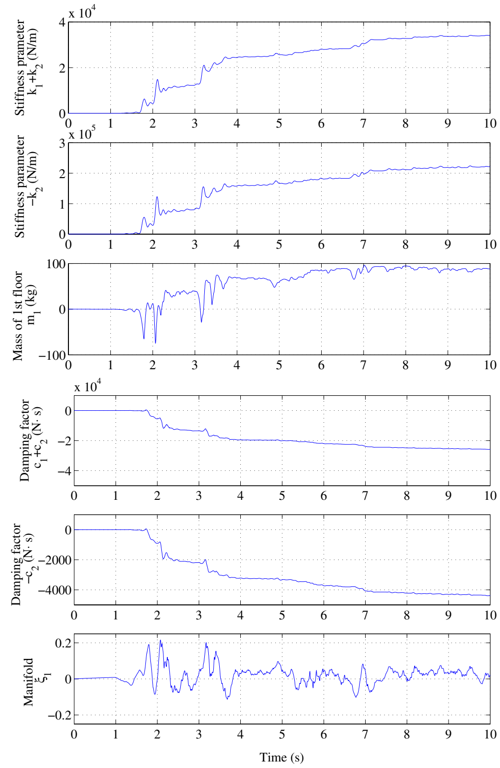
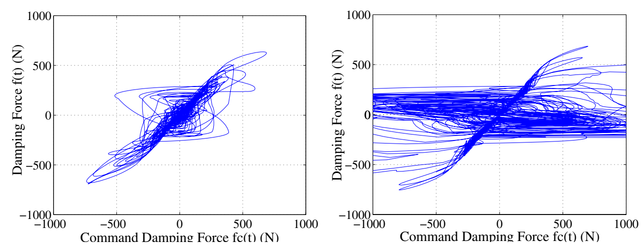


Fig. 10. Parameter convergence of adjustable parameters of adaptive reference feedback controller



(a) (b)

Fig. 11. Command damping force f_c (horizontal axis) and actual damping force f (vertical axis): (a) Proposed fully adaptive control, and (b) LQG control

to the optimal LQG controller. Compared to the LQG controller, the proposed adaptive algorithm can better attain the linear relationship $f = f_c$ than the optimal LQG controller with the perfect knowledge.

VI. Conclusion

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 proposed algorithm can be applicable even in the presence of uncertainties in both MR damper model and structure. It is shown in simulations that the linearization can be efficiently attained, comparing with the LQ control. Furthermore, stability of the total system has also been investigated and the stability condition is clarified on some assumptions.

REFERENCES

[1] G. Yang, Large-scale magnetorheological fluid damper for vibration mitigation : modeling, testing and control, The University of Notre Dame, Indiana, 2001.

[2] B. F. Spencer Jr., S. J. Dyke, M. K. Sain and J. D. Carlson, "Phenomenological model of a magnetorheological damper", ASCE Journal of Engineering Mechanics, Vol.123, No.3, pp.230-238, 1997.

[3] Gongyu Pan, Hiroshi Matshushita and Yoshihisa Honda, "Analytical Model of a Magnetorheological Damper and Its Application to the Vibration Control," Proc, IECON(Industrial Electronics Conferense), Vol.3, pp.1850-1855(2000).

[4] L. Pang, G. M. Kamath and N. M.Wereley, "Analysis and testing of a linear stroke magnetorheological damper," AIAA Structural Dynamics and Materials Conference, Reston, USA, Vol.4, pp.2841-2856, 1998.

[5] S-B. Choi and S-K. Lee, "A hysteresis model for the field-dependent damping force of a magnetorheological damper", J. of Sound and Vibration, Vol.245, No.2, pp.375-383, 2001.

[6] Xio Qing Ma, En Rong Wang, S.Rakheja and C.-Y.Su, "Modeling hysteretic characteristics of MR-fluid damper and model validation", Proc. IEEE Conf. Decision and Control, Las Vegas, USA, pp.1675-1680, 2002.

[7] C. Canudas, H. Olsson, K. J. Åström, and P. Lischinsky, "A new model for control of systems with friction", IEEE Transactions on Automatic Control, Vol.40, No.3, pp.419-425, 1995.

[8] René Jiménez and Luis Alvarez, "Real time identification of structures with magnetorheological dampers", Proceedings of the 41st IEEE Conference on Decision and Control, pp.1017-1022, 2002.

[9] C. Sakai, H. Ohmori and A. Sano, "Modeling of MR damper with hysteresis for adaptive vibration control", Proc. 42th IEEE CDC, Hawaii, 2003.

[10] S. J. Dyke, B. F. Spencer Jr., M. K. Sain, and J. D. Carlson, "Modeling and control of magnetorheological dampers for seismic response reduction", Smart Materials and Structures, Vol.5, pp.565-575, 1996.

[11] C. Y. Lai and W. H. Liao, "Vibration control of a suspension systems via a magnetorheological fluid damper", Journal of Vibration and Control, Vol.8, pp.525-547, 2002.

[12] C.-C. Chang and L. Zhou, "Neural network emulation of inverse dynamics for a magnetorheological damper", ASCE Journal of Structural Engineering, Vol.128, No.2, pp.231-239, 2002.

[13] H. Nishimura and R. Kayama, "Gain-scheduled control of a semi-active suspension using an MR damper", Transactions of the Japan Society of Mechanical Engineers, Vol.68, No.676(C), pp.3644-3651, 2002.

[14] Lei Zuo, Jean-Jacques E.Slotine, and Samir A.Nayfeh, "Experimental Study of a Novel Adaptive Controller for Active Vibration Isolation", Proceeding of the 2004 American Control Conference Boston, Massachusetts June30-July2, 2004

VII. APPENDIX: STABILITY ANALYSIS

We discuss the stability condition such that the stability of the total adaptive control system integrating two adaptive controller and structure can be assured. The inverse controller giving $v(t)$ has a nonlinear form with respect to the adjustable parameters, so the stability analysis is so complicated. Thus, in order to investigate the stability, we will assume that the parameters σ_0, σ_b and a_0 in the MR damper model are known. From the assumption, the internal state z is directly accessible, i.e., $\hat{z} = z$, and the required voltage input $v_c(t)$ becomes linear with respect to the unknown parameters σ_1, σ_2 and σ_a. It is also that the input voltage v_c in (14) is not saturated. Those assumptions can make the analysis feasible.

On the assumption, the expression of the integrated system becomes as

$$m_1\ddot{x}_1 + (c_1 + c_2)\dot{x}_1 - c_2\dot{x}_1 + (k_1 + k_2)x_1 - k_2x_2 \quad (27)$$

$$= -f - m_1\ddot{x}_g \quad (28)$$

$$f = \sigma_a z + \sigma_0 z v_c - \sigma_1 a_0|\dot{x}_1|z + (\sigma_1 + \sigma_2)\dot{x}_1 + \sigma_b\dot{x}_1 v_c \quad (29)$$

$$v_c = \frac{f_c - \{\hat{\sigma}_a z - \hat{\sigma}_1 a_0|\dot{x}_1|z + (\hat{\sigma}_1 + \hat{\sigma}_2)\dot{x}_1\}}{\sigma_0 z + \sigma_b\dot{x}_1} \quad (30)$$

$$f_c = \kappa\xi_1 - \boldsymbol{\varphi}^T\tilde{\boldsymbol{\theta}}_S \quad (31)$$

Let α and β be denoted by $\alpha = \sigma_0 z + \sigma_b\dot{x}$ and $\beta = \hat{\sigma}_a z - \hat{\sigma}_1 a_0|\dot{x}_1|z + (\hat{\sigma}_1 + \hat{\sigma}_2)\dot{x}_1$. Then, substituting (30) into (29) gives that

$$\begin{aligned} f &= \boldsymbol{\theta}_M^T\boldsymbol{\varphi}_M \\ &= \sigma_a z + \sigma_0 z(\frac{1}{\alpha}f_c - \frac{\beta}{\alpha}) - \sigma_1 a_0|\dot{x}_1|z \\ &+ (\sigma_1 + \sigma_2)\dot{x} + \sigma_b\dot{x}(\frac{1}{\alpha}f_c - \frac{\beta}{\alpha}) \\ &= f_c - \beta + \sigma_a z - \sigma_1 a_0|\dot{x}_1|z + (\sigma_1 + \sigma_2)\dot{x} \\ &= f_c - \tilde{\theta}_1 z + \tilde{\theta}_3|\dot{x}_1|z - \tilde{\theta}_4\dot{x}_1 \end{aligned}$$

Let a candidate of the Lyapunov function be denoted by

$$V = \frac{1}{2}\tilde{\boldsymbol{\theta}}_M^T\boldsymbol{\Gamma}^{-1}\tilde{\boldsymbol{\theta}}_M + \frac{1}{2}m_1\xi_1^2 + \frac{1}{2}\tilde{\boldsymbol{\theta}}_S^T\boldsymbol{P}^{-1}\tilde{\boldsymbol{\theta}}_S \quad (32)$$

where $\boldsymbol{\theta}_M = (\theta_1,\ \theta_3,\ \theta_4)^T$ from (4) on the assumption that σ_0, σ_b and a_0 are known.

Then by using the above expressions, and the adaptive laws $\dot{\tilde{\boldsymbol{\theta}}}_S = -\boldsymbol{P}\boldsymbol{\varphi}_S\xi_1$ and $\dot{\tilde{\boldsymbol{\theta}}}_M = -\boldsymbol{\Gamma}\boldsymbol{\varphi}_M\varepsilon$, and taking time-derivative of V and using the above expressions, we have

$$\begin{aligned} \dot{V} &= -\tilde{\boldsymbol{\theta}}_M^T\boldsymbol{\varphi}_M^T\boldsymbol{\varphi}_M\tilde{\boldsymbol{\theta}}_M + \xi_1(-f - \boldsymbol{\varphi}_S\boldsymbol{\theta}_S) + \dot{\tilde{\boldsymbol{\theta}}}_S\boldsymbol{P}^{-1}\tilde{\boldsymbol{\theta}}_S \\ &= -\tilde{\boldsymbol{\theta}}_M^T\boldsymbol{\varphi}_M^T\boldsymbol{\varphi}_M\tilde{\boldsymbol{\theta}}_M - \kappa\xi_1^2 + \xi_1(\tilde{\theta}_1 z - \tilde{\theta}_3|\dot{x}_1|z + \tilde{\theta}\cdot x_1) \\ &= -\kappa\xi_1^2 - z^2(\tilde{\theta}_1^2 - \frac{\xi_1}{z}\tilde{\theta}_1) - |\dot{x}_1|^2z^2(\tilde{\theta}_3^2 + \frac{\xi_1}{|\dot{x}_1|z}\tilde{\theta}_3) \\ &\qquad -\dot{x}^2(\tilde{\theta}_4^2 - \frac{\xi_1}{\dot{x}_1}\tilde{\theta}_4) \\ &= -\kappa\xi_1^2 - \frac{1}{2}z^2\tilde{\theta}_1^2 - \frac{1}{2}|\dot{x}_1|^2z^2\tilde{\theta}_3^2 - \frac{1}{2}\dot{x}_1^2\tilde{\theta}_4^2 \\ &\quad -\frac{1}{2}z^2(\tilde{\theta}_1 - \frac{\xi_1}{z})^2 + \frac{1}{2}\xi_1^2 - \frac{1}{2}|\dot{x}_1|z^2(\tilde{\theta}_3 - \frac{\xi_1}{|\dot{x}_1|z})^2 \\ &\quad +\frac{1}{2}\xi_1^2 - \frac{1}{2}\dot{x}^2(\tilde{\theta}_4 - \frac{\xi_1}{\dot{x}_1})^2 + \frac{1}{2}\xi_1^2 \end{aligned}$$

Then, if $\kappa > 3/2$, we can have

$$\dot{V} \le -(\kappa - \frac{3}{2})\xi_1^2 - \frac{1}{2}z^2\tilde{\theta}_1^2 - \frac{1}{2}|\dot{x}|z^2\tilde{\theta}_3^2 - \frac{1}{2}\dot{x}_1^2\tilde{\theta}_4^2 \le 0 \quad (33)$$

Therefore, if κ is chosen so that $\kappa > 3/2$, it gives from the above that $\dot{V} \le 0$. In ideal situations, κ can take any positive constant, but the stability analysis on the proposed fully adaptive algorithm has revealed the stability condition on κ.