FULLY ADAPTIVE SEMI-ACTIVE CONTROL OF VIBRATION ISOLATION BY MR DAMPER

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Abstract: This paper is concerned with a new fully adaptive control scheme 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 to be acted on a controlled structure. The input voltage is decided using a nonlinear adaptive observer with identified model parameters of the MR damper which expresses hysteresis behavior of nonlinear dynamic friction mechanism of the MR fluid. 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 uncertainties in both models of MR damper and structure. Theoretical analysis and experimental results are also shown to validate its effectiveness.

Keywords: Vibration control. Adaptive control. Semi-active control. MR damper. Adaptive identification. Vibration isolation.

1. INTRODUCTION

Magnetorheological (MR) damper is a promising semi-active device in which the viscosity of MR fluid is controllable depending on input voltage. The MR damper 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 (Yang, 2001)(Spencer Jr. and Carlson, 1997). Static or quasi-static models include no dynamics but can express a nonlinear mapping from velocity to damping force (Yang, 2001)(Pan and Honda, 2000)(Choi and Lee, 1998). It is not easy to identify the hysteresis curve by using a small number of model parameters from actual nonstationary seismic input-output data. To model the hysteresis dynamics explicitly, the Bouc-Wen model and its variations have also been investigated, in which the input-output relation is expressed by a set of nonlinear differential equations (Yang, 2001)(Spencer Jr. and Carlson, 1997). The model can simulate the nonlinear behavior of the MR damper, however it includes too many nonlinear model parameters to be identified in real-time manner. Alternative modeling is based on the LuGre friction model (René and Alvarez, 2002) which was originally developed to describe nonlinear friction phenomena (Canudas and Lischinsky, 1995). It has rather simple structure and the number of model parameters can also be reduced, however, it is not adequate for real-time design of an inverse controller. We have given an MR damper model based on the LuGre model and an analytical method for adaptive inverse controller (Sakai and Sano, 2003).

It is desired that the input voltage of MR damper is determined so that the specified damping forces are produced to attenuate vibrations of structures. The necessary damping force can be calculated to minimize the LQ or LQG performance when the linear dynamic equation is given for the controlled structure. A clipped-optimal control algorithm has been proposed (Dyke and Carlson, 1996), in which a linear optimal controller combined with a force feedback loop was designed to adjust the input voltage, which is set at either zero or its maximum level according to the gap between the calculated desired damping force and the actual force. Its modification was also considered (Lai and Liao, 2002). These approaches did not use any inversion dynamics of MR damper. Neural network (NN) approaches have also been developed to construct an inverse model of the MR damper

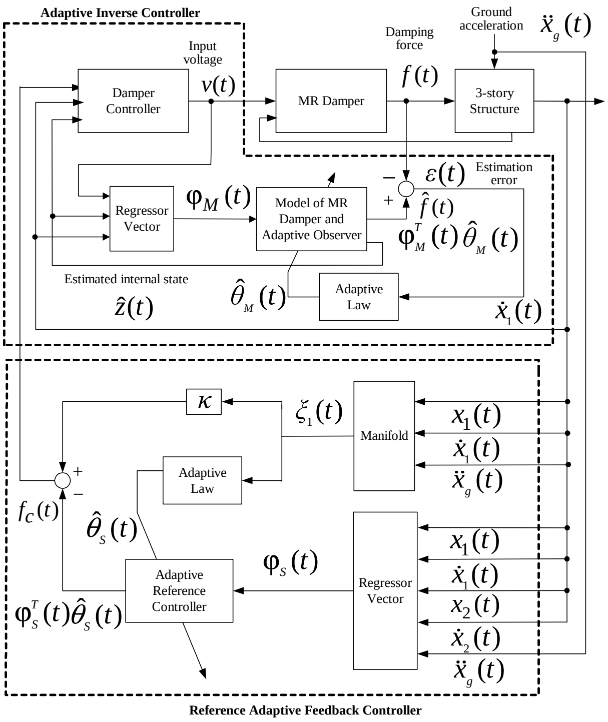


Fig. 1. Proposed fully adaptive vibration isolation control system

(Chang and Zhou, 2002), while it takes much time to update the parameters in NN. By regarding the total system including the MR damper and structure as a nonlinear controlled system, nonlinear control design methods can also be applied, such as sliding mode control (Lai and Liao, 2002), adaptive control (Zuo and Nayfeh, 2004), gain scheduled control and others.

The purpose of the present paper is to give a fully adaptive control approach which can cope with uncertainties in both models of MR damper and structure. The proposed approach consists of two adaptive control: 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 a command damping force. The other is an adaptive reference feedback control which gives the command force to 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. Validity of the proposed algorithm is discussed in experimental studies and stability analysis.

2. FULLY ADAPTIVE APPROACH

Fig.1 shows a schematic diagram of the proposed fully adaptive vibration isolation control system for a three-story structure. The fully adaptive algorithm consists of two controllers: One is an adaptive inverse controller which can give required input voltage v to MR damper so that the damping force f be equal to specified command damping force f_c. If the adaptive inverse controller is perfectly designed so that the linearization from $f_c(t)$ to $f(t)$ is attained, that is, $f_c(t) = f(t)$, we can realize almost active control. The other is an adaptive reference feedback control which can match the dynamics of the first floor of structure to a desired reference dynamics even when the structure model involves parametric uncertainty. Since the MR damper is actually a nonlinear semi-active device, it is difficult to make it work as an active device, and it needs very fine and complicated tuning of both the adaptive inverse controller and adaptive reference controller. Straightforward use of the optimal LQG control in the feedback loop cannot attain good performance as shown later.

3. ADAPTIVE INVERSE CONTROL

3.1 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 (Yang, 2001)(Spencer Jr. and Carlson, 1997), the LuGre model has simpler structure and smaller number of parameters needed for expression of its behavior (René and Alvarez, 2002). 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 (Sakai and Sano, 2003).

The damping force f is expressed by

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

$$\dot{z} = \dot{x} - a_0 |\dot{x}| z \qquad (2)$$

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

$$\begin{aligned} f &= \sigma_a z + \sigma_0 z v - \sigma_1 a_0 |\dot{x}| z \\ &\quad + (\sigma_1 + \sigma_2)\,\dot{x} + \sigma_b \dot{x} v = \boldsymbol{\theta}_M^T \boldsymbol{\varphi}_M \end{aligned} \qquad (3)$$

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

Let the identified parameter vector $\hat{\boldsymbol{\theta}}_M$ be denoted by $\hat{\boldsymbol{\theta}}_M = (\hat{\theta}_1,\ \hat{\theta}_2,\ \hat{\theta}_3,\ \hat{\theta}_4,\ \hat{\theta}_5)^T$. Since the internal state z of the MR damper model cannot be measured, the regressor vector $\boldsymbol{\varphi}_M$ should be replaced with its estimate $\hat{\boldsymbol{\varphi}}_M$ as

$$\hat{\boldsymbol{\varphi}}_M = (\ \hat{z},\ \hat{z}v,\ -|\dot{x}|\hat{z},\ \dot{x},\ \dot{x}v\ )^T \tag{4}$$

where the estimate $\hat{z}$ is given later by using the updated model parameters. The output of the identification model is now described as

$$\hat{f} = \hat{\boldsymbol{\theta}}_M^T \hat{\boldsymbol{\varphi}}_M. \tag{5}$$

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

$$\dot{\hat{z}} = \dot{x} - \hat{a}_0|\dot{x}|\hat{z} - L\varepsilon, \tag{6}$$

where L is an observer gain such that $0 \leq L \leq 1/\hat{\sigma}_{1\max}$, 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 $N = \left(\rho + \hat{\boldsymbol{\varphi}}_M^T \hat{\boldsymbol{\varphi}}_M\right)^{1/2}$, $\rho > 0$. By dividing the signals and errors by N as $\boldsymbol{\varphi}_{MN} = \boldsymbol{\varphi}_M/N$, $\hat{\boldsymbol{\varphi}}_{MN} = \hat{\boldsymbol{\varphi}}_M/N$ and $\varepsilon_N = \hat{f}_N - f_N$, where $f_N = f/N$ and $\hat{f}_N = \hat{\boldsymbol{\theta}}^T \hat{\boldsymbol{\varphi}}_{MN}$, we can give the adaptive law with a variable gain for updating the model parameters as

$$\dot{\hat{\boldsymbol{\theta}}}_M = -\boldsymbol{\Gamma}\hat{\boldsymbol{\varphi}}_{MN}\varepsilon_N \tag{7}$$

$$\dot{\boldsymbol{\Gamma}} = \lambda_1\boldsymbol{\Gamma} - \lambda_2\boldsymbol{\Gamma}\hat{\boldsymbol{\varphi}}_{MN}\hat{\boldsymbol{\varphi}}_{MN}^T\boldsymbol{\Gamma} \tag{8}$$

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

3.2 Design of Inverse Controller

The role of the adaptive inverse controller shown in Fig.1 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

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

$$d_\rho = \begin{cases} \rho \text{ for } & \rho < -\delta, \quad \delta < \rho \\ \delta \text{ for } & -\delta \leq \rho \leq \delta \end{cases}$$

$$v_c = \frac{f_c - \{\hat{\sigma}_a\hat{z} - \sigma_1\hat{a}_0|\dot{x_1}|\hat{z} + (\sigma_1 + \hat{\sigma}_2)\dot{x_1} - L\varepsilon\}}{d_\rho}$$

$$v = \begin{cases} 0 & \text{for } v_c \leq 0 \\ v_c & \text{for } 0 < v_c \leq V_{\max} \\ V_{\max} & \text{for } V_{\max} < v_c \end{cases} \tag{9}$$

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

4. ADAPTIVE REFERENCE CONTROL

4.1 Structure and Reference Dynamics

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

$$\boldsymbol{M}\ddot{\boldsymbol{x}} + \boldsymbol{C}\dot{\boldsymbol{x}} + \boldsymbol{K}\boldsymbol{x} = \boldsymbol{\gamma}f - \boldsymbol{M}\boldsymbol{\lambda}\ddot{x}_g, \tag{10}$$

where $\boldsymbol{M}$ is a mass matrix defined by $\boldsymbol{M} = diag\,[m_1,\ m_2,\ m_3,\ m_4]$, and $\boldsymbol{C}$ a damping matrix by

$$\boldsymbol{C} = \begin{bmatrix} c_1 + c_2 & -c_2 & 0 & 0 \\ -c_2 & c_2 + c_3 & -c_3 & 0 \\ 0 & -c_3 & c_3 + c_4 & -c_4 \\ 0 & 0 & -c_4 & c_4 \end{bmatrix}$$

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 $\boldsymbol{\lambda}$ is a vector with 1 in all entries, and $\boldsymbol{\gamma}$ is a location vector defined by $\boldsymbol{\gamma} = (-1,\ 0,\ 0,\ 0)^T$ 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 to be realized as

$$\ddot{x}_1 + 2\zeta\omega\dot{x}_1 + \omega^2 x_1 = -\ddot{x}_g \tag{11}$$

4.2 Adaptive Reference Controller

It follows from (10) that the dynamic equation of the first floor is expressed by

$$m_1\ddot{x}_1 + (c_1 + c_2)\dot{x}_1 - c_2\dot{x}_2 + (k_1 + k_2)x_1 - k_2x_2 = -f - m_1\ddot{x}_g \tag{12}$$

Then let the manifold surface ξ_1 be defined as

$$\xi_1 = \dot{x}_1 + (s + 2\zeta\omega)^{-1}(\omega^2 x_1 + \ddot{x}_g) \tag{13}$$

Let a candidate of the Lyapunov function be

$$V_S = \frac{1}{2}m_1\xi_1^2(t) + \frac{1}{2}\tilde{\boldsymbol{\theta}}_S(t)^T\boldsymbol{P}^{-1}\tilde{\boldsymbol{\theta}}_S(t) \tag{14}$$

where $\boldsymbol{P}$ is a pre-selected symmetric positive definite matrix, and let the unknown parameter vector $\boldsymbol{\theta}_S$ and regressor signal vector $\boldsymbol{\varphi}_S(t)$ be denoted by

$$\boldsymbol{\theta}_S = (\ k_1 + k_2,\ -k_2,\ c_1 + c_2,\ -c_2,\ m_1\ )^T$$

$$\boldsymbol{\varphi}_S(t) = (\ x_1\ \ x_2\ \ \dot{x}_1\ \ \dot{x}_2\ \ \ddot{x}_g - \frac{s}{s + 2\zeta\omega}(\omega^2 x_1 + \ddot{x}_g)\ )^T$$

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

$$\begin{aligned}\dot{V}_S &= m_1\xi_1(t)\dot{\xi}_1(t) + \dot{\tilde{\boldsymbol{\theta}}}_S(t)^T\boldsymbol{P}^{-1}\tilde{\boldsymbol{\theta}}_S(t)\\ &= m_1\xi_1(t)\left\{\ddot{x}_1 + \frac{s}{s+2\zeta\omega}(\omega^2x_1+\ddot{x}_g)\right\}\\ &\quad +\dot{\tilde{\boldsymbol{\theta}}}_S(t)^T\boldsymbol{P}^{-1}\tilde{\boldsymbol{\theta}}_S(t)\\ &= \xi_1(t)\{-(c_1+c_2)\dot{x}_1 + c_2\dot{x}_2 - (k_1+k_2)x_1\\ &\quad +k_2x_2 - f - m_1\{\ddot{x}_g - \frac{s}{s+2\zeta\omega}(\omega^2x_1+\ddot{x}_g)\}\}\\ &\quad +\dot{\tilde{\boldsymbol{\theta}}}_S(t)^T\boldsymbol{P}^{-1}\tilde{\boldsymbol{\theta}}_S(t) \qquad (15)\end{aligned}$$

By using the notation of $\boldsymbol{\varphi}_S(t)$ and $\tilde{\boldsymbol{\theta}}_S(t)$ in (15), we have

$$\dot{V}_S = \xi_1(t)\{-f - \boldsymbol{\varphi}_S(t)^T\boldsymbol{\theta}_S\} + \dot{\tilde{\boldsymbol{\theta}}}_S(t)^T\boldsymbol{P}^{-1}\tilde{\boldsymbol{\theta}}_S(t) \qquad (16)$$

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

$$f = \kappa\xi_1(t) - \boldsymbol{\varphi}_S(t)^T\hat{\boldsymbol{\theta}}_S(t) \qquad (17)$$

and the adaptation law as

$$\dot{\hat{\boldsymbol{\theta}}}_S(t) = \dot{\tilde{\boldsymbol{\theta}}}_S(t) = -\boldsymbol{P}\boldsymbol{\varphi}_S(t)\xi_1(t) \qquad (18)$$

Then substituting the above into (16), we have

$$\dot{V}_S = -\kappa\xi_1^2(t) \le 0 \qquad (19)$$

Thus it leads to that

$$\lim_{t\to\infty}\xi_1(t) = 0 \qquad (20)$$

then the desired reference dynamics of the first floor in (11) can be attained even in the presence of uncertainties in any story structure.

Now as shown in Fig.1, we combine the two adaptive controllers (9) and (17) to construct the fully adaptive algorithm, in which the desired damping force $f_c(t)$ is generated as

$$f_c(t) = \kappa\xi_1(t) - \boldsymbol{\varphi}_S(t)^T\hat{\boldsymbol{\theta}}_S(t) \qquad (21)$$

5. STABILITY ANALYSIS

We discuss the stability of the integrated system including two adaptive controllers and structure. 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 assured that the input voltage v_c in (9) is not saturated. Those assumptions can make the analysis feasible.

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

$$\begin{aligned} m_1\ddot{x}_1 + (c_1+c_2)\dot{x}_1 - c_2\dot{x}_1 + (k_1+k_2)x_1 - k_2x_2 &\\ = -f - m_1\ddot{x}_g \qquad (22)\end{aligned}$$

$$\begin{aligned} f = \sigma_a z + \sigma_0 z v_c - \sigma_1 a_0|\dot{x}_1|z &\\ +(\sigma_1+\sigma_2)\dot{x}_1 + \sigma_b\dot{x}_1 v_c \qquad (23)\end{aligned}$$

$$v_c = \frac{f_c - \{\hat{\sigma}_a z - \hat{\sigma}_1 a_0|\dot{x}_1|z + (\hat{\sigma}_1+\hat{\sigma}_2)\dot{x}_1\}}{\sigma_0 z + \sigma_b\dot{x}_1} \qquad (24)$$

$$f_c = \kappa\xi_1 - \boldsymbol{\varphi}^T\tilde{\boldsymbol{\theta}}_S \qquad (25)$$

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 (24) into (23) gives that

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

Let a candidate of the Lyapunov function be denoted by

$$V = \frac{1}{2}\tilde{\boldsymbol{\theta}}_M^T\boldsymbol{\Gamma}^{-1}\tilde{\boldsymbol{\theta}}_M + \frac{1}{2}m_1\xi_1^2 + \frac{1}{2}\tilde{\boldsymbol{\theta}}_S^T\boldsymbol{P}^{-1}\tilde{\boldsymbol{\theta}}_S \qquad (26)$$

where $\boldsymbol{\theta}_M = (\theta_1,\ \theta_3,\ \theta_4)^T$ from (3) 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

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

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

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

Therefore, if κ is chosen so that $\kappa > 3/2$, it gives from the above that $\dot{V} \le 0$. In ideal situations, κ

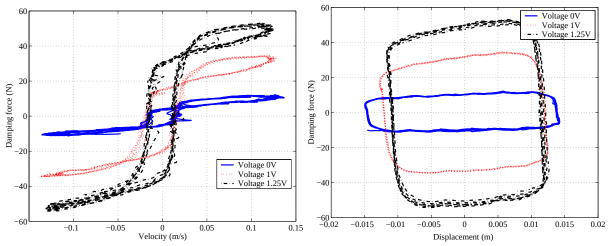
Fig. 2. Experimental setup for fully adaptive approach

can take any positive constant, but the stability analysis on the proposed fully adaptive algorithm has revealed the stability condition on κ.

6. EXPERIMENTAL RESULTS

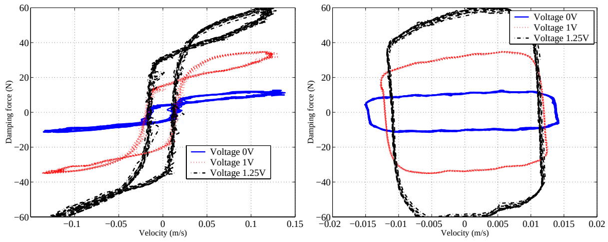
We constructed a 4-story structure shown in Fig.2. We used the random input and the NS component of the 1940 El Centro seismic data as the ground acceleration $\ddot{x}_g$ which is reproduced according to the scale of the shaker table. As the semi-active device, the MR damper (RD-1097-01) provided by Lord Corporation was adopted to isolate the first floor from the ground acceleration. Two laser displacement sensors were placed to measure the displacement x_1 of the piston rod of the MR damper and the displacement x_2. A strain sensor was installed in series with the damper to measure the damping force f. The MR damper model parameters were identified by (6) $\sim$ (8), and convergence of all the parameters to constants were attained within two seconds (Sakai and Sano, 2003).

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.3(a), and the hysteresis property between f and x shown in Fig.3(b). On the other hand, Figs.4(a)(b) show the hysteresis properties, which were obtained by the proposed adaptive identification of the model parameters with the adaptive observer.



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

Fig. 3. Measured hysteresis characteristics of MR damper



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

Fig. 4. Estimated hysteresis characteristics of MR damper obtained by the proposed adaptive identification method with adaptive observer

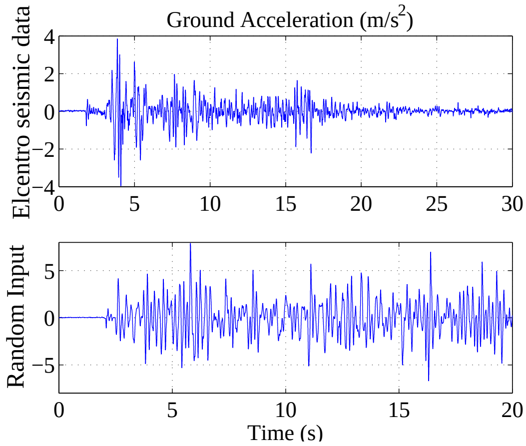


Fig. 5. Applied input accelerations as ground accelerations. *Above*: Scaled El Centro seismic data. *Below*: Stationary random acceleration

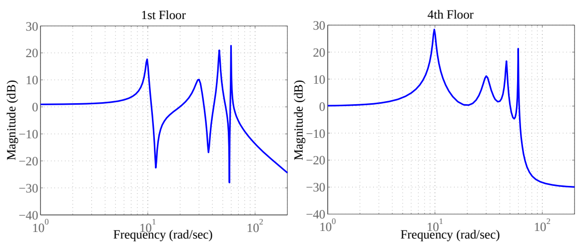


Fig. 6. Identified frequency responses of the structure of first and fourth floor

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. Fig.5 shows their time

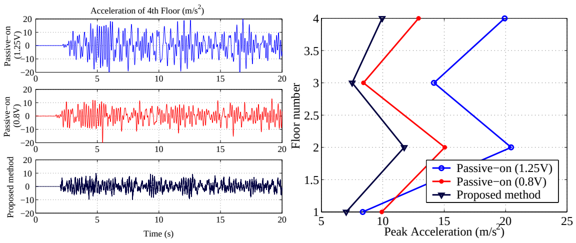


Fig. 7. Acceleration of 4th floor: Comparison of proposed fully adaptive approach with passive-on: Stationary random acceleration case

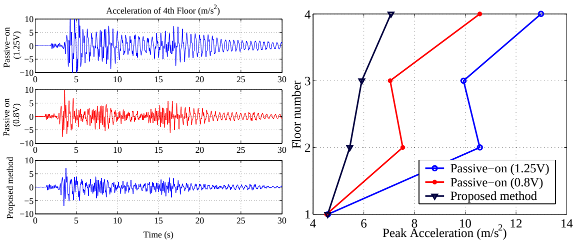


Fig. 8. Acceleration of 4th floor: Comparison of proposed fully adaptive approach with passive-on: Scaled El Centro seismic acceleration case

profiles of the acceleration respectively. As shown in Fig.2, the structure has four stories, and the structure dynamics is expressed by using the next matrices, which were identified by the subspace method and parameter fitting in the frequency domain:

$$\boldsymbol{M} = \begin{bmatrix} 1.3778 & 0 & 0 & 0 \\ 0 & 1.1609 & 0 & 0 \\ 0 & 0 & 1.1746 & 0 \\ 0 & 0 & 0 & 1.2733 \end{bmatrix} kg$$

$$\boldsymbol{C} = \begin{bmatrix} 8.4643 & -0.8751 & 0 & 0 \\ -0.8751 & 0.8991 & -0.024 & 0 \\ 0 & -0.024 & 0.0817 & -0.0577 \\ 0 & 0 & -0.5777 & 0.5777 \end{bmatrix} \mathrm{N} \cdot s/m$$

$$\boldsymbol{K} = \begin{bmatrix} 1709.4 & -1324.6 & 0 & 0 \\ -1324.6 & 2420.7 & -1096.1 & 0 \\ 0 & -1096.1 & 2267.9 & -1171.8 \\ 0 & 0 & -1171.8 & 1171.8 \end{bmatrix} \mathrm{N}/m$$

The frequency responses from the ground acceleration to the first and fourth floor accelerations are plotted in Fig.6. In the case of stationary random ground acceleration, Fig.7 gives comparisons of the controlled acceleration result of fourth floor obtained by the proposed method with the results obtained by the MR damper with fixed voltages (0.8V and 1.25V). By adaptively controlling the voltage input to the MR damper, the accelerations can be nicely suppressed. The peak accelerations of all stories can also be improved. In case of the El Centro seismic data shown in Fig.8, the acceleration of the fourth floor and the peak acceleration can also be suppressed by the proposed fully adaptive control compared to fixed voltage input to the MR damper.

7. 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 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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