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Research Article

Vibration Control of Buildings Using Magnetorheological Damper: A New Control Algorithm

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This paper presents vibration control of a building model under earthquake loads. A magnetorheological (MR) damper is placed in the building between the first floor and ground for seismic response reduction. A new control algorithm to command the MR damper is proposed. The approach is inspired by a quasi-bang-bang controller; however, the proposed technique gives weights to control commands in a fashion that is similar to a fuzzy logic controller. Several control algorithms including decentralized bang-bang controller, Lyapunov controller, modulated homogeneous friction controller, maximum energy dissipation controller, and clipped-optimal controller are used for comparison. The new controller achieved the best reduction in maximum interstory drifts and maximum absolute accelerations over all the control algorithms presented. This reveals that the proposed controller with the MR damper is promising and may provide the best protection to the building and its contents.

1. Introduction

In recent years, due to developments in design technology and material qualities in civil engineering, the structures become more light and slender. This will cause the structures to be subjected to severe structural vibrations when they are located in environments where earthquakes or high winds occur. These vibrations may lead to serious structural damage and potential failure. Structural control is one area of current research that looks promising to attain more resilient designs under dynamic loads. Structural sustainability can be achieved by adding a mechanical system that is installed in the structure to reduce vibrations. The vibrations can be controlled by various means, such as modifying rigidities, masses, damping, or shape, and by providing passive or active counterforces.

Structural control methods that can be used include [1] passive control systems, active control systems, and semiactive control systems. The advantages and disadvantages of each method have been well documented and the choice of which approach to use has largely depended on engineering preference, type of structure, location, nature of the dynamic load, and project commissioning.

A passive control system does not require an external power source. However, a passive control system has limited ability because it is not able to adapt to structural changes or varying usage patterns and loading conditions. To overcome these shortcomings, active and semiactive control schemes can be used.

An active control scheme uses a power source to drive actuator(s) that apply forces to a primary structure in a prescribed manner. These forces can be used to both add and dissipate energy in the structure. Active control strategies for structural systems have been developed as one means by which to minimize the effects of environmental dynamic loads [1–4]. A common example of an active control system is the active tuned mass damper (ATMD). Although ATMDs are effective in reducing structural responses under dynamic loads, especially in tall buildings under winds [5–8], they are large and heavy and take up valuable space. Moreover, they present an additional cost to a constructional project. Active control systems require external power, routine maintenance, high-performance digital signal processors, and bulky power amplifiers to drive actuators; in addition, they may become potentially unstable. To alleviate these problems, semiactive control systems can be used.

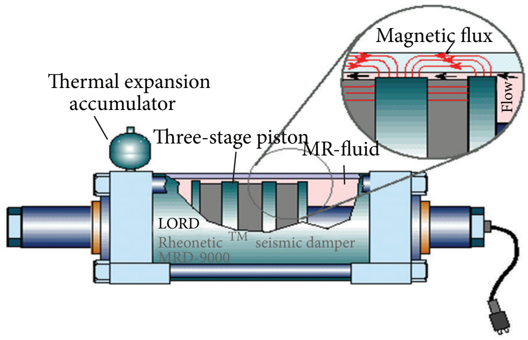

Figure 1: Schematic of a full-scale 20-ton MR fluid damper [9].

Semiactive control strategies combine active and passive control schemes and attempt to offer the advantages of both systems with better performance. Smart damping technology is a type of semi-active control that employs variable dampers, for example, variable orifice dampers, magnetorheological (MR) fluid dampers, and electrorheological (ER) fluid dampers [10, 11]. Smart damping technology assumes the positive aspects of both passive and active control devices; it can provide increased performance over passive control without the concerns of energy and stability associated with active control. A promising semiactive control device is an MR fluid damper, which is a type of viscous damper with controllable damping force. Figure 1 shows a schematic representation of a full-scale 20-ton MR fluid damper [9]. MR dampers exhibit variable damping coefficients depending on the strength of the accompanying magnetic field. A high magnetic field creates a nearly unyielding damper filled with a semisolid fluid while no magnetic field produces an ordinary viscous damper.

In the past two decades, MR dampers have been enjoying renewed interest as an attractive means for protecting civil infrastructure systems against severe earthquake and wind loading [12–20]. Due to their low-power requirements and fail safe property, MR dampers have been intensively studied by many researchers as control devices for civil engineering structures [9, 21–24]. Several approaches have been proposed in the literature to control the MR dampers [25].

In this paper, a new control algorithm to command an MR damper implemented in a three-story building model is proposed. The controller is inspired by a quasi-bang-bang controller; however, the proposed approach gives weights to the output in a fashion that is similar to a fuzzy logic controller (see [26]). In addition to changing the input voltage of the MR damper to the values V_0 (minimum voltage) and $V_{\max}$ (maximum voltage) over time, the proposed controller makes use of the values in between. The new controller assigns time varying values to the input voltage. Several control algorithms including decentralized bang-bang controller, Lyapunov controller, modulated homogeneous friction controller, maximum energy dissipation controller, and clipped-optimal controller are used to command the MR damper. The proposed controller shows its capability in reducing all floors' absolute accelerations as well as interstory drifts, in addition to requiring a minimum control force.

2. Dynamic Model

Before a control scheme for a certain structure can be studied, the governing equation of the dynamic system must be obtained.

2.1. Equation of Motion. The equation of motion of a controlled multistory building can be obtained using Newton's second law of motion or by applying the influence coefficients method. The following assumptions are considered for a shear building model:

(i) the floors' slaps are rigid and the total mass is lumped at floors' levels;

(ii) there is no rotation of the horizontal section at slap's level;

(iii) the floors are subjected only to one-dimensional horizontal ground acceleration.

Consider an n degree-of-freedom structure (multi-story building), subjected to one-dimensional earthquake acceleration, as shown in Figure 2. Using Newton's second law of motion, the equation of motion may be written as follows:

$$\begin{aligned}
&m_1\ddot{x}_1 + c_1\dot{x}_1 + k_1 x_1 - c_2(\dot{x}_2 - \dot{x}_1) - k_2(x_2 - x_1) \\
&\quad = -m_1\ddot{x}_g - f_2 + f_1, \\
&m_2\ddot{x}_2 + c_2(\dot{x}_2 - \dot{x}_1) + k_2(x_2 - x_1) - c_3(\dot{x}_3 - \dot{x}_2) \\
&\quad - k_3(x_3 - x_2) = -m_2\ddot{x}_g - f_3 + f_2, \\
&\quad\vdots \\
&m_{n-1}\ddot{x}_{n-1} + c_{n-1}(\dot{x}_{n-1} - \dot{x}_{n-2}) + k_{n-1}(x_{n-1} - x_{n-2}) \\
&\quad - c_n(\dot{x}_n - \dot{x}_{n-1}) - k_n(x_n - x_{n-1}) = -m_{n-1}\ddot{x}_g - f_n + f_{n-1}, \\
&m_n\ddot{x}_n + c_n(\dot{x}_n - \dot{x}_{n-1}) + k_n(x_n - x_{n-1}) = -m_n\ddot{x}_g + f_n.
\end{aligned} \tag{1}$$

Or in a matrix form, the above equation can be expressed as follows:

$$\mathbf{M}_s\ddot{\mathbf{x}} + \mathbf{C}_s\dot{\mathbf{x}} + \mathbf{K}_s\mathbf{x} = -\mathbf{M}_s\mathbf{\Lambda}\ddot{x}_g + \mathbf{\Gamma}\mathbf{f}, \tag{2}$$

where $\mathbf{M}_s$ is a mass matrix, kg; $\mathbf{x}$ is a vector of floors' displacements; $\mathbf{C}_s$ is a damping matrix, N·s/m; $\mathbf{K}_s$ is a stiffness matrix, N/m; $\ddot{x}_g$ is a one-dimensional horizontal ground acceleration, m/s^2; $\mathbf{\Gamma}$ is a matrix representing position of control forces; $\mathbf{\Lambda}$ is a vector of ones; and $\mathbf{f}$ is a vector of control forces, N.

2.2. State-Space Representation. The dynamic system considered in this study is described by ordinary differential equations in which time is the independent variable. By use

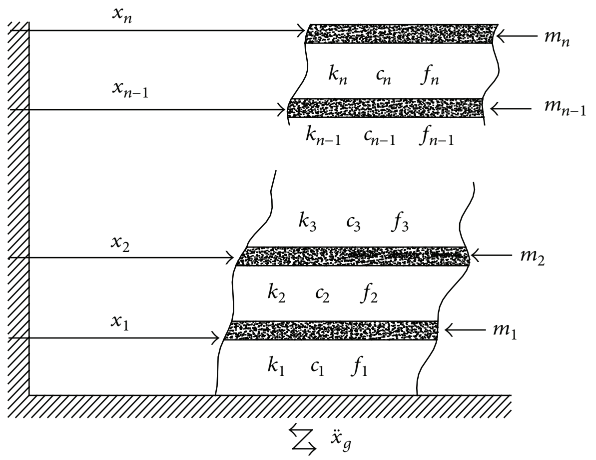

FIGURE 2: Lumped mass model of a multistory building with n floors under acceleration ground input: $x_1, x_2, \ldots$, and x_n indicate floors' displacements; $k_1, k_2, \ldots$, and k_n indicate floors' stiffness coefficients; $c_1, c_2, \ldots$, and c_n indicate floors' damping coefficients; $f_1, f_2, \ldots$, and f_n indicate distributed control forces; $m_1, m_2, \ldots$, and m_n indicate floors' lumped masses; $\ddot{x}_g$ indicates one-dimensional ground acceleration.

of vector-matrix notation, an n order differential equation may be expressed by a first-order vector-matrix differential equation as follows [27]:

$$\dot{\mathbf{z}} = \mathbf{A}\mathbf{z} + \mathbf{B}\mathbf{f} + \mathbf{E}\ddot{\mathbf{x}}_g, \tag{3}$$

$$\mathbf{yy} = \mathbf{C}\mathbf{z} + \mathbf{D}\mathbf{f}, \tag{4}$$

$$\mathbf{A} = \begin{bmatrix} \mathbf{0}_{n\times n} & \mathbf{I}_{n\times n} \\ -\mathbf{M}_s^{-1}\mathbf{K}_s & -\mathbf{M}_s^{-1}\mathbf{C}_s \end{bmatrix}, \qquad \mathbf{B} = \begin{bmatrix} \mathbf{0}_{1\times n} \\ \mathbf{M}_s^{-1}\mathbf{\Gamma} \end{bmatrix},$$

$$\mathbf{C} = \begin{bmatrix} \mathbf{M}_s^{-1}K_s & \mathbf{M}_s^{-1}\mathbf{C}_s \\ \mathbf{I}_{n\times n} & \mathbf{0}_{n\times n} \\ \mathbf{0}_{n\times n} & \mathbf{I}_{n\times n} \end{bmatrix}, \qquad \mathbf{D} = \begin{bmatrix} \mathbf{M}_s^{-1}\Gamma \\ \mathbf{0}_{2n\times n} \end{bmatrix}, \tag{5}$$

$$\mathbf{E} = -\begin{bmatrix} \mathbf{0}_{1\times n} \\ \mathbf{\Lambda} \end{bmatrix},$$

where $\mathbf{z}$ is the state vector; $\mathbf{A}$, $\mathbf{B}$, $\mathbf{C}$, $\mathbf{D}$, and $\mathbf{E}$ are state space matrices; $\mathbf{f} = [f_1, f_2, f_3, \ldots, f_n]^T$ is a vector of measured control forces; $\mathbf{yy}$ is the measured output; and n is the number of degrees of freedom (number of stories).

3. Semiactive Control Algorithms

In the current study, the following controllers are used with an application example.

3.1. Controller Based on Lyapunov Stability Theory. Leitmann [28] applied Lyapunov's direct approach for the design of a semi-active controller. In this approach, a Lyapunov function is chosen of the form

$$\mathbf{U}(z) = \frac{1}{2}\|\mathbf{z}\|_P \mathbf{P}^2, \tag{6}$$

where $\|\mathbf{z}\|_P$ is the P-norm of the states defined by

$$\|\mathbf{z}\|_P = \left[\mathbf{z}^T\mathbf{P}\mathbf{z}\right]^{0.5} \tag{7}$$

and $\mathbf{P}$ is a real, symmetric, and positive definite matrix. In the case of a linear system, to ensure $\dot{\mathbf{U}}(z)$ is negative definite, the matrix $\mathbf{P}$ is found using the Lyapunov equation

$$\mathbf{A}^T\mathbf{P} + \mathbf{P}\mathbf{A} = -\mathbf{Q}_P. \tag{8}$$

For a positive definite matrix, $\mathbf{Q}_P$, the derivative of the Lyapunov function for a solution of (3) is

$$\dot{\mathbf{U}} = -\frac{1}{2}\mathbf{z}^T\mathbf{Q}_P\mathbf{z} + \mathbf{z}^T\mathbf{P}\mathbf{B}\mathbf{f} + \mathbf{z}^T\mathbf{P}\mathbf{E}\ddot{x}_g. \tag{9}$$

Thus, the control law which will minimize $\dot{\mathbf{U}}$ is

$$V_i = V_{\max} H\left(\left(-\mathbf{z}^T\right)\mathbf{P}B_i f_i\right), \tag{10}$$

where $V_{\max}$ is the maximum allowable input voltage to the current driver of the MR damper, $H(\cdot)$ is the Heaviside step function, f_i is the measured force produced by the ith MR damper, and B_i is the ith column of the $\mathbf{B}$ matrix in (3). Note that this algorithm is classified as a bang-bang controller and is dependent on the sign of the measured control force and the states of the system. However, one challenge in the use of the Lyapunov algorithm is in the selection of an appropriate $\mathbf{Q}_P$ matrix.

3.2. Decentralized Bang-Bang Controller. McClamroch and Gavin [29] used an approach similar to Lyapunov control algorithm to develop a decentralized bang-bang control law. In this approach, the Lyapunov function was chosen to represent the total vibratory energy in the structure (kinetic plus potential energy), as in

$$\mathbf{U} = \frac{1}{2}\mathbf{x}^T\mathbf{K}_s\mathbf{x} + \frac{1}{2}\left(\dot{\mathbf{x}} + \Lambda\dot{x}_g\right)^T\mathbf{M}_s\left(\dot{\mathbf{x}} + \Lambda\dot{x}_g\right). \tag{11}$$

Using a similar approach to that in Lyapunov design, the resulting control law that will minimize $\mathbf{U}$ is

$$V_i = V_{\max} H\left(-\left(\dot{\mathbf{x}} + \Lambda\dot{x}_g\right)^T\mathbf{\Gamma}_i\ f_i\right). \tag{12}$$

The pseudovelocity $\dot{x}_g$ is obtained by integrating the absolute acceleration [21] using the following transfer function:

$$H(s) = \frac{39.5s}{39.5s^2 + 8.89s + 1}. \tag{13}$$

3.3. Clipped-Optimal Controller. One algorithm that has been shown to be effective with the MR damper is the clipped-optimal control approach proposed by Dyke et al. [30, 31]. The clipped-optimal control approach requires the design of a linear optimal controller $\mathbf{K}_c(s)$ that calculates a vector of desired control forces, $\mathbf{f}_c = [f_{c1}, f_{c2}, \ldots, f_{cn}]^T$, based on the measured structural responses $\mathbf{yy}$ and the measured control forces vector $\mathbf{f}$ applied to the structure:

$$\mathbf{f}_c = L^{-1}\left\{-\mathbf{K}_c(s)\,L\left\{\begin{Bmatrix}\mathbf{yy}\\ \mathbf{f}\end{Bmatrix}\right\}\right\}, \tag{14}$$

where $L\{\cdot\}$ is the Laplace transform. The control law is expressed as follows:

$$V_i = V_{\max} H\left(\left(f_{ci} - f_i\right) f_i\right). \quad (15)$$

3.4. Modulated Homogeneous Friction Controller. The modulated homogenous friction control algorithm was originally developed for use with variable friction devices and was modified for MR dampers by Jansen and Dyke [25]. The control law is presented as follows:

$$V_i = V_{\max} H\left(f_{ni} - \left|f_i\right|\right), \quad (16)$$

where $f_{ni} = g_{ni}|\Delta_i(t-s)|$, $s = \{\min x \geq 0 : \Delta_i(t-x) = 0\}$ and $\Delta_i(t-s)$ is the most recent local extrema in the deformation of the ith device. The proportionality constant g_{ni} has units of stiffness (i.e., N/m), and its optimal value is dependent on the amplitude of the ground excitation.

3.5. Maximum Energy Dissipation Controller. This algorithm considers a Lyapunov function that represents the relative vibratory energy in the structure (i.e., without including the velocity of the ground in the kinetic energy term) [25]. The control law for this algorithm is as follows:

$$V_i = V_{\max} H\left(-\dot{x}^T \Lambda_i f_i\right). \quad (17)$$

3.6. Quasi-Bang-Bang Controller. The quasi-bang-bang control algorithm for the application of the MR dampers uses two distinct control laws depending on whether the building is moving towards or away from its static equilibrium or rest position [32]. The control algorithm is written as follows:

$$V_i = \begin{cases} V_{\max}, & (\text{if moving away from center}), \\ 0, & (\text{if moving towards center}). \end{cases} \quad (18)$$

3.7. Proposed Controller. This is a new control algorithm proposed in the current study. The approach is inspired by the quasi-bang-bang controller; however, the proposed method gives weights to the output in a way that is similar to a fuzzy logic controller (see [26]). In addition to commanding the current driver of the MR damper with the values V_0 (minimum voltage) and $V_{\max}$ (maximum voltage), the proposed controller makes use of the values in between. The control algorithm is expressed as follows:

$$V_i = \begin{cases} \alpha_c V_{\max}, & (\text{If } \operatorname{sign}(x) = 1, \operatorname{sign}(\dot{x}) = 1), \\ \beta_c V_{\max}, & (\text{If } \operatorname{sign}(x) = -1, \operatorname{sign}(\dot{x}) = -1), \\ \gamma_c V_{\max}, & (\text{If } \operatorname{sign}(x) = 1, \operatorname{sign}(\dot{x}) = -1), \\ V_{\max}, & (\text{Otherwise}), \end{cases} \quad (19)$$

where the values of α_c, β_c, and γ_c are between 0 and 1.

4. An Application Example

To show the applicability of the proposed controller, a three-story building model with a single MR damper is considered.

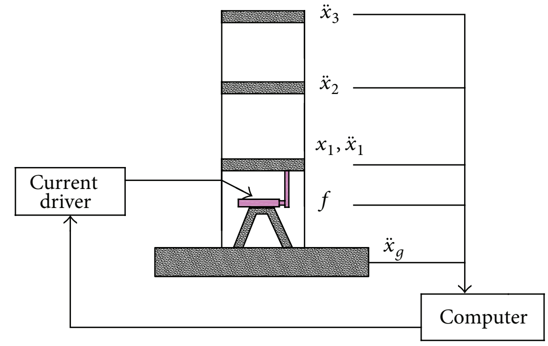

FIGURE 3: Schematic representation of an MR damper implemented in a three-story building.

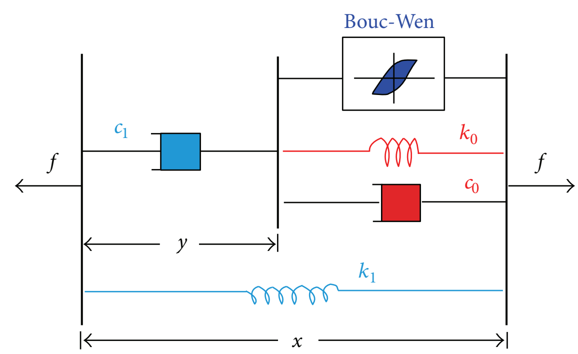

FIGURE 4: Mechanical model of the MR damper.

The MR damper is rigidly connected between ground and first floor of the building model. Figure 3 shows a schematic diagram of the building with the MR damper. The mechanical model of the MR damper presented in Dyke et al. [12] is used in the current study (see Figure 4). The force predicted by the model is given by

$$\begin{aligned} f &= \alpha z + c_0(\dot{x} - \dot{y}) + k_0(x - y) + k_1(x - x_0), \\ \dot{z} &= -\gamma|\dot{x} - \dot{y}|z|z|^{n-1} - \beta(\dot{x} - \dot{y})|z|^n + A(\dot{x} - \dot{y}), \\ \dot{y} &= \frac{1}{(c_0 + c_1)}\left[\alpha z + c_0\dot{x} + k_0(x - y)\right]. \end{aligned} \quad (20)$$

The parameters, c_0, and c_1 depend on the input control voltage, V, to the current driver of the MR damper as follows:

$$\begin{aligned} \alpha &= \alpha_a + \alpha_a u, \\ c_1 &= c_{1a} + c_{1b} u, \\ c_0 &= c_{0a} + c_{0b} u, \\ \dot{u} &= -\eta(u - V). \end{aligned} \quad (21)$$

The numeric values of the constants in (20) and (21) are given in Dyke et al.'s [12]. Figure 5 shows simulated damper's force under a harmonic displacement input (sine wave with an amplitude of 0.015 m and a frequency of 2.5 Hz). These numerically simulated force versus displacement and force

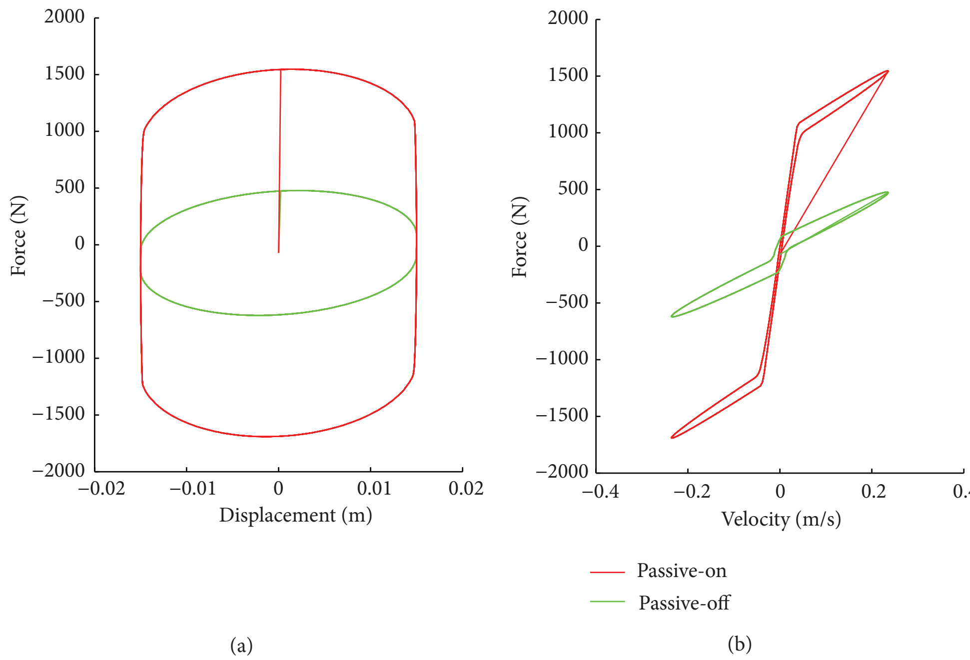

Figure 5: Simulated damper's force for a harmonic displacement input (sine wave with an amplitude of 0.015 m and a frequency of 2.5 Hz): (a) force versus displacement and (b) force versus velocity.

versus velocity characteristics are similar to those obtained experimentally in Dyke et al.'s [12].

The building model used in this example is a simple model of the scaled three-story test structure, described in Dyke et al.'s [3, 33], which has been used in previous studies at the Structural Dynamics and Control/Earthquake Engineering Laboratory (SDC/EEL) at the University of Notre Dame. The parameters of the building model are given as follows:

$$\mathbf{M}_s = \begin{bmatrix} 98.3 & 0 & 0 \\ 0 & 98.3 & 0 \\ 0 & 0 & 98.3 \end{bmatrix}, \text{kg},$$
$$\mathbf{C}_s = \begin{bmatrix} 175 & -50 & 0 \\ -50 & 100 & -50 \\ 0 & -50 & 50 \end{bmatrix}, \text{N} \cdot \text{s/m}, \quad (22)$$
$$\mathbf{K}_s = 10^5 \times \begin{bmatrix} 12.0 & -6.84 & 0 \\ -6.84 & 13.7 & -6.84 \\ 0 & -6.84 & 6.84 \end{bmatrix}, \text{N/m}.$$

The input ground acceleration used in the current study is the one-dimensional component of the 1940 El Centro earthquake [34]. Since the dynamic system under consideration is a scaled model, the earthquake is produced at five times the recorded rate. Time history and power spectrum of the input ground acceleration are shown in Figure 6.

Dyke et al.'s [12] obtained the responses of this model for the uncontrolled, passive-off, passive-on, and clipped-optimal control cases. The purpose of this application example is to permit a comparison among the results of the methodology proposed in the current study and those published in the literature.

Table 1 lists the peak responses of the building model, when subjected to the north-south component of the 1940 EL Centro earthquake signals. In the table, uncontrolled case means that the MR damper was not implemented in the building model. Passive-off and passive-on mean that the input voltage to the current driver of the MR damper is set to zero and to the maximum value ($V_{\max} = 2.25$ volt), respectively. It is shown that the MR damper with both passive-off and passive-on control cases is capable of reducing the structural responses over the uncontrolled case. The passive-on case is better than the passive-off case in reducing the maximum displacements. However, the passive-off case is better than the passive-on case in reducing the maximum absolute accelerations. The results of the uncontrolled, the passive-off, and the passive-on cases are similar to those presented in [12].

Two controllers (A and B) are designed based on Lyapunov stability method. For controller A, the matrix $\mathbf{Q}$ was selected as $\mathbf{Q}$ = [ones(1,6); zeros(5,6)] while for controller B, $\mathbf{Q}$ = [zeros(3,6); eye(3) zeros(3,3)],

$$\text{where eye}(3) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}. \quad (23)$$

A time history of the input control voltage, V, to the current driver for all the controllers is shown in Figure 7. The passive-on controller gives a constant control input of 2.25 volt ($V_{\max}$) to the current driver of the MR damper. Except for the proposed controller all the controllers provide an input to the MR damper with values varying from 0 volt to 2.25 volt over the time. However, the proposed controller is giving input control voltage to the current driver of the MR damper

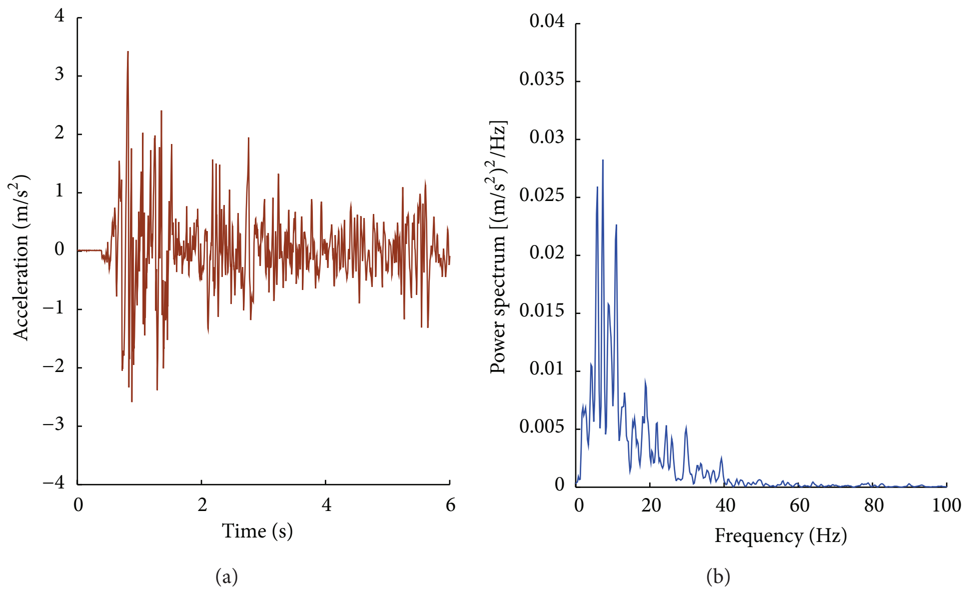

FIGURE 6: Time history (a) and power spectrum (b) of the input ground acceleration.

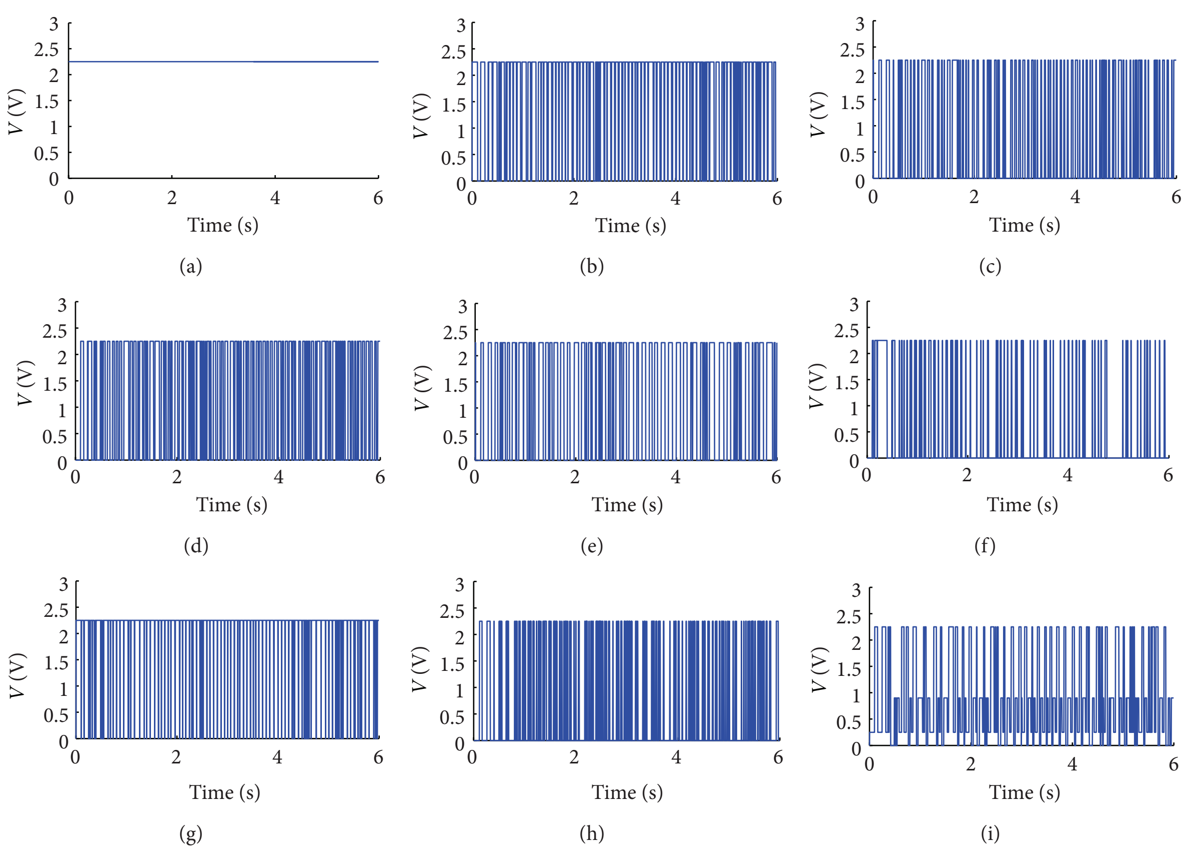

FIGURE 7: Input control voltage to the current driver of the MR damper: (a) passive on, (b) Lyapunov controller (A), (c) Lyapunov controller (B), (d) quasi-bang-bang controller, (e) decentralized bang-bang controller, (f) modulated homogenous friction controller, (g) maximum energy dissipation controller, (h) clipped-optimal controller, and (i) proposed controller.

Table 1: Peak responses of the three-story building model under El Centro earthquake loads.

Control strategy	X_n (m)	D_n (m)	A_n (m/s^2)	f (N)
Uncontrolled	0.0055	0.0055	8.720	—
	0.0083	0.0031	10.60	
	0.0097	0.0020	14.02	
Passive-off	0.0021	0.0021	4.216	259.2
	0.0036	0.0016	4.832	
	0.0045	0.0010	7.176	
Passive-on	0.0008	0.0008	2.914	992.8
	0.0020	0.0017	4.976	
	0.0031	0.0011	7.710	
Lyapunov controller (A)	0.0009	0.0009	6.356	1023
	0.0021	0.0017	5.373	
	0.0031	0.0010	7.183	
Lyapunov controller (B)	**0.0013**	0.0013	5.613	993.3
	0.0018	0.0012	7.326	
	0.0023	0.0011	7.709	
Quasi-bang-bang controller	**0.0013**	0.0013	5.015	1002
	0.0016	0.0014	7.230	
	0.0023	0.0010	7.010	
Decentralized bang-bang controller	0.0015	0.0015	**3.776**	923
	0.0025	0.0013	**4.310**	
	0.0032	0.0008	**5.416**	
Modulated homogenous friction controller	0.0019	0.0019	5.330	503
	0.0029	0.0013	5.916	
	0.0038	0.0010	6.790	
Maximum energy dissipation controller	0.0008	0.0008	3.150	993
	0.0020	0.0017	5.023	
	0.0031	0.0011	7.731	
Clipped-optimal controller	0.0014	0.0014	6.000	918
	0.0021	0.0014	4.551	
	0.0026	0.0008	5.553	
Proposed controller	0.0012	**0.0012**	**5.008**	**848.9**
	0.0019	**0.0012**	**4.159**	
	0.0027	**0.0007**	**5.053**	

with values changing from 0 volt, 0.25 volt, and 0.9 volt to 2.25 volt over the time.

The results listed in Table 1 show that, for all the controllers presented, Lyapunov controller B and the quasi-bang-bang controller provide the best reduction in the maximum floor displacement (X_n). Considering the maximum absolute acceleration of the passive-off case as a reference, the Lyapunov controller B increased the response by 7.4% while the quasi-bang-bang controller did not show significant reduction. The decentralized bang-bang controller provides an excellent reduction in the absolute floor accelerations; however, it is not able to reduce the displacements over the passive-on case. The clipped-optimal control algorithm gives a high reduction in both the inter-story drifts and the maximum floor displacements; also, it gives a good reduction in the maximum absolute accelerations. A time domain comparison among all the controllers used is shown in Figure 8. The comparison shows the capability of the proposed controller in reducing the absolute acceleration response over all the controllers presented in the literature. The proposed controller gives the best reduction in both the inter-story drift and the maximum absolute accelerations of the floors. Also, there is a good reduction in the displacement of the top story. For the proposed controller, the numeric values of its parameters are $\alpha_c = 0$, $\beta_c = 0.11$, and $\gamma_c = 0.4$.

5. Discussion

The inherently dissipative nature of the force produced by the MR damper (e.g., [35]) permits a designer to choose among several control methods without any concerns about the stability of the control system. This allows much freedom in the selection of a control technique for MR dampers implemented in real structures. A new controller is inspired

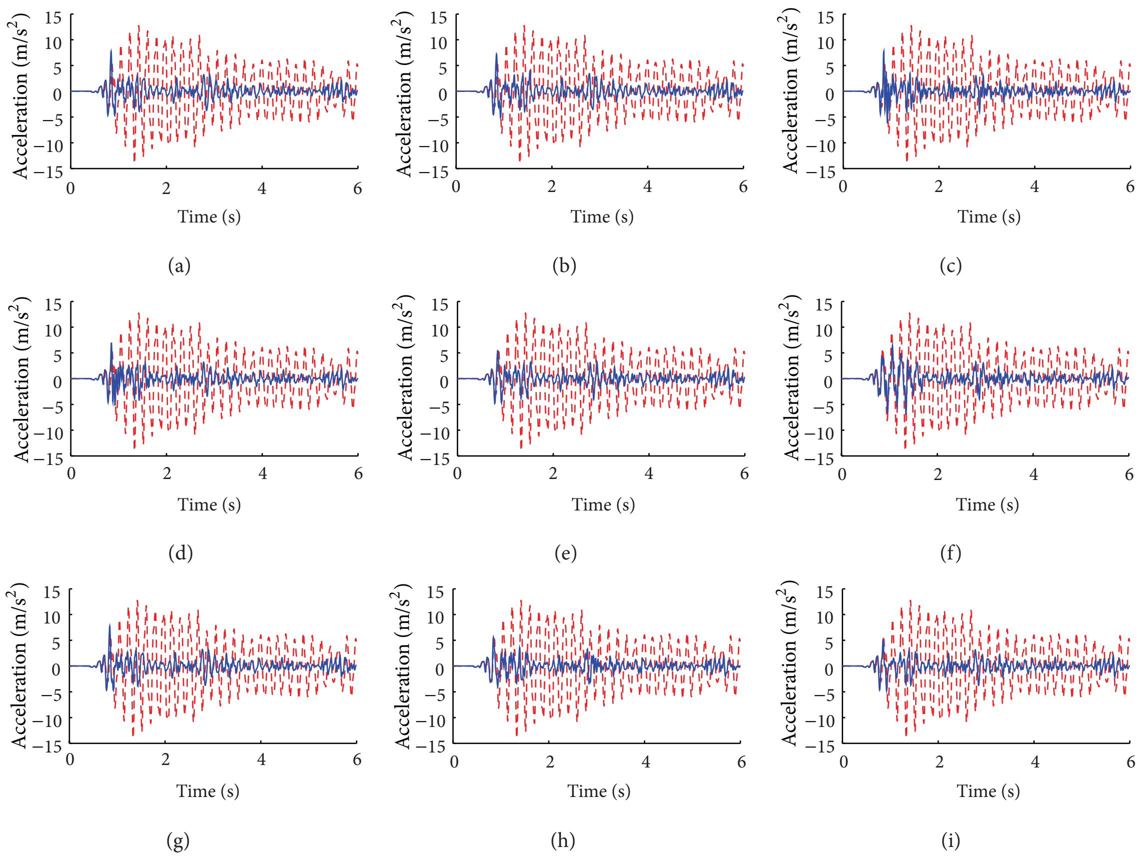

Figure 8: Controlled and uncontrolled (red dashed line) acceleration response of the third floor: (a) passive on, (b) Lyapunov controller (A), (c) Lyapunov controller (B), (d) quasi-bang-bang controller, (e) decentralized bang-bang controller, (f) modulated homogenous friction controller, (g) maximum energy dissipation controller, (h) clipped-optimal controller, and (i) proposed controller.

by the quasi-bang-bang controller; however, the proposed approach gives weights to the output in a fashion similar to a fuzzy logic controller. For the application example used in the current study, the proposed controller reduced the third floor absolute acceleration by 29.6% over the passive-off case (the passive-off case was better in reducing the accelerations than the passive-on case). The decentralized bang-bang controller reduced the third floor absolute acceleration by 24.5% over the passive-off case. However, the proposed controller achieved better reduction in both floor displacements and inter-story drifts over the decentralized bang-bang controller. The Lyapunov controller and the quasi-bang-bang controller provided the best reduction in the floor displacements (25.8% reduction in the top floor displacement over the passive-on case). Both controllers did not show significant reduction in the maximum absolute acceleration over the passive-off case. Among all the controllers presented in the current study, the results show that the new controller may provide the best protection to the building and its contents under seismic loads by offering the best reduction in the inter-story drifts and absolute accelerations, respectively.

The results presented in the current study show that the MR damper is highly controllable and the application of its controllability is fruitful. The controllable nature of the MR damper permits achieving different control objectives (e.g., reducing floor displacements, drifts, and absolute accelerations) by using various control algorithms. The message raised from the use of the proposed controller is that, even when many control algorithms exist in the literature, research towards a better controller is still promising. The door is open for interested researchers to come up with new methodology. Further research on the applicability of the proposed controller to cover several vibration control cases under different excitation inputs (e.g., earthquake, wind and traffic loads) is recommended. Research addressing the dependence (if any) of the parameters α_c, β_c, and γ_c on the physical properties of the primary structure, as well as the type of the excitation input (earthquake or wind), is recommended for future studies.

6. Conclusions

The current study shows that the MR damper is highly controllable in a manner that permits a designer to achieve different control objectives. Among several controllers used with an MR damper implemented in a three-story building model, Lyapunov controller and quasi-bang-bang controller showed their capability in reducing displacement response (25.8% reduction in top floor displacement over the best passive case). At the same time, both controllers did not show significant reduction in the maximum absolute acceleration, over the best passive case. A new controller was inspired by the quasi-bang-bang controller; however, the proposed approach gives weights to the output in a fashion similar to a fuzzy logic controller. The proposed controller reduced the third floor absolute acceleration by 29.6% over the best passive case. The decentralized bang-bang controller reduced the third floor acceleration by 24.5% over the best passive case. Nevertheless, the proposed controller achieved better reduction in both floor displacements and inter-story drifts over the decentralized bang-bang controller. Among several controllers presented in the current study, results show that the new controller provided the highest reduction in both the inter-story drifts and the absolute floor accelerations. This reveals that the proposed controller is promising and may provide the best protection to the building and its contents. Further research on the application of the proposed controller to cover several vibration control cases under different excitation inputs is recommended.

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