

Modified Bang-Bang Control of Seismically Exited Structures Using MR Dampers

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Abstract

Magnetorheological (MR) dampers are a new class of devices that mesh well with the requirements and constraints of seismic applications, including having very low power requirements. This paper proposes a semi-active control strategy based on optimal bang-bang control principle for controlling MR dampers to reduce structural responses due to seismic loads. A numerical example, employing shear-mode MR dampers which located on the first and second floor of the model structure, is presented to illustrate the effectiveness of the approach.

1. Introduction

The first full-scale application of active control to a building was accomplished by the Kajima Corporation in 1989(Kobri 1994). Although nearly a decade has passed since construction of the Kobashi Seiwa building, a number of serious challenges remain to be resolved before feedback control technology can gain general acceptance by the engineering and construction professions at large. These challenges include: (i) reduction of capital cost and maintenance, (ii) eliminating reliance on external power, (iii) increasing system reliability and robustness, and (iv) gaining acceptance of nontraditional technology by the profession. Semi-active control strategies appear to be particularly promising in addressing a number of these challenges(Spencer 1996).

One challenge in the use of semi-active technology is in developing nonlinear control algorithms that are appropriate for implementation in full scale structures. A number of control algorithms have been adopted for semi-active systems. In one of the first examinations of semi-active control, Karnopp et al. (1974) proposed a "skyhook" damper control algorithm for a vehicle suspension system and demonstrated that this system offers improved performance over a passive system when applied to a single-degree-of-freedom system. Feng and Shinozukah (1990) developed a bang-bang controller for a hybrid controller on a bridge. More recently a control strategy based on Lyapunov stability theory has been proposed for ER dampers (Brogan, 1991; Leitmann, 1994). The goal of this algorithm is to reduce the responses by minimizing the rate of change of a

Lyapunov function. McClamroch and Gavin (1995) used a similar approach to develop a decentralized bang-bang controller. This control algorithm acts to minimize the total energy in the structure. A modulated homogeneous friction algorithm (Inaudi, 1997) was developed for a variable friction device. Clipped-optimal controllers have also been proposed and implemented for semi-active systems (Sack and Patten, 1994; Dyke, 1996). The purpose of this study is to develop an effective control algorithms for controlling MR dampers to reduce structural responses due to seismic loads.

2. Shear-Mode MR Damper

A prototype shear mode MR damper was obtained from the Lord Corporation for experimental testing (Yi et al., 1998, 1999; Dyke, et al. 1999). A schematic diagram of the prototype device is shown in Fig. 1. The simple mechanical model shown in Fig. 2 was developed and shown to accurately predict the behavior of a shear-mode MR damper over a wide range of inputs (Yi, et al., 1998, 1999; Dyke et al, 1999). The equations governing the force f predicted by this model are

$$f = c_0 \dot{x} + \alpha z \quad (1)$$

$$\dot{z} = -\gamma |\dot{x}| z |z|^{n-1} - \beta \dot{x} |z|^n + A \dot{x} \quad (2)$$

where z is an evolutionary variable that accounts for the history dependence of the response. The model parameters depend on the voltage v to the current driver as follows

$$\alpha = \alpha_a + \alpha_b u \quad \text{and} \quad c_0 = c_{0a} + c_{0b} u \quad (3)$$

where u is given as the output of the first-order filter

$$\dot{u} = -\eta(u - v) \quad (4)$$

Eq. (4) is used to model the dynamics involved in reaching rheological equilibrium and in driving the electromagnet in the MR damper (Yi et al, 1998, 1999; Dyke et al., 1999).

3. Control Algorithms

3.1 Clipped Optimal Control

One algorithm that has been shown to be effective for use with the MR damper is a clipped-optimal control approach, proposed by Dyke, et al. (1996). The clipped-optimal control approach is to design a linear optimal controller $K_c(s)$ that calculates a vector of desired control forces $f_c = [f_{c1}, f_{c2}, \dots, f_{cn}]^T$ based on the measured structural responses y and the measured control force vector f applied to the structure, i.e.,

$$f_c = L^{-1} \left\{ -K_c(s) L \left\{ \begin{matrix} y \\ f \end{matrix} \right\} \right\} \quad (5)$$

where $L\{\cdot\}$ is the Laplace transform.

To induce the MR damper to generate approximately the corresponding desired optimal control force f_{ci} , the command signal v_i is selected as follows. When the i_{th} MR damper is providing the desired optimal force (i.e., $f_i = f_{ci}$), the voltage applied to the damper should remain at the present level. If the magnitude of the force produced by the damper is smaller than the magnitude of the desired optimal force and the two forces have the same sign, the voltage applied to the current driver is increased to the maximum level so as to increase the force produced by the damper to match the desired control force. Otherwise, the commanded voltage is set to zero. The algorithm for selecting the command signal can be concisely stated as

$$v_i = V_{\max} H(\{f_{ci} - f_i\} f_i) \quad (6)$$

3.2 Modified Bang-Bang Control

A suboptimal bang-bang control law can be derived by minimizing the time derivative of a Lyapunov function of the system. First define a quadratic function of the state variables as (Wu et al. 1996)

$$V(z) = z^T S z \quad (7)$$

where matrix S is solution of the Lyapunov matrix equation

$$A^T S + S A = -Q \quad (8)$$

Since open-loop system matrix A is stable and the weighting matrix Q can be selected to be a symmetric and positive semidefinite matrix, then solution matrix S is also symmetric and positive. Thus, the function $V(z)$ is a Lyapunov function of the open-loop system. The time derivative of the Lyapunov function is

$$\dot{V}(z) = \dot{z}^T S z + z^T S \dot{z} \quad (9)$$

Substituting the closed-loop state equation into Eq (9), one obtains

$$\dot{V}(z) = -z^T Q z + 2u B^T S z \quad (10)$$

It is clear that, if the control force takes the form

$$u(t) = -u_{\max} \cdot \text{sgn}[B^T S z(t)] \quad (11)$$

$\dot{V}(z)$ will be minimum. The control law given by Eq (11) is called as suboptimal bang-bang control, which avoids on-line evaluation of the differential equations.

Although rheological equilibrium of MR damper can be achieved in a few milliseconds, some modifications are necessary for practical application such as full-scale 20-ton MR fluid damper. Cai et al (2000) modify the controller as follows. Sign function, $\text{sgn}(x)$, can be expressed approximately as the following continuous and smooth exponential function:

$$\text{sgn}(x) \approx \frac{1 - e^{-\alpha x}}{1 + e^{-\alpha x}} \quad (12)$$

where α is a positive constant. The bigger the α is, the less is the error in Equation (12). Thus, the controller given by Equation (11) can be written as follows:

$$u(t) = -u_{\max} \cdot \frac{1 - e^{-\alpha B^T S t}}{1 + e^{-\alpha B^T S t}} \quad (13)$$

4. Numerical Example

To evaluate control algorithms for MR damper, a numerical example is considered in which a model of a six-story building is controlled with four MR dampers. Two devices are rigidly connected between the ground and the first floor, and two devices are rigidly connected between the first and second floors, as shown in Fig. 3. Each MR damper is capable of producing a force equal to 1.8% the weight of the entire structure, and the maximum voltage input to the MR devices is V_{\max} is 5V. The governing equations can be written by defining the mass of each floor, m_i , as $0.227N/(cm/sec^2)$, the stiffness of each floor, k_i , as $297N/cm$, and a damping ratio for each mode of 0.5%. This system is a simple representation of the scaled, six-story. (Jansen and Dyke, 2000)

In this example, the structural measurements available for calculating the control action include the absolute accelerations of the structure and the forces produced by the MR devices (i.e., $y = [\ddot{x}_{a1}, \ddot{x}_{a2}, \ddot{x}_{a3}, \ddot{x}_{a4}, \ddot{x}_{a5}, \ddot{x}_{a6}, f_1, f_2]^T$). Thus, the governing equations can be written in the state-space form by defining

$$\begin{aligned} A &= \begin{bmatrix} 0 & I \\ -M_s^{-1}K_s & -M_s^{-1}C_s \end{bmatrix}, & B &= \begin{bmatrix} 0 \\ M_s^{-1}A \end{bmatrix}, & E &= \begin{bmatrix} 0 \\ \Gamma \end{bmatrix} \\ C &= \begin{bmatrix} -M_s^{-1}K_s & -M_s^{-1}C_s \end{bmatrix}, & D &= \begin{bmatrix} -M_s^{-1}A \end{bmatrix} \end{aligned} \quad (14)$$

The MR damper parameters used in this study are $c_{0a} = 0.0064 \text{ Nsec/cm}$, $c_{0b} = 0.0052 \text{ Nsec/cmV}$, $\alpha_a = 8.66N/cm$, $\alpha_b = 8.86N/cmV$, $\gamma = 300cm^2$, $\beta = 300cm^2$, $A = 120$ and $n = 2$. These parameters were selected based on the identified model of the shear-mode prototype MR damper tested at Washington University (Yi, et al., 1999).

In simulation, the model of the structure is subjected to the NS component of the 1940 El Centro earthquake. Because the building system considered is a scaled model, the amplitude of the earthquake was scaled to ten percent of the full-scale earthquake to represent the magnitude of displacements that would be observed in laboratory experiments with this structure.

The first evaluation criterion is a measure of the normalized maximum floor displacement relative to the ground, given as

$$J_1 = \max_{i,j} \left(\frac{|x_i(t)|}{x_{\max}} \right) \quad (15)$$

where $x_i(t)$ is the relative displacement of the i_{th} floor over the entire response, and x_{\max} denotes the uncontrolled maximum displacement. The second evaluation criterion is a

measure of the reduction in the interstory drift. The maximum of the normalized interstory drift is

$$J_2 = \max_{i,j} \left(\frac{|d_i(t)/h_i|}{d_n^{\max}} \right) \quad (16)$$

where h_i is the height of each floor (30cm), $d_i(t)$ is the interstory drift of the above ground floors over the response history, and d_n^{\max} denotes the normalized peak interstory drift in the uncontrolled response. The third evaluation criterion is a measure of the normalized peak floor accelerations, given by

$$J_3 = \max_{i,j} \left(\frac{|\ddot{x}_{ai}(t)|}{\ddot{x}_a^{\max}} \right) \quad (17)$$

where the absolute accelerations of the i_{th} floor, $\ddot{x}_{ai}(t)$ are normalized by the peak uncontrolled floor acceleration, denoted $\ddot{x}_a^{\max}(t)$.

The final evaluation criteria considered in this study is a measure of the maximum control force per device, normalized by the weight of the structure, given by

$$J_4 = \max_{i,j} \left(\frac{|f_i(t)|}{W} \right) \quad (18)$$

where W is the total weight of the structure (1335N).

The corresponding uncontrolled responses are as follows: $x_{\max} = 1.313\text{cm}$, $d_n^{\max} = 0.00981\text{cm}$, $\ddot{s}_a^{\max} = 146.95\text{cm/sec}^2$. The resulting evaluation criteria are presented in Table 1 for the control algorithms considered.

To compare the performance of the semi-active system to that of comparable passive systems, two cases are considered in which the MR dampers are used in a passive mode by maintaining a constant voltage to the devices. The results of both a passive-off (0V) and passive-on (5V) configuration are included. The passive-off system reduces the maximum floor displacement, maximum interstory displacement, and maximum absolute acceleration by 14%, 20%, and 10%, respectively, over the uncontrolled case. The passive-on system is able to further reduce the maximum floor displacement and maximum interstory displacement. However, notice that the passive-on system results in a larger acceleration than the passive-off system.

5. Concluding Remarks

The work presented in this paper focuses on the development of implementable control strategies that can provide improved peak-response control performance using MR damper. Based on an evaluation of advantages and disadvantages of the traditional clipped optimal control and bang-bang control, a modified bang-bang control algorithm has been proposed. The simulation results presented in this paper show that the new control strategy can be more effective than clipped optimal control in some cases.

Moreover, one challenge of selection of an appropriate Q_p matrix in the use of the Lyapunov algorithm is resolved.

References

- Brogan, W.L. (1991). *Modern Control Theory*, Prentice Hall, Englewood Cliffs, New Jersey.
- Cai G.P., Huang, J.Z., Sun F. and Wang C. (2000). "Modified Sliding-Mode Bang-Bang Control for Seismically Excited Linear Structures," *Earth. Eng. And Struct. Dynt*, 29, pp. 1647-1657.
- Dyke, S.J., Spencer Jr., B.F., Sain, M.K. and Calson, J.D., (1996), "Modeling and Control of Magnetorheological Dampers for Seismic Response Reduction," *Smart Mat. And Struct.*, Vol. 5, pp. 565-575.
- Dyke, S.J. Yi, F. and Carlson, J.D. (1999). "Application of Magnetorheological Dampers to Seismically Excited Structures," *Proc. of the Intl. Modal Anal. Conf.*, Kissimmee, Florida, February 8-11.
- Feng, Q., and Shinozuka, M. (1990). "Use of a variable Damper for Hybrid Control of Bridge Response Under Earthquake," *Proc., U.S. Nat. Workshop on Struct. Control Res.*, USC Publ. No. CE-9013.
- Inaudi, J.A. (1997). "Modulated Homogeneous Friction: A Semi-active Damping Strategy," *Earthquake Engineering and Structural Dynamics*, Vol. 26, No. 3, pp. 361.
- Sack, R.L. and Patten, W. (1994). "Semi-active Hydraulic Structural Control." *Proc. of the Int. Workshop on Structural Control*, USC Publication Number CE-9311, pp. 417-431.
- Karnopp, D.C., Crosby, M.J., and Harwood, R.A. (1974). "Vibration Control Using Semi-Active Force Generators," *ASME Journal of Engineering for Industry*, Vol. 96, No. 2, May.
- Kobori, T. (1994), "Future Direction on Research and Development of Seismic-Response-Controlled Structure," *Proc. 1st World Conf. On Struct. Control*, LA, California,,Panel:19-31.
- Jansen, L.M and S.J. Dyke, (2000). "Semiactive Comparative Strategies for MR dampers: Comparative Study," *J. of Engineering Mech.*, Vol. 126, No8, pp. 795-803.
- Leitmann, G (1994). "Semi-active Control for Vibration Attenuation," *J. of Intelligent Material Systems and Structures*, Vol. 5 September, pp. 841-846.
- McClamroch, N.H. and Gavin, H.P. (1995). "Closed Loop Structural Control Using Electrorheological Dampers," *Proc. of the Amer. Ctrl. Conf.*, Seattle, Washington, pp. 4173-77.
- Spencer Jr., B.F. (1996), "Recent Trends in Vibration Control in the U.S.A.," *Proc. 3rd Int. Conf. On Motion and Vibr. Control*, Chiba, Japan.,Vol. II, pp. K1-K6.
- Yi, F., Dyke, S.J., Frech, S. and Carlson, J.D. (1998). "Investigation of Magnetorheological Dampers for Earthquake Hazard Mitigation" *Proc. of the 2nd Intl. Conf. on Struc. Control*, Kyoto, JAPAN, June 30-July 2, pp. 349-358.
- Yi, F., Dyke, S.J., Caicedo, J.M., and Carlson, J.D. (1999). "Seismic Response Control Using Smart Dampers," *Proceedings of the 1999 American Control Conference*, San Diego, California, June 23-25, pp. 1022-26.
- Wu, Z. and Soong, T. T (1996). "Modified Bang-Bang Control Law for Structural Control Implementation," *J. of Eng. Mech.*, 122(8), pp. 771-777.

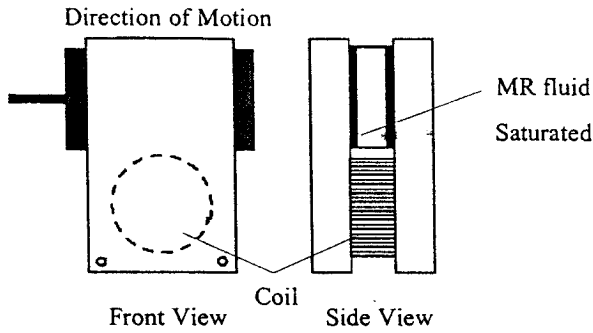


Figure 1. Schematic Diagram of Shear-Mode MR Damper

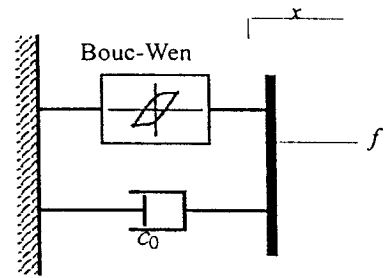


Figure 2. Simple Mechanical Model of the Parallel-Plate MR Damper

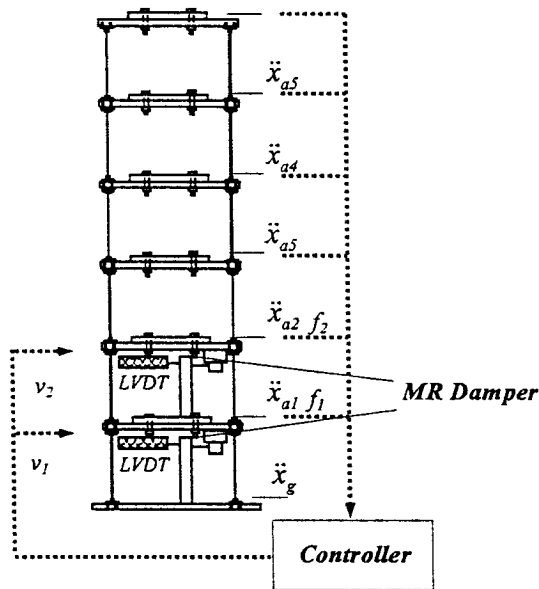


Figure 3. Diagram of MR Damper Implementation

Table 1: Normalized Controlled Maximum Responses due to El-Centro Earthquake.

Control Strategy	J_1	J_2	J_3	J_4
Passive-Off	0.862	0.801	0.904	0.00292
Passive-On	0.506	0.696	1.41	0.0178
Clipped Optimal	0.405	0.547	1.25	0.0178
Clipped Bang-Bang	0.376	0.553	1.43	0.0178