지진하중을 받는 구조물의 수정된 분산뱅뱅 제어기법을 이용한 MR Damper 제어

Modified Decentralized Bang-Bang Control Seismically Excited Structures Using MR Dampers

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국문요약

Magnetorheological(MR) 댐퍼는 적은 용량의 전력을 사용하고 반응속도가 빠른 장점 때문에 구조물의 내진제어에 적당하여, 근래에 주목받고 있는 새로운 장치이다. MR 댐퍼는 반능동 제어장치로써, 능동 질량감쇠기와는 다른 특성을 갖는다. 즉 필요한 제어력을 제어신호로 직접 생성해 낼 수 없는 대신에 MR 댐퍼의 입력전원을 제어하여 간접적으로 제어한다. 따라서 MR 댐퍼의 반능동 제어장치로써의 특성을 고려하는 효과적인 제어기법이 요구된다. 그러므로 본 연구에서는 지진에 대한 구조물의 응답을 줄이기 위해서, MR댐퍼를 제어할 수 있는 반능동 제어기법을 Lyapunov 안정성 이론을 바탕으로 제안하고자 한다. 제안방법을 검증하기 위해, 전단형 MR 댐퍼를 1층과 2층에 설치한 수치예제를 수행하였다.

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,

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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

$$f = c_0 \dot{x} + \alpha z \tag{1}$$

$$\dot{z} = -\gamma \, |\dot{x}| z |z|^{n-1} - \beta \, \dot{x} |z|^n + A\dot{x} \tag{2}$$

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

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

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

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

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 $f_c = [f_{c1}, f_{c2}, \cdots f_{cn}]^T$

based on the measured structural responses y and the measured control force vector f applied to the structure, i.e.,

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

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 vi is selected as follows. When the ith 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

$$\mathrm{v}_i = V_{\max} H(\{f_{ci} - f_i\} f_i) \tag{6}$$

3.2 Modified Decentralized Bang-Bang Control

A decentralized 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 (Jansen and Dyke 2000)

$$V(z) = \frac{1}{2} x^T K x + \frac{1}{2}(\dot{x} + \Gamma \dot{x}_g)^T M (\dot{x} + \Gamma \dot{x}_g) \tag{7}$$

The time derivative of the Lyapunov function is

$$\dot{V}(z) = \frac{1}{2} x^T K \dot{x} + (\dot{x} + \Gamma \dot{x}_g)^T (-C\dot{x} - Kx + \Lambda f) \tag{8}$$

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

$$u(t) = -u_{\max} \cdot \mathrm{sgn}[-(\dot{x} + \Gamma \dot{x}_g)^T \Lambda f] \tag{9}$$

$\dot{V}(z)$ will be minimum. The control law given by Eq (9) is called as decentralized bang-bang control. 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, *sgn*(x), can be expressed approximately as the following continuous and smooth exponential function:

$$\mathbf{sgn}(x) \approx \frac{1 - e^{--\alpha x}}{1 + e^{-\alpha x}} \tag{10}$$

where α is a positive constant. The bigger the α is, the less is the error in Equation (10). Thus, the controller given by Equation (9) can be written as follows:

$$u(t) = -u_{\max} \cdot \frac{1-e^{-\alpha x}}{1+e^{-\alpha x}} \tag{11}$$

where $x = -(\dot{x} + \Gamma \dot{x}_g)^T \Lambda f$

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 $0.227 N/(cm/sec^2)$, the stiffness of each floor, k_i, as $297 N/cm$, 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

$$A = \begin{bmatrix} 0 & I \\ -M_s^{-1}K_s & -M_s^{-1}C_s \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ M_s^{-1}\Lambda \end{bmatrix}, \quad E = -\begin{bmatrix} 0 \\ \Gamma \end{bmatrix} \tag{12}$$
$$C = \begin{bmatrix} -M_s^{-1}K_s & -M_s^{-1}C_s \end{bmatrix}, \quad D = \begin{bmatrix} -M_s^{-1}\Lambda \end{bmatrix}$$

The MR damper parameters used in this study are c_{0a}= 0.0064 $Nsec/cm$, c_{0b}= 0.0052 $Nsec/cmV$, α_a= 8.66N/cm, α_b= 8.86N/cmV, γ = 300cm^2, β = 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

$$J_1 = \max_{t,i}\left(\frac{|x_i(t)|}{x^{\max}}\right) \tag{13}$$

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

$$J_2 = \max_{t,i}\left(\frac{|d_i(t)/h_i|}{d_n^{max}}\right) \tag{14}$$

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

$$J_3 = \max_{t,i}\left(\frac{|\ddot{x}_{ai}(t)|}{\ddot{x}_a^{max}}\right) \tag{15}$$

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

$$J_4 = \max_{t,i}\left(\frac{|f_i(t)|}{W}\right) \tag{16}$$

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

The corresponding uncontrolled responses are as follows: x_{max}= 1.313cm, d_n^{max} = 0.00981 cm, $\ddot{s}_a^{max}$ = 146.95cm/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 type control, a modified decentralized bang-bang control 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 any other Lyapunov type controller is resolved. This new control strategy provide α for the conventional decentralized bang-bang control to be improved in the performance.

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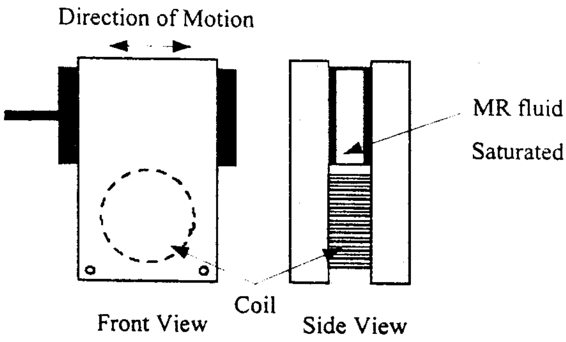

Figure 1. Schematic Diagram of Shear-Mode MR Damper

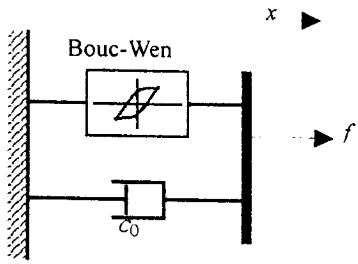

Figure 2. Simple Mechanical Model of the Parallel-Plate MR Damper

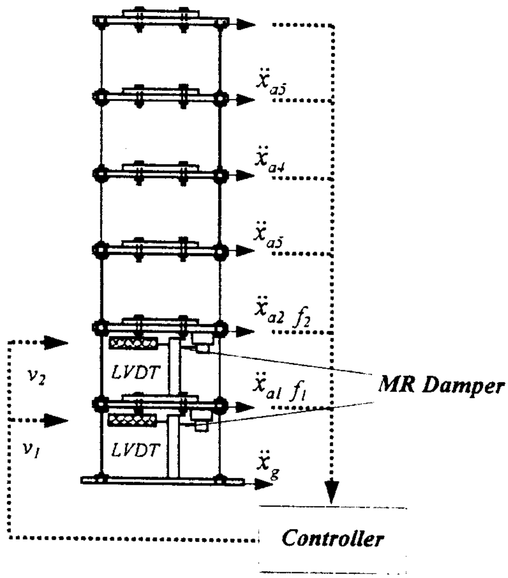

Figure 3. Diagram of MR Damper Implementation

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	0.576	0.673	1.18	0.0119