24th International Symposium on Automation & Robotics in Construction (ISARC 2007)
Construction Automation Group, I.I.T. Madras

SEMI-ACTIVE DIRECT CONTROL OF CIVIL STRUCTURE SEISMIC RESPONSES USING MAGNETO-RHEOLOGICAL DAMPERS

M. T. Nguyen, N. M. Kwok, Q. P. Ha, J. Li and B. Samali
Faculty of Engineering, University of Technology, Sydney
Broadway, NSW 2007, Australia
{minnguye, nmkwok, quangha, lij}@eng.uts.edu.au; Bijan.Samali@uts.edu.au

ABSTRACT

As building structures frequently collapse and cause losses of lives and properties, due to excessive vibrations induced during earthquake periods, it is crucial to reduce the structural vibrations. This paper develops a Lyapunov-based controller for Magnetorheological (MR) dampers embedded in building structures to mitigate quake-induced vibrations. In this work, MR dampers are used as semi-active devices, taking the advantages of the fail-safe operation and low power requirement. To enhance the system performance, a Lyapunov-based controller is proposed here for direct control of the supply currents of the MR dampers placed in a multi-storey building. The effectiveness of the proposed technique is verified in simulation by using a ten-storey building model subject to quake-like excitations.

KEYWORDS

Structural Control, MR Dampers, Semi-Active Control, Lyapunov-Based Control, Seismic Response

1. INTRODUCTION

There has been a large amount of research effort devoted to the development in building and civil infra-structure control. The ultimate objective is the suppression of earthquake induced vibrations or dynamic loading as of wind or heavy traffic [1]. In the review conducted therein, control methodologies applied in buildings are broadly classified into the active [2] and semi-active [3] categories. The former techniques require a certain amount of energy to drive the actuators to accomplish the control objective. On the other hand, semi-active control requires a relatively small amount of driving power and the actuators can also be operated in passive mode. The philosophy adopted in these approaches is to effectively absorb the vibration energy by modifying the control device characteristics. The control devices include fluid viscous, electrorheological (ER) and magnetorheological (MR) dampers. In [4], a comparison was conducted on the efficiency and performance of approaches using semi-active against active tuned mass dampers for building control.

The ER and MR dampers are popular devices in semi-active building control. In essence, they are equivalent in construction to conventional hydraulic dampers except that the characteristics of the fluids can be altered upon the application of currents induced magnetic fields. Although these devices are analogies to each other, the MR damper [5] requires lower voltage which is very attractive for safety and practical reasons. Owing to this advantage, the MR damper is being increasingly employed in vehicle suspension applications [6] where high voltage supplies are not available. In the building control paradigm, the MR damper has also been applied in the passive mode [7] and brace configuration [8].

A recent survey of MR damper controller designs for building control has been published including designs based on Lyapunov stability, decentralised bang-bang, maximum energy dissipation, modulated homogeneous and clipped-optimal control [9] [10].

In the later approach, the value of the desired force is derived by a linear-quadratic-Gaussian (LQG) controller and a secondary current-control loop is used to derive the appropriate current supplied to the MR damper. All these controllers are affected via the damping force instead of directly controlling the current supplied to the MR damper.

In this work, a Lyapunov-based control strategy will be proposed with the objective to minimise an internal energy function by forcing its time rate of change to be as negative as possible, see, e.g. [11] for structural control with ER materials. For building control with MR dampers, unlike [12], where the MR dampers were characterised by a well-known dynamic friction model, here a current-input model describing explicitly the damper force-velocity relationship [13] is used for direct control of the magnetization currents of the dampers, embedded in a general ten-storey building model. To counteract the force-offset problem for a single damper, a differential configuration is also proposed.

The remainder of the paper is organised as follows. In Section 2, the building structure together with the damper configuration is described. The current-inputs state-space model of the system and the design of the proposed Lyapunov-based controller are presented in Section 3. Simulation results are given in Section 4 to verify the effectiveness of the proposed approach. Finally, a conclusion is drawn in Section 5.

2. SYSTEM DESCRIPTION

2.1 Equation of Motion

Consider a building model subject to vibration under the influence of the ground excitation $\ddot{x}_g$ during an earthquake. Let vibrational displacements of the storeys, x_p, $p = 1,...n$, and n is the number of storeys, be assigned the positive polarity from left-to-right. Each storey has respectively mass m_p, viscous damping coefficient c_p and the stiffness coefficient k_p. These variables are lumped into corresponding matrices $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$. The motion of the building structure can be described by

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{\Gamma} f + \mathbf{M\Lambda}\ddot{x}_g , \qquad (1)$$

where $\ddot{\mathbf{x}}$ is the storey acceleration, $\dot{\mathbf{x}}$ is the velocity and f is the overall force generated by the dampers. Matrix $\mathbf{\Gamma} = [-1 \quad 0 \quad ... \quad 0]^T$ is the gain matrix determining the control effect on the building, and $\mathbf{\Lambda} = [1 \quad ... \quad 1]^T$ is a distribution matrix showing the effect of earthquake acceleration. The equation can be further rewritten in the state-space form by defining a system state $\mathbf{y} = \begin{bmatrix}\mathbf{x}^T & \dot{\mathbf{x}}^T\end{bmatrix}^T$ and is given as

$$\dot{\mathbf{y}} = \mathbf{A}_0\mathbf{y} + \mathbf{B}_0 f + \mathbf{E}_0 , \qquad (2)$$

$$\mathbf{E}_0 = \begin{bmatrix}\mathbf{0}\\ \mathbf{\Lambda}\end{bmatrix}\ddot{x}_g ,\ \mathbf{B}_0 = \begin{bmatrix}\mathbf{0}\\ \mathbf{M}^{-1}\mathbf{\Gamma}\end{bmatrix},$$

$$\mathbf{A}_0 = \begin{bmatrix}\mathbf{0} & \mathbf{I}\\ -\mathbf{M}^{-1}\mathbf{K} & -\mathbf{M}^{-1}\mathbf{C}\end{bmatrix},$$

Where $\mathbf{A}_0$ is the system matrix, $\mathbf{B}_0$ is the gain matrix and $\mathbf{E}_0$ is the disturbances.

2.2 MR Damper Model

The MR damper is fabricated similarly to a conventional hydraulic damper, i.e., with a moving piston and hydraulic fluid contained in a cylinder. A drawback of damper is non-linear and hysteretic response between the force-displacement and force-velocity relationships. Various models have been proposed to represent the hysteretic behaviour of the MR damper [14][15]. To simplify the design for direct control of the current supplied to the dampers, a static hysteresis model [13] is used in this paper. Accordingly, the damper force generated by damper j is given by

$$\begin{aligned} f_i &= c_{dj}\dot{x}_{dj} + k_{dj}x_{dj} + \alpha_{dj}z_{dj} + g_j \\ z_{dj} &= \tanh\left(\beta_j\dot{x}_{dj} + \delta_j sign(x_{dj})\right) \end{aligned} , \qquad (3)$$

where the values of damper parameters $c_{dj}, k_{dj}, \alpha_{dj}, g_j, \beta_j$, depend explicitly on the supplied damper current. The relationships between these parameters and the supplied current can be approximated by first- or second-order polynomials.

It is also noticed that due to the need of sufficient travelling strokes to accommodate the frame movement, the dampers have to be connected to the frame in their compressed state. Hence, offset damper forces are produced and may further complicate the controller design. In the sequel, a differential configuration is used to counteract the offset forces as shown in Fig 1.

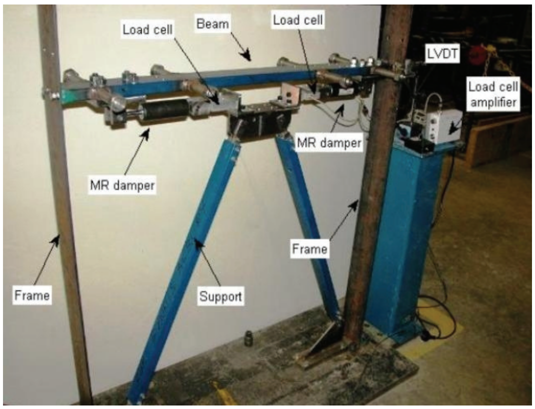


Figure 1 Differential Configuration Implementation of MR Dampers

3. CONTROLLER DESIGN

3.1 State-space Model with Current Input

In the direct control approach proposed in this work, it is assumed that the differential damper configuration is installed on the first storey. The corresponding motion equation, e.g., for the first storey, can be rewritten as below to incorporate the damper current by noting:

$$m_1\ddot{x}_1 + c_1\dot{x}_1 + k_1 x_1 = -\begin{pmatrix} \bar{c}_{d1}\dot{x}_1 + \bar{k}_{d1}x_1 + \\ \left(\bar{c}_{d2}\dot{x}_1 + \bar{k}_{d2}x_1\right)i + \bar{\alpha} z_d \end{pmatrix} + m_1\ddot{x}_g, \tag{4}$$

where m_1, c_1 and k_1 represent respectively the mass, damping and stiffness of the first storey. By defining the system state $\mathbf{y} = \begin{bmatrix}\mathbf{x}^T & \dot{\mathbf{x}}^T\end{bmatrix}^T$, control current input i and using (4), the state-space equation for the building structure with identical MR dampers installed on the first storey can be written as

$$\dot{\mathbf{y}} = \mathbf{A}\mathbf{y} + \mathbf{B}i + \mathbf{E}, \tag{5}$$

$$\mathbf{A} = \begin{bmatrix} \mathbf{0} & \mathbf{I} \\ -\mathbf{M}^{-1}\overline{\mathbf{K}} & -\mathbf{M}^{-1}\overline{\mathbf{C}} \end{bmatrix},$$

$$\mathbf{B} = \begin{bmatrix} \mathbf{0}_n \\ -m^{-1}\left(\bar{c}_{d2}\dot{x}_1 + \bar{k}_{d2}x_1\right) \\ \mathbf{0}_{2n} \end{bmatrix}, \ \mathbf{E} = \mathbf{E}_1 + \mathbf{E}_2,$$

$$\mathbf{E}_1 = \begin{bmatrix} \mathbf{0}_n \\ -m_1^{-1}\bar{\alpha} z_d \\ \mathbf{0}_{2n} \end{bmatrix}, \mathbf{E}_2 = \begin{bmatrix} \mathbf{0} \\ \mathbf{\Lambda} \end{bmatrix}\ddot{x}_g,$$

with all elements of $\overline{\mathbf{K}}$ and $\overline{\mathbf{C}}$ remaining the same as of $\mathbf{K}$ and $\mathbf{C}$ in (1), except $\overline{K}_{11} = K_{11} + \bar{k}_{d1}$, and $\overline{C}_{11} = C_{11} + \bar{c}_{d1}$, respectively.

3.2 Lyapunov-based Control Design

Consider the Lyapunov function candidate

$$V = \mathbf{y}^T\mathbf{P}\mathbf{y}, \tag{6}$$

where $V = 0$, if and only if $\mathbf{y} = 0$, $V > 0$, $\forall \mathbf{y} \neq 0$, and $\mathbf{P}$ is a positive definite symmetric matrix to be determined. Now taking the time derivative of V gives

$$\begin{aligned} \dot{V} &= \dot{\mathbf{x}}^T\mathbf{P}\mathbf{x} + \mathbf{x}^T\mathbf{P}\dot{\mathbf{x}} \\ &= \mathbf{x}^T\left(\mathbf{A}^T\mathbf{P} + \mathbf{P}\mathbf{A}\right)\mathbf{x} + 2\mathbf{x}^T\mathbf{P}\left(\mathbf{B}i + \mathbf{E}\right) \\ &= -\mathbf{x}^T\mathbf{Q}\mathbf{x} + 2\mathbf{x}^T\mathbf{P}\left(\mathbf{B}i + \mathbf{E}\right), \end{aligned} \tag{7}$$

where $\mathbf{A}^T\mathbf{P} + \mathbf{P}\mathbf{A} = -\mathbf{Q}$ for $\mathbf{Q} = \mathbf{Q}^T$, $\mathbf{Q} > 0$, is the Lyapunov equation where matrix $\mathbf{P}$ is the solution with a given matrix $\mathbf{Q}$. Furthermore, the choice of matrix $\mathbf{Q}$ can be determined by assigning the rate of decrease of the Lyapunov function V. In addition, using the inequality $\mathbf{y}^T\mathbf{Q}\mathbf{y} \geq \lambda_{\min}\|\mathbf{y}\|^2$, where $\lambda_{\min}$ is the minimum eigenvalue of $\mathbf{Q}$, one has

$$\dot{V} < -\lambda_{\min}\|\mathbf{y}\|^2 + 2\mathbf{y}^T\mathbf{P}\left(\mathbf{B}i + \mathbf{E}\right) \tag{8}$$

By choosing $\mathbf{Q}$ as an identity matrix, i.e., $\mathbf{Q} = \mathbf{I}$, then $\lambda_{\min} = 1$ and the Lyapunov derivative can be expressed as

$$\dot{V} < -\|\mathbf{y}\|^2 + 2\mathbf{y}^T\mathbf{P}\left(\mathbf{B}i + \mathbf{E}\right) \tag{9}$$

In order to obtain a stable system, it is suggested by the Lyapunov stability theory that the derivative should be negative [16], i.e., $\dot{V} < 0$. To satisfy the requirement of a stable system, an analytical form of the supplied current i can be chosen or it can be cast as an optimization problem of searching for a suitable current value $i \in [0, \ i_{\max}]$ to minimize the Lyapunov function derivative (7).

$$\begin{aligned} &\text{minimize}: \dot{V}(\mathbf{y}, i) \\ &\text{s.t.}: \dot{V} < 0; 0 \le i \le i_{\max} \end{aligned} \tag{10}$$

For this, to minimise the Lyapunov function derivative, an exhaustive search is conducted on all feasible control current values $i_q \in [0, \ i_{\max}]$ with some user-specified current precision, where $q = 1,...N$ and N is the number of feasible currents

$$i = \begin{cases} 0, & \text{for } \dot{V}(i_q) > 0 \\ i_q, & \text{for } \dot{V}(i_q) \le 0, q = \arg\min_q \{\dot{V}(i_q)\} \end{cases} \tag{11}$$

4. RESULTS

4.1 System Setup

In the following, for the sake of simulations, a ten-storey building model is used and embedded with one pair of identical MR dampers placed on the first storey, with the parameters of the dampers given in [13]. Therefore, building model parameters are given as

$$\begin{aligned} m_i &= 98.3kg, i = 1...10 \\ c_1 &= 75\,(Ns/m) \\ c_{2...10} &= 50\,(Ns/m) \\ k_1 &= 5.16\times10^5\ (N/m) \\ k_{2...10} &= 6.84\times10^5\ (N/m), \end{aligned} \tag{12}$$

4.2 Controlled Responses

Simulations are conducted on the MATLAB platform using the forth-order Runge-Kutta routine to solve the system differential equation (5) for benchmark records of El-Centro earthquake scaled by 0.5. Fig. 3 shows time responses of the derived current, damping force, Lyapunov function derivative. First storey displacement, velocity and acceleration are also illustrated.

The scaled earthquake record, shown in Fig. 3(a), exhibits a peak approximately at $1.7m\ /\ s^2$ and endures $30s$. The applied damper current is illustrated in Fig. 3(b) which is always positive and smaller than $i_{\max} = 2A$ as required. Fig. 3(c) depicts the force generated from dampers and presents a resemble of the earthquake. The Lyapunov function derivative is shown in Fig. 3(d) indicating the system stability in most of the earthquake period except where the magnitude is too large. However, the derivative returns to negative and the building structure under control becomes stable. The first storey displacement, velocity and acceleration are shown in Fig. 3(e). The responses (solid lines) display reductions in displacement, velocity and acceleration as compared to the no control responses (dotted lines). As can be seen from Fig. 3(e) that by using the proposed Lyapunov-based control, the reduction in quake-induced displacement is remarkable compared to that from no control.

4.3 Evaluation Criteria

The effectiveness on reductions in earthquake induced vibrations on the building structure is further evaluated by a set of performance indices comparing the control response against the results obtained from an un-controlled case. The criteria, adopted from [10], encompass ratios of storey displacements and accelerations. They are formulated as follows:

1. *Absolute storey displacement ratio*

$$J_1 = \frac{\max\{|x_{k,c}(t)|\}}{\max\{|x_{k,u}(t)|\}} \tag{13}$$

where the subscript $k = 1...10$ stands for the storey index and subscripts c, u denote controlled and un-controlled displacement.

2. *Absolute storey acceleration ratio*

$$J_2 = \frac{\max\{|\ddot{x}_{k,c}(t)|\}}{\max\{|\ddot{x}_{k,u}(t)|\}} \tag{14}$$

where the notation $\ddot{x}$ presents the storey acceleration.

3. *Inter-storey drift ratio*

$$J_3 = \frac{\max\{|\bar{x}_{k,c}(t)|\}}{\max\{|\bar{x}_{k,u}(t)|\}} \tag{15}$$

where the inter-storey displacement is given by $\bar{x}_1 = x_1$, $\bar{x}_{k>1} = x_k - x_{k-1}$.

4. *Root-mean-squared storey displacement ratio*

$$J_4 = \frac{\tilde{x}_{k,c}(t)}{\tilde{x}_{k,u}(t)} \tag{16}$$

where the root-mean-square (RMS) values are calculated from $\tilde{x} = \sqrt{T^{-1}\sum\{\delta_t x_k^2(t)\}}$, δ_t is the sampling time and T is the total excitation duration.

5. *RMS storey acceleration ratio*

$$J_5 = \frac{\tilde{\ddot{x}}_{k,c}(t)}{\tilde{\ddot{x}}_{k,u}(t)} \tag{17}$$

where the RMS values are calculated as above.

Table 1 Response ratios: (a) Current $i = 0$; (b) Current Generated from Lyapunov-Based Controller

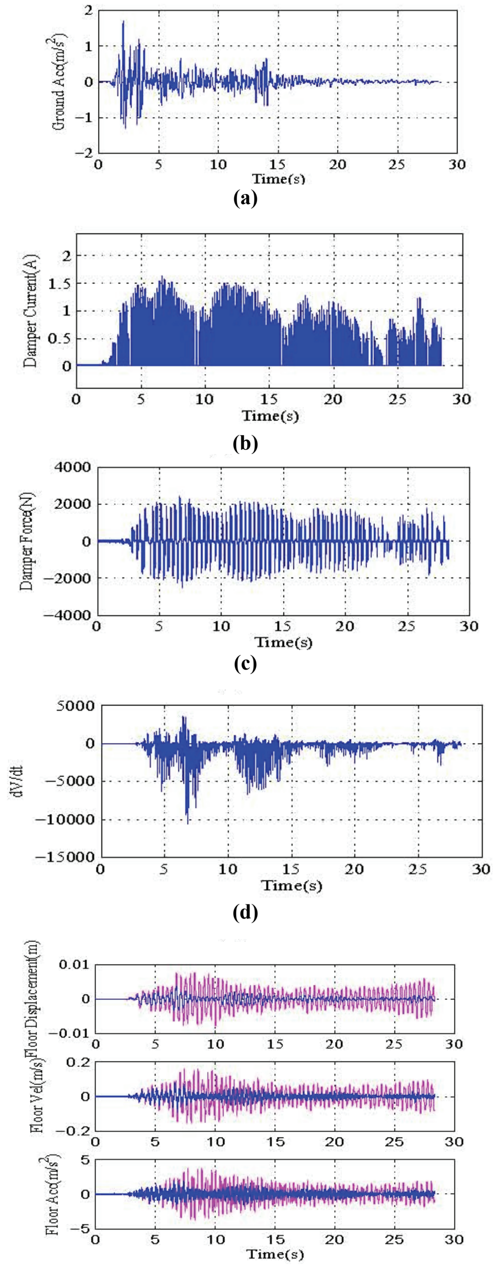
Floors / Criteria	J_1	J_2	J_3	J_4	J_5
1st	0.75	0.55	0.75	0.53	0.38
2nd	0.76	0.58	0.78	0.54	0.40
3rd	0.77	0.63	0.79	0.55	0.43
4th	0.78	0.67	0.81	0.55	0.47
5th	0.79	0.69	0.76	0.56	0.51
6th	0.82	0.72	0.72	0.56	0.55
7th	0.81	0.76	0.68	0.56	0.56
8th	0.75	0.55	0.75	0.53	0.38
9th	0.76	0.58	0.78	0.54	0.40
10th	0.77	0.63	0.79	0.55	0.43

(a)

Floors / Criteria	J_1	J_2	J_3	J_4	J_5
1st	0.47	0.49	0.47	0.28	0.33
2nd	0.53	0.44	0.68	0.35	0.32
3rd	0.58	0.52	0.71	0.38	0.34
4th	0.62	0.53	0.71	0.41	0.38
5th	0.64	0.60	0.60	0.42	0.42
6th	0.65	0.61	0.58	0.43	0.45
7th	0.64	0.67	0.52	0.43	0.46
8th	0.62	0.64	0.49	0.44	0.45
9th	0.61	0.52	0.57	0.44	0.44
10th	0.61	0.57	0.68	0.44	0.44

(b)

Comparisons of evaluation criteria between the passive mode $(i = 0)$ and semi-active mode (the proposed Lyapunov-based controller) are provided in the Table above, as can be seen from the table, all the corresponding ratios with Lyapunov-based controller are much smaller than that with no control $(i = 0)$



(e)

Figure 3 El-Centro Responses: (a) Earthquake Record, (b) Current, (c) Damper Force, (d) Lyapunov Function Derivative, (e) 1st Storey Displacements, Velocity and Accelerations

5. CONCLUSION

This paper has presented an effective semi-active control approach for building structures embedded with MR dampers for mitigation of the vibrations induced from seismic excitations. Furthermore, a Lypunov-based controller is designed such that the supplied currents to the dampers can be directly controlled for improved performance, making use of a static hysteretic model for MR dampers. Promising results obtained indicate the prospective use of MR dampers as semi-active devices in smart structures in quake-prone regions.

6. ACKNOWLEDGMENT

This work is supported by an Australian Research Council (ARC) Discovery Project Grant DP0559405, by the UTS Centre for Built Infrastructure Research and by the Centre of Excellence programme, funded by the ARC and the New South Wales State Government.

7. REFERENCES

[1] Nishitani, A. & Inoue Y. (2001) Overview of the application of active/semiactive control to building structures in Japan, Earthquake Engineering and Structural Dynamics, Vol. 30, No. 11, 1565-1574.

[2] Datta, T.K. (2003) A state-of-the-Art Review on Active Control of Structures, ISET Journal of Earthquake Technology, Vol. 41, No. 1, 1-17.

[3] Symans, M.D. & Constaninou, M.C. (1999) Semi-active Control Systems for seismic Protection of Structures: A State-of-the-Art Review, Engineering Structures, Vol. 21, 469-487.

[4] Lin, P.Y., Chung, L.L. & Loh, C.H. (2005) Semiactive Control of Building Structures with Semiactive Tuned Mass Dampers, Computer-Aided Civil and Infracture Engineering, Vol. 20, 35-51.

[5] Carlson, D., Catanzarite, D.M. & Clair, K.A.S. (1996) Commercial Magnetorheological Fluid Devices, International Journal of Modern Physics B, Vol. 10, 2857-2865.

[6] Karkoub, M.A. & Zribi, M. (2006) Active/Semi-active Suspension Control Using Magnetorheological Actuators, International Journal of System Science, Vol. 37, No. 1, 35-44.

[7] Cho, S.W., Jung, H.J. & Lee, I.W. (2005) Smart Passive System Based on Magnetorheological Damper, Smart Materials and Structures, Vol. 14, 707-714.

[8] Hiemenz, G.J., Choi, Y.T. & Wereley, N.M. (2003) Seismic Control of Civil Structures Ultilizing Semi-active MR Braces, Computer-Aided Civil and Infrastructure Engineering, Vol. 18, 31-44.

[9] Dyke, S.J., et al., (1996) Modeling and control of magnetorheological dampers for seismic response reduction, Smart Materials and Structures, Vol. 5, 565-575.

[10] Djajakesukma, S.L., Samali, B. & Nguyen H., (2002) Study of a Semi-active Stiffness Damper under Various Earthquake Inputs, Earthquake Engineering and Structural Dynamics, Vol. 31, 1757-1776.

[11] Gavin, H.P., (2001) Control of Seismically Excited Vibration Using Electrorheological Materials and Lyapunov Methods, IEEE Trans. on Control System Technology, Vol. 9, No. 1, 27-36.

[12] Alvarez, L. & Jimenez, R. (2003) Semi-active Control of Civil Structures Using Magnetorheological Dampers, Proceedings of American Control Conference, Denver, Colorado, 1428-1433.

[13] Kwok, N.M., Ha, Q.P., Nguyen, T.H., Li, J., Samali, B. (2006) A Novel Hysteretic Model for Magnetorheological Fluid Dampers and Parameter Identification Using Particle Swarm Optimization, Sensors & Actuators A: Physical, Vol. 132, No. 2, 441-451.

[14] Spencer, B.F. Jr, Dyke, S.J., Sian, M.K. & Carlson, J.D. (1997) Phonomenological Model for Magnetorheological Dampers, Journal of Engineering Machanics, Vol. 123, No. 3, 230-238.

[15] Djajakesukma, S.L., et al. (2002) Modelling and Identification of MR Damper for Semi-active Control Devices, Proceedings of the 6th International Conference on Motion and Vibration Control, Saitama, Japan, 565-575.

[16] Slotine, J.E. & Li, W. (1991) Appled Non-linear Control, Prentice-Hall Intl., Inc.: Englewood Cliffs, NJ.