2009 American Control Conference
Hyatt Regency Riverfront, St. Louis, MO, USA
June 10-12, 2009

Structural Performance Improvement Using MR Dampers with Adaptive Control Method

Maryam Bitaraf, *Student member, ASCE*, and Luciana R. Barroso, *Member*, *ASCE*

Abstract— **During the lifetime of a structural system, many severe events such as earthquakes and strong winds may happen to that system resulting in structural characteristic changes. The use of an adaptive control strategy is particularly appropriate as it can deal with these changes. In this study, the response of a 3-story building is controlled by a direct adaptive control strategy using MR dampers. The MR damper is one of the most promising semi-active devices for mitigating the seismic response of civil structures. In the analysis of the structure, some stiffness reduction is assumed as a result of potential damage in the first story of the building. The goal of this research is to improve the performance of the structure in the presence of damage using adaptive control strategy.**

I. INTRODUCTION

Several severe events such as earthquakes or winds may happen to the structural system during its lifetime and the characteristics of the structure may change because of those events. Adaptive control approaches are attractive methods to control the structural performance of the structure as it can deal with these changes. The use of an adaptive control strategy is appropriate to control structural behavior particularly when multi-level performance is desired, as it can continuously monitor its own performance in relation to a given condition and has a means of modifying its own parameters by a closed-loop action so as to approach optimum. As the parameters of the structures and their environmental and operational conditions may vary within a rather large range, the use of adaptive control methods is a particularly promising approach to the problem [1].

In this research, the undesired response of a 3-story building in the presence of damage is mitigated using one of the direct adaptive control approaches. The focus of this paper is on the steel moment resisting frames, specifically the SAC Phase II structures for the Los Angeles region that are also utilized for the third generation structural control benchmark problem [2]. Three possible designs are studied which are: (1) original design with no supplemental control; (2) structure with supplemental active tendon brace devices governed by an adaptive active control strategy; and (3) structure with supplemental semi-active dampers controlled by an adaptive control strategy. Simulations of these systems, both controlled and uncontrolled, are prepared using the earthquake record suite, also from the SAC Phase II project, having probability of exceedence of 10% in 50 years.

Magnetorheological (MR) dampers are used as the semi-active devices in this research to improve the performance of the structure subjected to the earthquake. Among many other semi-active devices that could be used as dampers in the structures, the MR damper is a newly developed semi-active device that shows great promises for civil structural vibration reductions. Because of its mechanical simplicity, high dynamic range, low power requirements, large force capacity and its high stability, robustness and reliability, this device is very attractive for civil engineers to protect the structures against severe earthquakes and wind loads [3]. MR dampers offer rapid variation in damping properties because they have the ability to reversibly change from free-flowing, linear viscous liquids to semisolids having controllable yield strength in milliseconds when exposed to a magnetic field [3]. Modeling the dynamic behavior of the MR dampers accurately is critical in order to achieve the desirable control performance.

Due to the inherent nonlinear behavior of the MR dampers, modeling the dynamic behavior of the MR dampers is one of the important challenges. There are two types of dynamic model for the MR dampers: nonparametric models and parametric models. The Bingham model [4], nonlinear hysteretic bi-viscous model [5] and Bouc-Wen hysteresis model [3] are some of the parametric models that have been used to model the behavior of the MR dampers.

Many control algorithms have been used to regulate the behavior of MR dampers or semi-active devices. In this paper, the simple adaptive control method, which is a type of direct adaptive control approaches, is used to control the MR dampers in a 3-story building. By using this method, any change in the characteristics of the structure during loading or uncertainties in the modeling of the structure during design is addressed.

Simple adaptive control technique has been implemented successfully since 1982. Sobel et al. [6] introduced the Simple Adaptive Control technique and this method has been developed further by Barkana, Kaufman, Wenn and Balas [7]. This technique can make the performance of an arbitrary system close to the ideal desired performance represented by the ideal model.

A steepest descent error minimization performance is one of the characteristics of the adaptive control gains [8]. Because of the less demanding conditions that guarantee asymptotically perfect tracking with the simple adaptive controllers in comparison with the constant controllers in the

Maryam Bitaraf (PhD student) and Luciana Barroso (Associate professor) are with the Department of Civil Engineering, Texas A&M University, College Station, TX 77843-3136, U.S.A. (Email: maryamb1@tamu.edu, lbarroso@civil.tamu.edu)

978-1-4244-4524-0/09/$25.00 ©2009 AACC

linear time-invariant (LTI) systems, the adaptive controllers can reach a better performance than constant controllers [1]. In particular, asymptotic adaptive tracking with no general LTI tracking solution is possible because the control parameters are fitted to the specific problem by adaptive controller.

The present paper is organized as follows. In Section II, the basis of the simple adaptive control method is briefly described. Section III deals with the dynamic model of the MR damper. The performance of the SAC building under the ground motion is studied and the controlled structure performance with active and semi-active devices are compared with the performance of the uncontrolled building in section IV, followed by the concluding remarks.

II. SIMPLE ADAPTIVE CONTROL

Simple adaptive control method forces the error between the plant and the model to approach zero without the need for parameter identification. Equations 1 to 4 show the governing equations in the state space form for the plant and the model [1].

$$\dot{x}_p(t) = A_p x_p(t) + B_p u_p(t) + d_i(t) \tag{1}$$

$$y_p(t) = C_p x_p(t) + d_0(t) \tag{2}$$

$$\dot{x}_m(t) = A_m x_m(t) + B_m u_m(t) \tag{3}$$

$$y_m(t) = C_m x_m(t) \tag{4}$$

where A_p and A_m are state matrices, B_p and B_m are input matrices and C_p and C_m are the output matrices for the plant and model, respectively. x_p and x_m are plant and model state vectors. y_p is plant output vector while y_m is model output vector, u_p is input control vector and u_m is input command vector. The plant order is considered to be n, with m inputs and m outputs. The order of the model is n_m and y_m is m-order vector. The model order, n_m, could be very low but it should be large enough to create the desired command for the plant. The variables $d_i(t)$ and $d_0(t)$ represent input and output disturbances. Fig. 1 shows the block diagram of the adaptive control system.

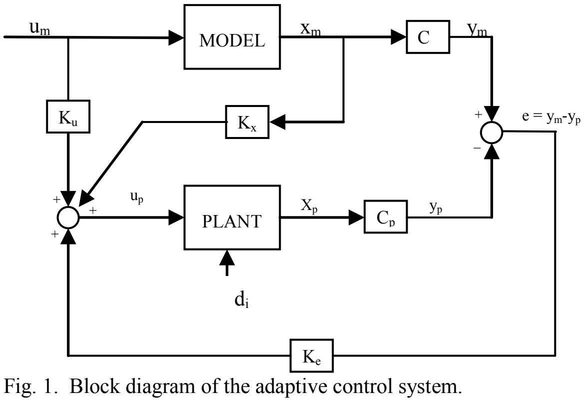

Fig. 1. Block diagram of the adaptive control system.

The goal of the adaptive control approach is to force the plant to behave in the desired way so the plant is required to asymptotically track the output of the model. Time-varying adaptive gains are used in the simple adaptive control method to bring the tracking error to zero. Equation 5 shows how control command, up, can be calculated [7].

$$u_p = K(t)\ r(t) \tag{5}$$

where

$$K(t) = [K_e(t), K_x(t), K_u(t)] = K_I(t) + K_P(t) \tag{6}$$

$$r^T(t) = [y_m - y_p \quad x_m^T(t) \quad u_m^T(t)] \tag{7}$$

$K(t)$ is the sum of the integral gain, $K_I(t)$, and proportional gain, $K_p(t)$ (equations 8 and 9).

$$\dot{K}_I(t) = (y_m(t) - y_p(t))\ r^T(t)\ T - \sigma K_I(t) \tag{8}$$

$$K_p(t) = (y_m(t) - y_p(t))\ r^T(t)\ \overline{T} \tag{9}$$

T and $\overline{T}$ are selected positive definite scale matrices and can control the rate of adaptation. The integral gain is required for the stability and tracking of the system and the proportional gain can increase the rate of convergence of the plant performance to the desired performance. The sigma term in equation (8) is used to prevent the integral gain from reaching very high values or diverging in the presence of the disturbance and the coefficient σ can be very small [8].

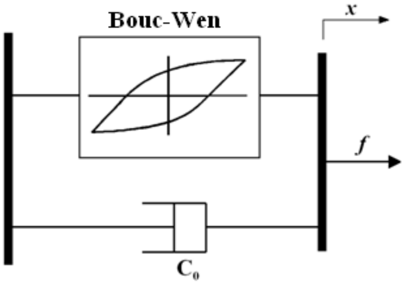

Fig. 2. Mechanical model for MR Damper.

III. DYNAMIC MODEL OF MR DAMPERS

Fig. 2 shows the simple mechanical model for the MR dampers based on Bouc-Wen hysteresis model. The governing equation for the behavior of the MR dampers is as follows [3]:

$$f = c_0 \dot{x} + \alpha z \tag{10}$$

where f and $\dot{x}$ are the MR damper force and velocity, respectively; c_0 is viscous damping at large velocity and z is the evolutionary variable which describes the hysteretic behavior of MR dampers and is governed by:

$$\dot{z} = -\gamma \left|\dot{x}\right| z \left|z\right|^{n-1} - \beta \dot{x} \left|z\right|^{n} + A\dot{x} \tag{11}$$

γ, β, n, and A are hysteresis parameters for the yielding element in MR damper. The model parameters of the MR damper governing equation are functions of applied voltage, v (equations 12 to 14) [3].

$$\alpha = \alpha_a + \alpha_b u \tag{12}$$

$$c_0 = c_{0a} + c_{0b} u \tag{13}$$

$$\dot{u} = -\eta (u - v) \tag{14}$$

where u and v are the input and output voltages of the first-order filter and η is the time constant of the first order filter. α_a, α_b, c_{0a} and c_{0b} are parameters that account for the dependence of the MR damper force on voltage applied to the current driver and the resulting magnetic current [9]. To find the required voltage for MR dampers to produce the forces calculated from the adaptive control method, an inverse model of MR damper is used. The following equations show how the voltage and force are related together in the inverse model.

$$z \cong \operatorname{sign}(\dot{x}) \left(\frac{A}{\gamma + \beta} \right)^{1/n} \tag{15}$$

$$u = \frac{f - c_{0a}\dot{x} - \alpha_a z}{c_{0b}\dot{x} + \alpha_b z} \tag{16}$$

$$v = u + \frac{\dot{u}}{\eta} \tag{17}$$

In the inverse Bouc-Wen model equations, it is assumed that the evolutionary variable, z, can be approximated as its ultimate hysteretic strength (equation 15) [10].

IV. NUMERICAL EXAMPLE

A. *Description of the problem*

To evaluate the efficiency of the adaptive control strategy for use with MR dampers, a numerical example is considered in which the model of a three story building is controlled with three MR dampers, one MR damper in each story, under the ground motion. The structure analyzed in this study is a steel moment resisting frame building (SMRF), 3-stories tall, designed as part of a SAC steel project for the Los Angeles area. The mass of the ground, first, and second floor is 65.6 kip-s^2/ft each and the mass of the roof (3rd floor) is 71 kip-s^2/ft. The stiffness of the first, second and third story are 298823, 275440 and 718641 kips/in, respectively. It is assumed that the model of the structure has a Rayleigh damping with the 2% damping ratio for the first two modes. Fig. 3 shows the acceleration time history of the ground motion record that is used in the simulation of the structure.

To simulate potential damage during a seismic event, it is assumed that a 10% stiffness reduction occurred in the first story of the building. The goal is to make the damaged structure behavior like undamaged building behavior using adaptive control method. So in the MATLAB simulation file, the plant is the damaged building and the model is the undamaged building.

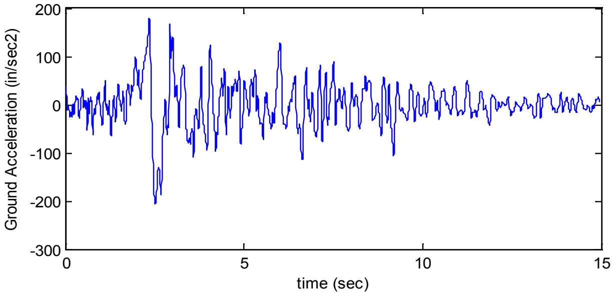

Fig. 3. Acceleration time history of the ground motion used in the analysis.

It is assumed that the story velocities are the outputs of the plant and the model, y_p and y_m. To find the optimum value for the adaptive parameters, the impulse input is applied to the plant and the model and responses of the structure and model are calculated for several different values of σ, $T$and $\bar{T}$. Fig. 4 illustrates how accurately the plant response can track the model response using different values of σ. Considering the results of Table I and Fig. 4, the value of σ, $T$and $\bar{T}$ are chosen to be 0.1, 1000 $I_{12\times12}$ and 1000 $I_{12\times12}$, respectively. The error indicated in the Fig. 4 and Table I is defined as:

$$error = \frac{\sum \left| \text{response}_{\text{plant}} - \text{response}_{\text{model}} \right|}{\sum \left| \text{response}_{\text{model}} \right|} \times 100\% \tag{27}$$

TABLE I
THE FIRST STORY DISPLACEMENT ERROR WHEN AN IMPULSE INPUT IS APPLIED TO THE SYSTEM FOR DIFFERENT VALUES OF **T**.

T	100 $I_{12\times12}$	1000 $I_{12\times12}$	10000 $I_{12\times12}$	100000 $I_{12\times12}$
error %	9.67	2.99	0.94	0.05368

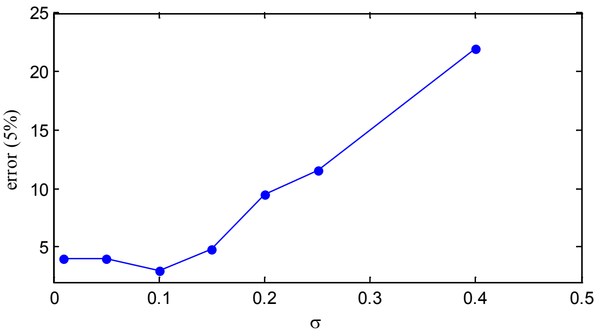

Fig. 4. First story displacement error respect to σ when an impulse input is applied to the system.

B. Results

The first, second and third story displacement of the controlled damaged structure, the model (undamaged structure) and the uncontrolled damaged structure subjected to the earthquake load are shown in figures 5 to 7. The figures show that the controlled damaged structure can track the model response very well. The error obtained for the first, second and third story displacement and velocity are presented in Table II.

Figures 8 to 10 depict the velocity response of the plant, model and uncontrolled structure when the ground motion is applied to them. The result indicates how the adaptive control strategy is efficient enough and the behavior of the controlled structure is very close to the behavior of the model (undamaged structure).

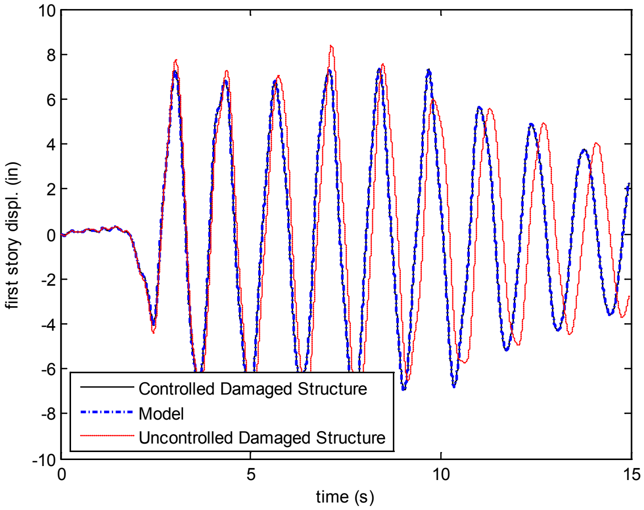

Fig. 5. First story displacement for the structure subjected to the earthquake.

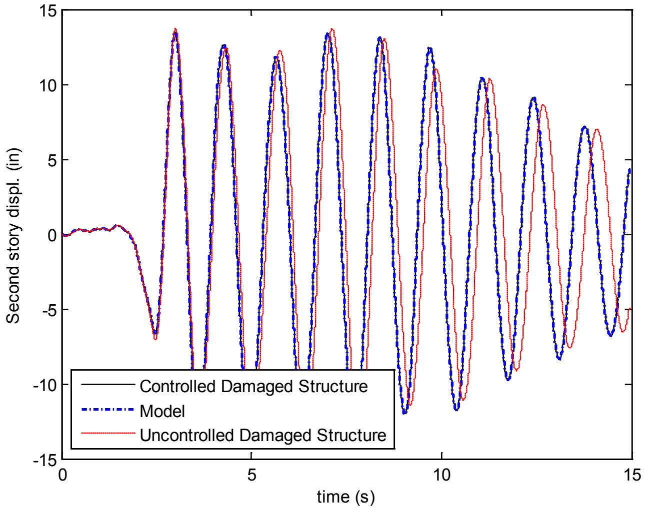

Fig. 6. 2nd story displacement for the structure subjected to the earthquake.

The results from figures 5 to 10 are obtained assuming the active actuators are used in the structures which can produce any needed force without any limitation. When semi-active devices such as MR dampers are used to control the structure, inherent limitation of these devices in producing the forces should be considered. The MR damper restriction is that there is an upper and lower limit on the force produced by MR dampers [11]. Because of this constraint, MR dampers cannot produce the exact forces calculated by adaptive control method.

The MR damper parameters in equations 10 to 14 are listed in Table III, which adopted from Spencer et al. [9] and G. Yang [12]. Because the value of the simple Bouc-Wen model parameters could not be obtained directly from these references, the least square method [13] is used to modify the parameters value. It means that some values for the force is generated using the equations from the model wich is given by Spencer et al. [9] and then the best value for the parameters c_{0a}, c_{0b}, α_a, α_b are calculated using the general least square method to minimize the error between the simple Bouc-Wen model and the modified Bouc-Wen model. Each MR damper can produce a force equal to 200 kN.

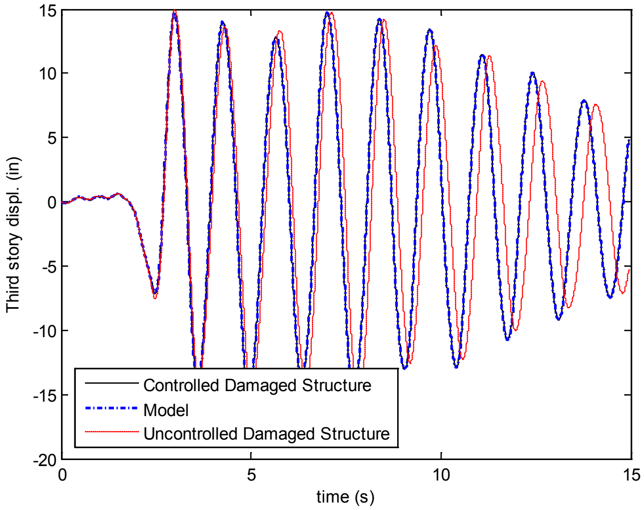

Fig. 7. 3rd story displacement for the structure subjected to the earthquake.

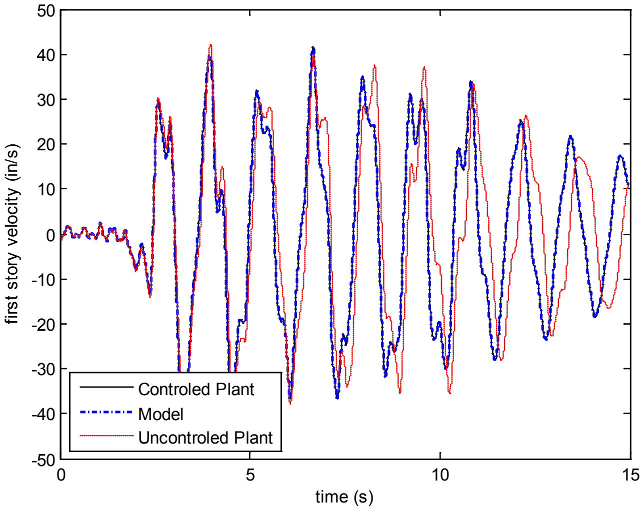

Fig. 8. first story velocity for the structure subjected to the earthquake.

The performance of the controlled structure using MR dampers, subjected to earthquake is shown in figures 11 and 12. As shown in these figures, the performance of the controlled structure is better than the performance of the damaged building, but the controlled damaged structure with MR damper cannot track the undamaged structure as well as it does using active devices. The difference between the controlled structure and undamaged structure lies in the limitations of the MR damper that were discussed earlier.

TABLE II
THE DISPLACEMENT AND VELOCITY ERRORS FOR THE CONTROLLED STRUCTURE UNDER GROUND MOTION

Error %	Displacement	Velocity
1st Story	0.0014	2.2086e-004
2nd Story	1.0456e-006	1.3099e-007
3rd Story	5.8826e-007	9.0949e-008

TABLE III
MR DAMPERS PARAMETERS

Parameter	Value
C_{0a}	137460 (N s/m)
C_{0b}	12553 (N s/m V)
α_a	103690 (N/m)
α_b	4904 (N/m V)
γ	3819.4 (m^{-1})
β	100.1 ($1/m^{-1}$)
A	833.45
n	2.39832
η	31.4 (s^{-1})

Figures 5 and 11 show that the response of the undamaged structure (model) when MR dampers are used is different from the undamaged structure response when active devices are used and the reason is that the MR damper is a semi-active device and it always has the passive effect on the structure when no power is used to activate the active part of the MR damper.

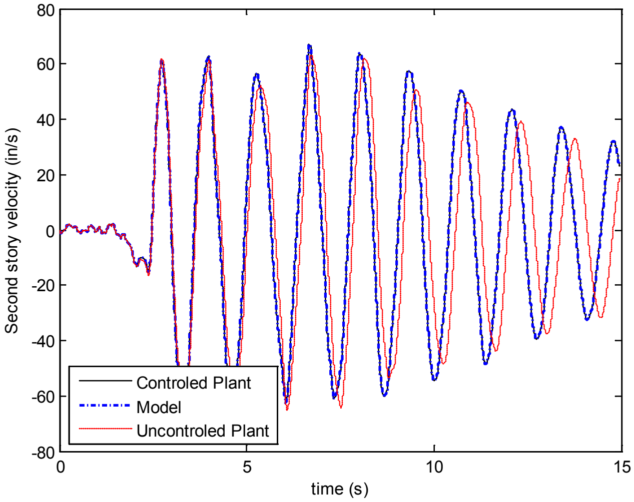

Fig. 9. 2nd story velocity for the structure subjected to the earthquake.

In the Simple Adaptive Control method, we can define the desired behavior of the structure based on the performance requirements. Instead of the undamaged structure behavior, the adaptive control objective can be set to keep the velocity or displacement trajectory inside the specified range. Then the MR damper would be a very efficient device to meet the adaptive control requirements.

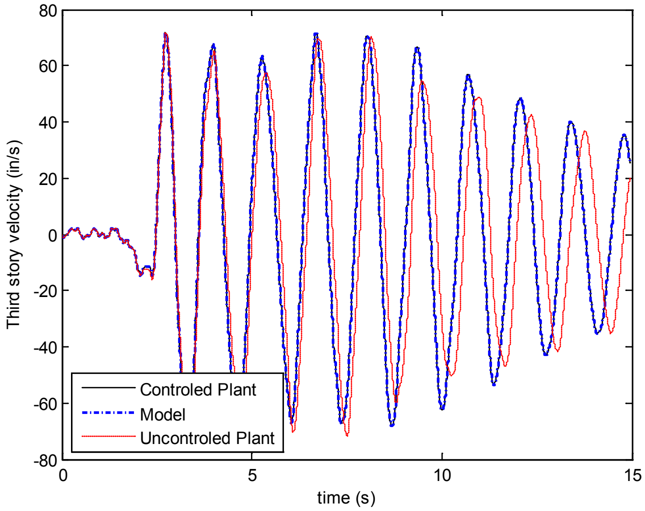

Fig. 10. 3rd story velocity for the structure subjected to the earthquake.

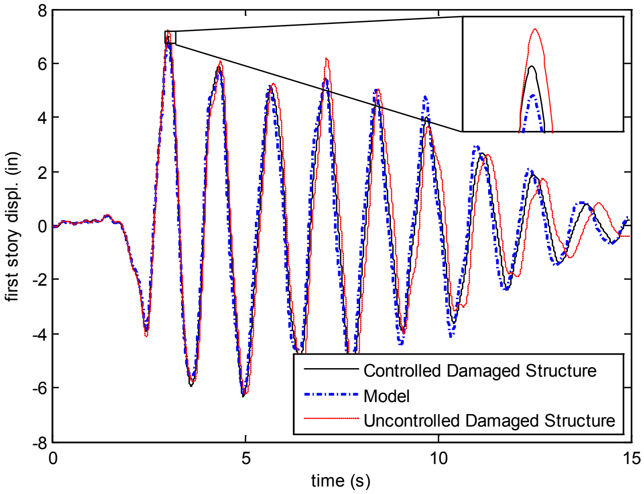

Fig. 11. First story displacement for the structure subjected to the earthquake and controlled by MR dampers.

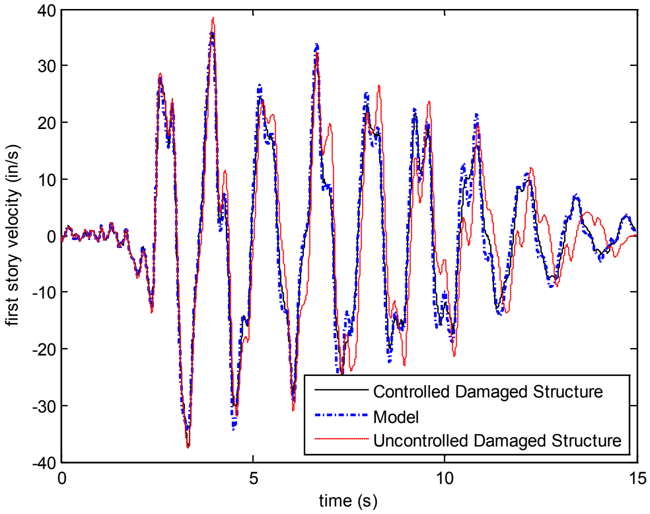

Fig. 12. First story velocity for the structure subjected to the earthquake and controlled by MR dampers.

V. CONCLUSION

In this study, simple adaptive control method was used to control the structure and MR dampers, one of the most promising semi-active devices for use in vibration control applications, were utilized to produce the required forces calculated from adaptive control to make the damaged structure behave like undamaged structure. The results show that using adaptive control method to control the structure to have the desired performance is satisfactory and the damaged structure can track the model very well when some active devices that can produce any desired forces are used. If the MR dampers are used as the semi-active devices to produce the needed forces obtained by the adaptive control strategy, the damage structure cannot track the model because of the limitations of the MR damper, but the performance of the controlled structure using MR damper was improved. As the future work, the more accurate dynamic model for the MR dampers could be used considering that the inverse of that model should be available. Using different types of model of the adaptive control method with different demands for the performance of the structure is suggested so the MR dampers would be more appropriate to satisfy the model demands.

REFERENCES

[1] I. Barkana and H. Kaufman, "Simple Adaptive Control of Large flexible space structures," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 29(4), pp. 1137-1149, 1993.

[2] L. R. Barroso, S. E. Breneman, et al., "Performance Evaluation of Controlled Steel Frames under Multilevel Seismic Loads," *Journal of structural engineering,* vol. 128(11), pp. 1368 -1378, 2003.

[3] L. M. Jansen and S. J. Dyke, "Semi-active Control Strategies for MR Dampers: Comparative Study*," Journal of Eng. Mechanics*, vol. 126(8), pp. 795-803, August 2000.

[4] D. Lee and N. M. Wereley, "Analysis of electro- and magneto-rheological flow mode dampers using Herschel-Bulkley model," *SPIE Smart Structure and Materials Conference*, Newport Beach, CA, Vol. 3989, March 2002, pp. 244-255.

[5] G. Kamath and N. Werely, "Nonlinear viscoelastic-plastic mechanism-based model of an electroheological damper," *J. Guidance, Control Dynamics,* vol. 20, pp. 1125, 1997.

[6] K. Sobel, H. Kaufman, et al. "Implicit Adaptive Control for a Class of MIMO Systems," *IEEE TRANSACTIONS ON AEROSPACE AND ELECTRONIC SYSTEMS AES*-18(5), 1982.

[7] I. Barkana, "Parallel feedforward and simplified adaptive control," *International Journal of Adaptive Control and Signal Processin*g, vol. 1(2), pp. 95-109, 1987.

[8] I. Barkana, "On gain convergence and stability of simple adaptive control," *AIAA paper*, pp. 2003-5327, August 2003.

[9] B. F. Spencer, S. J. Dyke, et al., "Phenomenological model of a magnetorheological damper," *J. Engng Mech ASCE*, vol. 123(3), pp. 230-238, 1997.

[10] T. Tse and C. C. Chang, "Shear-Mode Rotary Magnetorheological Damper for Small-Scale Structural Control Experiments," *J. of Structural Eng*., pp. 904-911, June 2004.

[11] H. H. Tsang, R. K. L. Su, et al., "Simplified inverse dynamics models for MR fluid dampers," *Engineering structures*, vol. 28, pp. 327-341, 2006.

[12] G. Yang, "Large-scale magnetorheological fluid damper for vibration mitigation: Modeling, testing and control," Ph.D. dissertation, Civil Eng., University of Notre Dame, United States, Indiana, 2002.

[13] J. L. Crassidis and J. L. Junkins, "Optimal Estimation of Dynamic Systems," New York, Chapman & Hall/CRC, 2004.