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Supervisory Semiactive Nonlinear Control of a Building-Magnetorheological Damper System

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***Abstract*-This paper proposes a supervisory semiactive nonlinear control of a building structure equipped with magnetorheological dampers. First, three sets of multi-input-single-output (MISO) linear controllers that are operated in local linear operating regions are designed such that the closed loop system is globally asymptotically stable and the performance on transient responses is also satisfied. Among them, two sets of the MISO linear controllers are blended into two lower level nonlinear controllers via a fuzzy interpolation method, while a set of the linear controllers are blended into a higher level nonlinear controller. Then, a supervisory semiactive nonlinear control system is developed through integration of the lower level nonlinear controllers with the high level controller. To demonstrate the effectiveness of the proposed methodology, the performance of the proposed supervisory control approach is compared with that of a fully decentralized semiactive nonlinear controller; while uncontrolled responses are used as the baseline.**

I. INTRODUCTION

In recent years, advanced control technologies, which include passive, active, and semiactive controls, have been applied to many large-scale civil engineering structures for mitigation of natural hazards such as earthquake and the strong wind. However, these control systems have been mostly implemented as so-called centralized controllers. In the centralized control system, there exist only a single central control unit to operate many actuators and sensors. One of the severe problems for the centralized control technologies is that the overall control system of the large-scale civil engineering structures will be broken down if the main central control unit mal-functions for some reasons during an earthquake event, e.g., shut down of power sources, broken sensors and wires. A solution to solve this problem is to use so-called decentralized control concept.

In general, a decentralized control is to divide the large-scale civil engineering structure into a number of sub-structures by first and then implement several controllers that are associated with each sub-structure, i.e., each sub-structure is controlled independently (Hashemian et al. 1996). This decentralized control system increases fail-safe reliability of the overall control system. Thus, the decentralized control systems have attracted attention for use with large-scale civil engineering building structures (Lynch and Law 2000; Rofooei and Monajemi-nezhad 2006). However, they have been mostly implemented based on linear control theories. Concurrently with the linear control-based decentralized control techniques, nonlinear decentralized controllers have been also applied to the large-scale civil structural systems, in particular neuro, fuzzy, and neuro-fuzzy control systems because they are easy to handle with nonlinearity and are inherently robust with respect to uncertainties (Xu et al. 2003; Park et al. 2005). However, their applications are limited to active control system implementations. Later, as a breakthrough, Reigles and Symans (2006) suggested a supervisory nonlinear fuzzy control system for use with a base-isolated building structure employing controllable fluid viscous dampers. They designed two decentralized fuzzy controllers for far- and near-field earthquake disturbances. Furthermore, control gains of those sub-controllers are adapted according to the command of a supervisor fuzzy logic system. However, their systems have been designed by a trial and error approach that use either investigators' experience or high-cost computation, i.e., as a model-free controller, it is trained using a set of input-output data. Although useful for the performance purpose, the ad-hoc approach may not provide a design guideline in a systematic way. Unfortunately, no systematic study has been conducted to design a supervisory semiactive nonlinear fuzzy control system for vibration control of seismically excited building structures equipped with nonlinear semiactive control devices. Therefore, a new research is recommended to develop a systematic design methodology for the supervisory semiactive nonlinear fuzzy control (SSNFC) system of large scale building structures employing magnetorheological dampers.

This paper is organized as follows. Section 2 describes a magnetorheological damper. In Sections 3, a systematic design framework is presented for a semiactive nonlinear fuzzy control (SNFC) system. In Section 4, a SSNFC system that consists of three nonlinear controllers is discussed. In Section 5, simulation results are described. Concluding remarks are given in Section 6.

II. MAGNETORHEOLOGICAL (MR) DAMPER

In this research, two 1000 kN MR dampers (Jung et al. 2003) are used for vibration control of a seismically excited large-scale building structure. A modified version of Bouc-Wen model (Fig. 1) is used to implement the MR damper into a SSNFC system.

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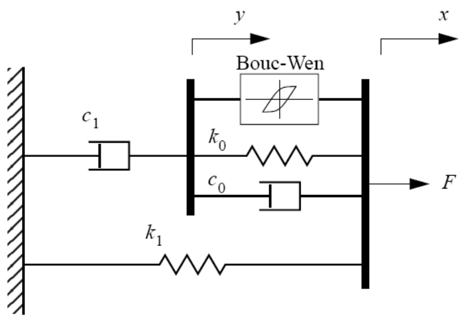

Fig. 1. Modified Bouc-Wen model of the MR damper (Spencer et al. 1997)

The equations of motion of the modified Bouc-Wen model are given by the following equations (Spencer et al. 1997)

$$F = c_1 y + k_1 (x - x_0), \tag{1}$$

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

$$\dot{y} = 1/(c_0 + c_1)\{\alpha z + c_0 \dot{x} + k_0 (x - y)\}, \tag{3}$$

$$\alpha = \alpha_a + \alpha_b v_o,\ c_1 = c_{1a} + c_{1b} v_o,\ c_0 = c_{0a} + c_{0b} v_o, \tag{4}$$

$$\dot{v}_o = -\eta(v_o - v), \tag{5}$$

where F is the force of the MR damper; z and α, called evolutionary variables, describe the hysteretic behavior of the MR damper; c_0 and c_1 are the viscous damping parameters at high and low velocities, respectively; k_0 and k_1 control the stiffness at large velocities and the stiffness of an accumulator, respectively; the x_0 is the initial displacement of the spring k_1; γ, β, and A are adjustable shape parameters of hysteresis loops; v and v_o are input and output voltages of a first-order filter, respectively; and η is the time constant of the first-order filter.

Remark 1: Once the MR dampers are installed into a building structure, the building-MR damper system behaves nonlinearly although the building structure is assumed to remain linear. A schematic of the building-MR damper system is given in Fig. 2.

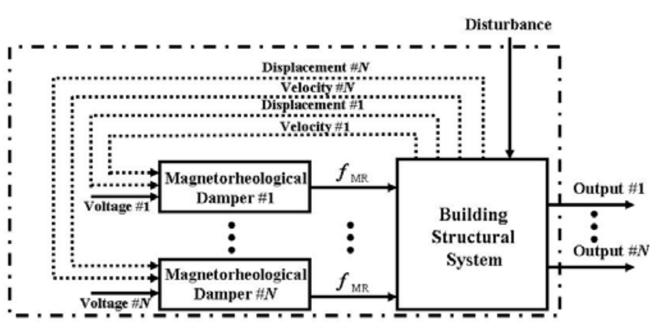

Fig. 2. A building structure employing multiple MR dampers

As seen in Fig. 2, three signals are feedback to each MR damper, i.e., the displacement, velocity, and voltage signals. Note, the displacement and velocity can not be directly controlled. Only a voltage signal is directly controlled by a semiactive control law.

III. Semiactive Nonlinear Fuzzy Control (SNFC)

In this research, a supervisory SNFC system is proposed that consists of two sub-controllers and a coordinator controller. Those controllers are formulated in terms of linear matrix inequalities (LMIs) such that the controlled building-MR damper system is globally asymptotically stable and the performance on transient responses is also satisfied. In what follows, Takagi-Sugeno fuzzy model and parallel distributed compensation that are backbones of this research are addressed. More detailed description can be found in authors' previous research (Kim and Langari 2007; Kim et al. 2008).

A. Takagi and Sugeno (TS) Fuzzy Model

The nonlinear building-MR damper system can be represented via a TS fuzzy model (Takagi and Sugeno 1985)

$$\begin{aligned} &\mathrm{R}_j: \text{If } z_{\mathrm{FZ}}^1 \text{ is } p_{1,j} \text{ and} \ldots \text{and } z_{\mathrm{FZ}}^n \text{ is } p_{n,j} \\ &\text{Then } \begin{cases} \dot{\mathbf{x}}(t) = \mathbf{A}_j \mathbf{x}(t) + \mathbf{B}_j \mathbf{u}(t) \\ \mathbf{y}(t) = \mathbf{C}_j \mathbf{x}(t) + \mathbf{D}_j \mathbf{u}(t) \end{cases}, \quad j = 1, 2, \ldots, N_r, \end{aligned} \tag{6}$$

where N_r is the number of fuzzy rules, $p_{1,j}$ are fuzzy sets centered at the j^{th} operating point, z_{FZ}^i is are premise variables that can be either input or output values, $\mathbf{x}(t)$ is the state vector, $\mathbf{u}(t)$ is the input vector, $\mathbf{y}(t)$ is the output vector, and $\mathbf{A}_j$, $\mathbf{B}_j$, $\mathbf{C}_j$, $\mathbf{D}_j$ are system matrices. The rule-based local linear models are blended into a global nonlinear model through a fuzzy interpolation method. The nonlinear blended TS fuzzy model for any current state vector $\mathbf{x}(t)$ and input vector $\mathbf{u}(t)$ is

$$\dot{\mathbf{x}}(t) = \frac{\sum_{j=1}^{N_r} \underline{w}_j \left(z_{\mathrm{FZ}}^i\right)\left[\mathbf{A}_j \mathbf{x}(t) + \mathbf{B}_j \mathbf{u}(t)\right]}{\sum_{j=1}^{N_r} \underline{w}_j \left(z_{\mathrm{FZ}}^i\right)}, \tag{7}$$

where $\underline{w}_j \left(z_{\mathrm{FZ}}^i\right) = \prod_{i=1}^{n} \mu_{p_{i,j}}(z_{\mathrm{FZ}}^i)$ and $\mu_{p_{i,j}}(z_{\mathrm{FZ}}^i)$ is the grades of membership of z_{FZ}^i in $p_{i,j}$. To control responses of the blended TS fuzzy model, an effective control law associated with Eq. (7), i.e., $\mathbf{u}(t)$ is designed. In this research, a set of optimum linear controllers associated with the local linear dynamic models are designed and then they are blended using the fuzzy interpolation method, which is named parallel distributed compensation.

B. Parallel Distributed Compensation (PDC)

Let us consider the j^{th} control rule of an active nonlinear fuzzy control (ANFC) system (Tanaka and Sugeno 1992)

$$\begin{aligned} &\mathrm{R}_j\text{:If } z_{\mathrm{FZ}}^1 \text{ is } p_{1,j} \text{ and} \ldots \text{and } z_{\mathrm{FZ}}^n \text{ is } p_{n,j} \\ &\text{Then} \quad \mathbf{u}_j(t) = -\mathbf{K}_j \mathbf{x}(t). \end{aligned} \tag{8}$$

The state feedback controller in the consequent part of the j^{th} IF-THEN rule is a local linear controller associated with a local linear dynamic system to be controlled. All the local state feedback controllers are integrated into a global nonlinear controller using the fuzzy interpolation method

$$\mathbf{u}(t) = \frac{\sum_{j=1}^{N_r} \underline{w}_j\left(z_{\mathrm{FZ}}^i\right)\left[-\mathbf{K}_j \mathbf{x}(t)\right]}{\sum_{j=1}^{N_r} \underline{w}_j\left(z_{\mathrm{FZ}}^i\right)}. \tag{9}$$

Note, the blended state feedback controller is truly nonlinear. By substituting Eq. (9) into Eq. (7), the final closed loop control system is derived

$$\dot{\mathbf{x}}(t) = \frac{\sum_{j}^{N_r}\sum_{q=1}^{N_r} \underline{w}_j\left(z_{\mathrm{FZ}}^i\right)\underline{w}_q\left(z_{\mathrm{FZ}}^i\right)\left[\mathbf{A}_j - \mathbf{B}_j\mathbf{K}_q\right]\mathbf{x}(t)}{\sum_{j}^{N_r}\sum_{q=1}^{N_r} \underline{w}_j\left(z_{\mathrm{FZ}}^i\right)\underline{w}_q\left(z_{\mathrm{FZ}}^i\right)}. \tag{10}$$

To implement the ANFC system Eq. (10), the next step is to design the multiple state feedback control gains, $\mathbf{K}_j$ $j = 1,...,N_r$ such that the controlled building structure is globally asymptotically stable and the performance on transient responses is also satisfied. Next, they are integrated with Kalman filters to convert the state feedback control system into output feedback system and then are integrated with clipped algorithms to convert the active control system into the semi-active one.

C. Stabilizing Control Formulation

In general, stability of a controlled structure is checked after controllers are designed. However, in some cases, many trial-and-errors are needed to satisfy the stability of the controlled structure. Therefore, it is desirable to formulate the stability checking process as a stabilizing control design procedure in terms of LMIs to minimize the trial-and-error stability checking procedures (Kim and Langari, 2007)

$$\mathbf{QA}_i^{\mathrm{T}} + \mathbf{A}_i\mathbf{Q} + \mathbf{M}_i^{\mathrm{T}}\mathbf{B}_i^{\mathrm{T}} + \mathbf{B}_i\mathbf{M}_i < 0, \;\; i = 1,2,...,N_r, \tag{11}$$

$$\begin{aligned} &\mathbf{QA}_i^{\mathrm{T}} + \mathbf{A}_i\mathbf{Q} + \mathbf{QA}_j^{\mathrm{T}} + \mathbf{A}_j\mathbf{Q} + \mathbf{M}_j^{\mathrm{T}}\mathbf{B}_i^{\mathrm{T}} + \\ &\mathbf{B}_i\mathbf{M}_j + \mathbf{M}_i^{\mathrm{T}}\mathbf{B}_j^{\mathrm{T}} + \mathbf{B}_j\mathbf{M}_i < 0, \;\; i = 1,2,...,N_r. \end{aligned} \tag{12}$$

These Eq. (11) and Eq. (12) are used to design the stabilizing feedback control gains. However, these stabilizing control formulations do not directly address the performance on transient responses. However, the performance-based design can be achieved through pole-placement algorithm.

D. Performance-based Control Formulation

In the structural systems, the performance on transient responses is an important issue; however, the LMI formulation for the stabilizing control does not directly address that issue. Therefore, the pole-assignment concept is recast by the LMI formulation. The formulation of the pole-placement in terms of LMI is motivated by Chilali and Gahinet (1996).

Theorem 1 (Hong and Langari 2000) The continuous closed loop TS fuzzy control system is *D*-stable if and only if there exists a positive symmetric matrix $\mathbf{Q}$ such that

$$\begin{pmatrix} -r_c\mathbf{Q} & q_c\mathbf{Q} + \mathbf{QA}_i^{\mathrm{T}} + \mathbf{M}_i^{\mathrm{T}}\mathbf{B}_i^{\mathrm{T}} \\ q_c\mathbf{Q} + \mathbf{A}_i\mathbf{Q} + \mathbf{B}_i\mathbf{M}_i & -r_c\mathbf{Q} \end{pmatrix} < 0, \tag{13}$$

where q_{c} and r_{c} are the center and radius of a circular LMI region, and $\mathbf{M}_i = \mathbf{K}_i\mathbf{Q}$. This LMI (13) directly deals with the performance on transient responses of the dynamic system.

In summary, three LMIs Eq. (11), Eq. (12), and Eq. (13) are solved simultaneously to obtain $\mathbf{Q}$ and $\mathbf{M}_i$. Then state feedback control gains $\mathbf{K}_i$ are determined in terms of the common symmetric positive definite matrix $\mathbf{P}$

$$\mathbf{K}_i = \mathbf{M}_i\mathbf{Q}^{-1} = \mathbf{M}_i\mathbf{P}, \;\; i = 1,2,...,N_r. \tag{14}$$

These state feedback control gains are integrated with a Kalman state estimator to construct output feedback controllers

$$f_{\mathrm{ANFC}} = \frac{\sum_{j=1}^{N_r}\prod_{i=1}^{n} \mu_{i,j}(z_{\mathrm{FZ}}^i)\left[-\mathbf{K}_j\hat{\mathbf{x}}(t)\right]}{\sum_{j=1}^{N_r}\prod_{i=1}^{n} \mu_{i,j}(z_{\mathrm{FZ}}^i)}. \tag{15}$$

Then, the output feedback control system is integrated with a clipped algorithm (Dyke et al., 1996) to construct a SNFC system

$$v = \mathrm{V}_a\mathrm{H}\left(\left\{\frac{\sum_{j=1}^{N_r}\prod_{i=1}^{n} \mu_{i,j}(z_{\mathrm{FZ}}^i)\left[-\mathbf{K}_j\hat{\mathbf{x}}(t)\right]}{\sum_{j=1}^{N_r}\prod_{i=1}^{n} \mu_{i,j}(z_{\mathrm{FZ}}^i)} - f_m\right\} f_m\right), \tag{16}$$

where v is the voltage signal applied to a MR damper, V_{a} is the maximum voltage, H is a Heaviside step function, f_m is the measurement of the MR damper, f_{ANFC} is the control action by the ANFC law. Eq. (16) is used to control the level of voltage sent to the MR damper. This control law might be called a SNFC law. In what follows, this SNFC system is extended into multi-input-multi-output (MIMO) SNFC system via the decentralized control concept.

IV. SUPERVISORY SNFC (SSNFC) SYSTEM

In this research, a MIMO SNFC system is developed through integration of a set of MISO SNFC systems with a coordinator controller.

A. Decentralized SNFC (DSNFC) System

A MIMO SNFC system can be designed as a diagonal or a block-diagonal controller that consists of a set of MISO controllers. In the decentralized control system, it is assumed that the building structure to be controlled is close to diagonal, i.e., the building structure is a collection of a number of independent substructures. Fig. 3 is a schematic of the decentralized control implementation. As can be seen, each sub-controller does not use all the state or output feedback information from the structural system to be controlled, i.e., each sub-controller that is independently operated uses local feedback information.

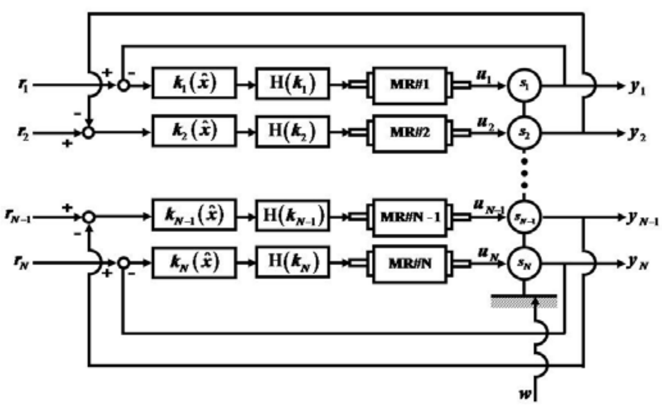

Fig. 3. A schematic of a DSNFC system

The decentralized diagonal controller is given by

$$\mathbf{K} = \operatorname{diag}\{k_i\} = \begin{bmatrix} k_1 & 0 & 0 & 0 & 0 \\ 0 & k_2 & 0 & 0 & 0 \\ 0 & 0 & \ddots & 0 & 0 \\ 0 & 0 & 0 & k_N & 0 \\ 0 & 0 & 0 & 0 & k_{N-1} \end{bmatrix}, \tag{1}$$

In Fig. 3, $k_i(\hat{\mathbf{x}})$ is the output feedback control gain associated with each sub-structure; $\mathrm{H}(k_i)$ is the semiactive converter that is implemented with a clipped algorithm; $\mathrm{MR}\,\#i$ is the MR damper force; u_i is the control force that is applied to the sub-structure; $\mathbf{y}_i$ is the output responses of the i^{th} floor level; r_i is the reference; w is the external disturbance, i.e., earthquake excitation; s_i is the sub-structure. Each DSNFC system is designed based on acceleration and drift feedback information. A procedure to design the decentralized control system consists of four steps.

Step 1: Selection of locations to be controlled within the given building structure.
Step 2: Development of a mathematical model for each sub-structure related to the locations to be controlled.
Step 3: Design of each sub-controller k_i associated with each sub-structure.
Step 4: Implementation of the independent sub-controllers into the given building structure.

In this research, each sub-controller is independently designed as a SNFC system whose design procedure is described in detail in author's previous research (Kim and Langari 2007; Kim et al. 2008). In the following section, the DSNFC system is generalized into a MIMO SNFC system through a supervisory control concept.

B. Supervisory SNFC (SSNFC) System

In the DSNFC system, any information between the sub-controllers is not communicated. However, the global performance of the overall control system can be improved by adding the higher level of a controller, so-called a coordinate controller (Lei and Langari 2000). Fig. 4 shows a schematic of the SSNFC system configuration. This coordinator system controls the magnitude of control gains of those sub-controllers according to velocity feedback information.

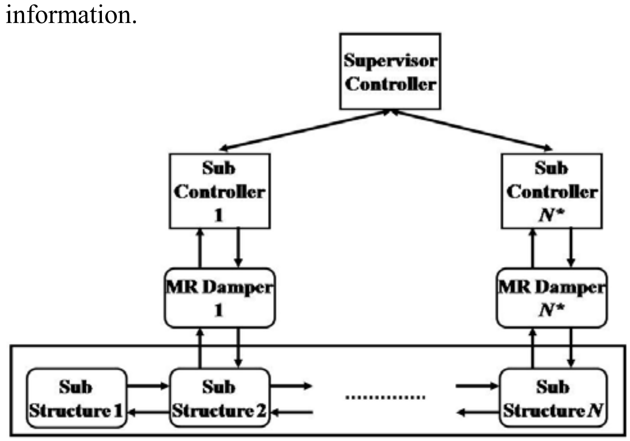

Fig. 4. A schematic of a SSNFC system

First, SNFC systems using acceleration and drift feedback are designed for sub-structures at the specific floor levels within the building structure for the lower level control systems. At the higher level, a velocity feedback-based nonlinear controller is built up to supervise the performance of the sub-controllers of the lower level. Then, the nonlinear sub-controllers at the lower level are integrated with the supervisory nonlinear controller. Hence the upper level controller monitors those velocities and makes the supervisory decision to be fed to the lower level controllers, i.e., it determines weight or penalty that is applied to the lower level controllers depending on the velocity information. In other words, the normalized control gains generated by the supervisory controller are used to multiply with the local control gains. Both higher and lower level nonlinear controllers are formulated in terms of linear matrix inequalities (LMIs) such that global asymptotical stability is guaranteed and the performance on transient response is also satisfied. Then, multiple Kalman estimators that are associated with the coordinator controller and sub-controllers are designed to construct output feedback regulators. Finally, those output active regulators are converted into semiactive nonlinear controllers by integration of the clipped algorithm.

V. SIMULATIONS

In order to demonstrate the effectiveness of the multi-input-multi-output (MIMO) SNFC system, an eight story building structure which has been used as a benchmark problem by a number of other researchers (Yang 1982; Yang et al. 1987; Soong 1990; Spencer et al. 1994) is investigated here. The mass of each floor $m_1 = m_2 = m_3 = m_4 = m_5 = m_6 = m_7 = m_8 = 345{,}600$ kg; the stiffness of each story $k_1 = k_2 = k_3 = k_4 = k_5 = k_6 = k_7 = k_8 = 344{,}400$ kN/m; and the damping coefficient of each floor $c_1 = c_2 = c_3 = c_4 = c_5 = c_6 = c_7 = c_8 = 2{,}937{,}000$ Ns/m. In this eight story building structure, two 1000 kN MR dampers (Jung et al. 2003) are installed on the 5th and 8th floor levels. Using Eq. (11), Eq. (12) and Eq. (13), we design decentralized state feedback controllers that guarantee global asymptotical stability and provide the desired transient response by constraining the closed loop poles in a region D such that $(q_c, r_c) = (5, 0.5)$. This region puts a lower bound on both the exponential decay rate and the damping ratio of the closed loop response. The time step for the time history analysis of the closed loop control system used in this research is 0.001; however, it can be decreased to 0.005 as well. At the lower level, two DSNFC systems are designed using acceleration and drift feedback information, i.e., the first DSNFC system uses the 5th floor absolute acceleration and the 4th-5th floor drift relative to the ground level as feedback signals, and the second DSNFC system is designed with the 8th floor absolute acceleration and the 7th-8th floor relative drift to the ground level; while the coordinator controller is designed using two velocity feedback information, i.e., the 4th-5th and 7th-8th relative velocities. Note, both DSNFC and SSNFC systems are truly nonlinear feedback controllers that consist of twelve linear state feedback controllers, respectively. Fig. 5 shows the 1940 El-Centro earthquake record that is used for a disturbance signal of the proposed control systems. Fig. 6 to Fig. 9 compare responses of the DSNFC and SSNFC systems using the responses at the 1st, 3rd, 5th, 8th (top) floor levels with a concentrated SNFC (CSNFC) system, i.e., a MISO SNFC system that all the MR dampers are installed on the top floor; while the uncontrolled system are used as the baseline. The reason to compare the proposed approach with the single output system is that the performance of a MIMO system is better than that of a MISO or a SISO system that other investigators effectively applied to the benchmark building structure, so far. The Simulation results indicate that the suggested CSNFC, DSNFC and SSNFC systems are effective in reducing the vibration of a building structure subjected to the 1940 El Centro earthquake. However, DSNFC and SSNFC systems are more effective than CSNFC system to mitigate the vibration level of the eight-story building structure. Furthermore, it is shown that SSNFC system has the best performance over CSNFC and DSNFC systems.

VI. CONCLUSIONS

In this paper, a decentralized semiactive nonlinear fuzzy control (DSNFC) and a supervisory semiactive nonlinear fuzzy control (SSNFC) are suggested for seismically excited response control of the building structures equipped with magnetorheological (MR) dampers in the MIMO variable sense. The performance of the DSNFC and SSNFC systems were compared with that of the MISO SNFC system, a centralized SNFC (CSNFC), while the uncontrolled responses are used as the baseline. It was from numerical examples demonstrated that both DSNFC and SSNFC systems are more effective than the CSNFC system to control seismically excited responses of a building structure employing MR dampers. Furthermore, the performance of DSNFC system is able to be improved by adding a coordinated controller, a supervisory controller; i.e., SSNFC system is better than the DSNFC and CSNFC systems.

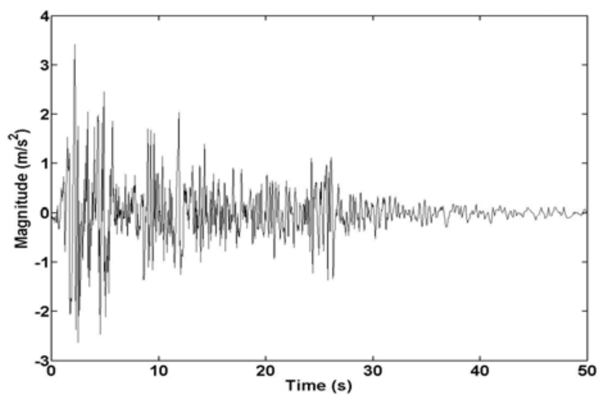

Fig. 5. 1940 El-Centro earthquake record

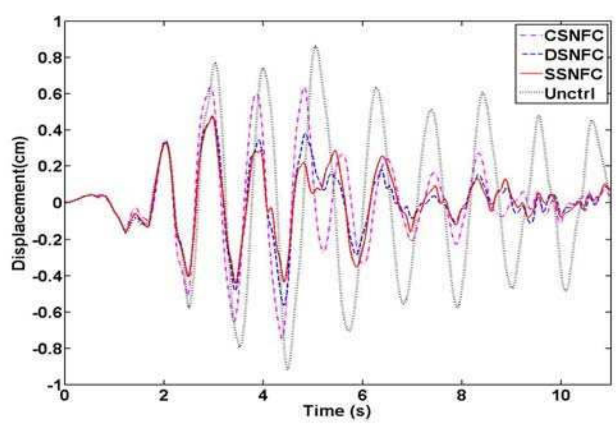

Fig. 6. Time histories response at the 1st floor level of an eight-story building-MR damper system

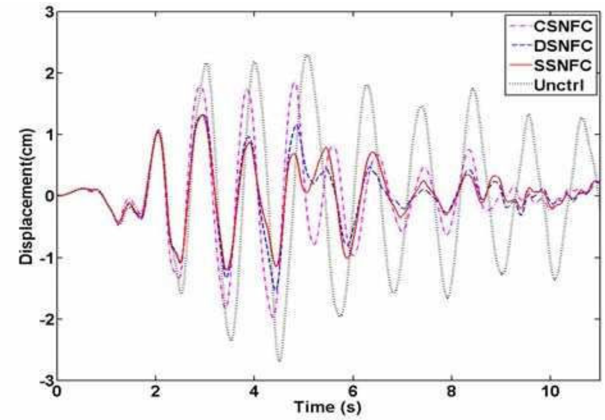

Fig. 7. Time histories response at the 3rd floor level of an eight-story building-MR damper system

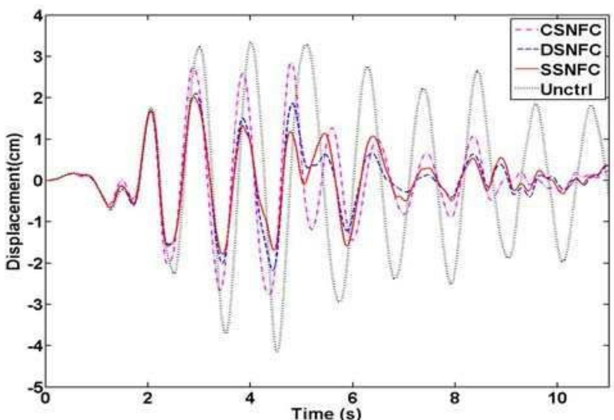

Fig. 8. Time histories response at the 5th floor level of an eight-story building-MR damper system

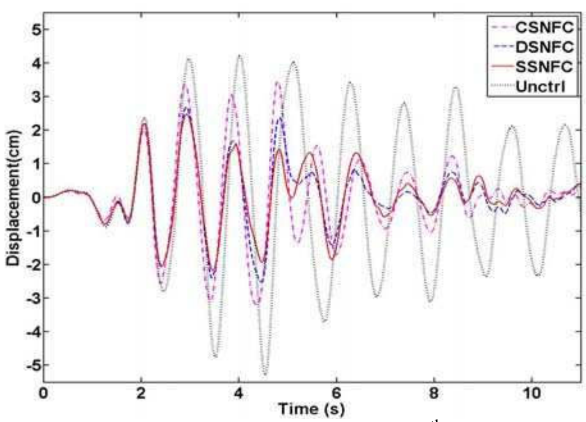

Fig. 9. Time histories responses at the 8th (Top) floor level of an eight-story building-MR damper system

REFERENCES

[1] Chilali, M. and P. Gahinet, "H^{∞} Design with Pole Placement Constraints: An LMI Approach," *IEEE Trans. Automatic Control*," vol. 41, no.3, pp. 358-367, 1996.

[2] Dyke, S.J., B.F. Spencer, M.K. Sain and J.D. Carlson (1996), "Modeling and Control of Magnetorheological Dampers for Seismic Response Reduction," *Smart Mater. and Struct.,* **5**(5), 565-575.

[3] Hashemian, H. and H. A. Ryaciotaki-Roussalis (1995), "Decentralized Approach to Control Civil Structures," *Proceedings of the American Control Conf.,* Seattle, WA, USA, Proc., 4, 2936-2937

[4] Hong, S. K. and R. Langari, "An LMI-based H^{∞} Fuzzy Control System Design with TS Framework," *Information Sciences*, vol. 123, no. 3, pp. 163-179, 2000.

[5] Jung, H.J, B.F. Spencer and I.W. Lee (2003), **"**Control of Seismically Excited Cable-Stayed Bridge Employing Magnetorheological Fluid Dampers," ASCE *J. Struct. Eng*., **129**(7), 873-883.

[6] Kim, Y. and R. Langari (2007), "Nonlinear Identification and Control of a Building Structure with a Magnetorheological Damper," *2007 American Control Conf.*, New York City, NY, Proc., CD-Rom.

[7] Kim, Y., R. Langari and S. Hurlebaus (2008), "A Multiple Model Approach for Semiactive Nonlinear Control of Building Structures with Magnetorheological Dampers," *IMAC XXVI: A Conf. and Exposition on Struct. Dynamics*, Orlando, Florida USA, Feb.

[8] Lynch, J. P. and K. H. Law (2000), "A Market-based Control Solution for Semi-Active Structural Control," *Computing in Civil and Building Eng.*, **1**, 588-595.

[9] Park, K.S., H.M. Koh, S.Y. Ok and C.W. Seo (2005), "Fuzzy Supervisory Control of Earthquake-excited Cable-stayed Bridges," *Eng. Struct*., **27**(7), 1086-1100.

[10] Reigles, D. G. and Symans, M.D. (2006), Supervisory Fuzzy Control of a Base-isolated Benchmark Building Utilizing a Neuro-fuzzy Model of Controllable Fluid Viscous Dampers, *Structural Control and Health Monitoring*, 13(2-3), 724-747.

[11] Rofooei, F.R. and S. Monajemi-nezhad (2006), "Decentralized Control of Tall Buildings," *The Structural Design of Tall and Special Buildings*, **15**(2), 153-170.

[12] Spencer, B.F. Jr., Suhardjo, J., & Sain, M.K. (1994), Frequency Domain Optimal Control Strategies for a Seismic Protection, *Journal of Engineering Mechanics*, 120(1), 135-158.

[13] Spencer, B.F. Jr., S.J. Dyke, M.K. Sain, and J.D. Carlson, "Phenomenological Model for Magnetorheological Dampers," ASCE *J. Eng. Mech*., vol. 123, pp. 230-238, 1997.

[14] Symans, M and S.W.Kelly, "Fuzzy Logic Control of Bridge Structures using Intelligent Semi-active Seismic Isolation Systems," *Earth. Eng. Struct. Dyna*., 28, no. 1, pp. 37-60, 1999.

[15] Takagi, T. and M. Sugeno, "Fuzzy Identification of Systems and Its Application to Modeling and Control," *IEEE Trans. Syst. Man. Cybern*. vol. 15, no.1, pp. 116-132, 1985.

[16] Tanaka, K and M. Sugeno, "Stability Analysis and Design of Fuzzy Control Systems," *Fuzzy Sets and Systems*, 45, no. 1, 135-156, 1992.

[17] Xu, B., Z.S. Wu and K. Yokoyama (2003), "Neural Networks for Decentralized Control of Cable-stayed Bridge," *J. Bridge Eng*., **8**(4), 229-236.