Seismic Response Control of a Large Civil Structure equipped with Magnetorheological Dampers

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Abstract-**This paper proposes a systematic design framework for vibration control of seismically excited civil structures employing magnetorheological (MR) dampers. The framework consists of nonlinear system identification and semiactive nonlinear control system: (1) a multi-input, multi-output (MIMO) autoregressive exogenous (ARX) input model-based Takagi-Sugeno (TS) fuzzy identifier is applied to a large building structure equipped with highly nonlinear hysteretic MR dampers subjected to earthquake disturbances (2) Based on the identified building-MR damper system model, a set of Lyapunov-based controllers are designed such that the building-MR damper system is globally asymptotically stable and its performance on transient responses is also satisfied. To demonstrate the performance of the proposed design framework, a twenty-story building structure employing multiple MR dampers is studied. It is shown from the simulation that the proposed control system design framework is effective to mitigate seismically excited responses of a large building-MR damper system.**

I. Introduction

In recent years, semiactive control has attracted great attention because the semiactive control strategies combine favorable features of both active and passive systems (Chu et al. 2005). Semiactive control devices include: variable-orifice dampers, variable-stiffness devices, variable-friction dampers, controllable-fluid dampers, shape memory alloy actuators, and piezoelectrics (Hurlebaus and Gaul 2006). In particular, one of the controllable-fluid dampers, magnetorheological (MR) damper has recently attracted attention because it has many attractive characteristics such as relatively inexpensive device, small power requirements, reliability, etc. (Spencer et al. 1997).

Selection of an appropriate control algorithm is very important to use best features of MR dampers for vibration control of large civil structures (Jansen and Dyke 2000). A number of control algorithms have been proposed for the vibration response reduction of building or bridge structures employing MR dampers. It includes linear quadratic regulator (Ni et al. 2004), linear quadratic Gaussian (Dyke et al. 1996; Yoshida and Dyke 2004; Jung et al. 2003), H_2/H_∞ control (Loh and Chang 2006); skyhook controller (Hiemenz et al. 2003), bang-bang controller (Metwally et al. 2006), Lyapunov controller (Yi et al. 2001; Sahasrabudhe and Nagarajaiah 2005), modulated homogenous friction algorithm (Zhou et al. 2006), fuzzy logic (Choi et al. 2004), neuro control (Bani-Hani and Sheban 2006; Lee et al. 2007), etc. In particular, fuzzy logic controller has received much attention because uncertainty and nonlinearity can be easily addressed (Subramaniam et al. 1996; Langari 1999); however, many trial-and-errors by experienced investigators are required to design fuzzy logic controllers for vibration control of civil structures equipped with MR dampers (Loh et al. 2003). Thus, some researchers have proposed to use soft-computing techniques to reduce the considerable time and effort of structural engineers. It includes genetic algorithm-based training (Kim and Roschke 2006; Yan and Zhou 2006) and neural network learning (Schurter and Roschke 2001). However, the implementation of these fuzzy controllers are realized via model-free design approaches, i.e., the rule base of the model-free fuzzy controller is selected via many trial and errors of either experienced investigators or high cost of computation using a set of input and output data (Yen and Langari 1998). Furthermore, stability conditions are not automatically formulated in the model-free fuzzy control system design; i.e., stability checking and re-design processes are required for the model-free fuzzy control system design, that is, the model-free fuzzy control design approach does not provide a systematic design guideline and is difficult for the stability conditions to be incorporated into the control system design procedure. Recently, the authors proposed a linear matrix inequality (LMI)-based semiactive nonlinear fuzzy control (SNFC) system for vibration mitigation of seismically excited building structures equipped with MR dampers (Kim et al. 2009) in a systematic way such that global asymptotical stability of the building-MR damper systems is guaranteed and the performance on transient responses is also satisfied. The effectiveness of the proposed LMI-based SNFC system was evaluated with a small-scale, simplified three-story building employing a single MR damper. It was shown that the proposed system is effective in mitigating vibration of a simplified building model under the El-Centro earthquake excitation.

In this paper, the effectiveness of the LMI-based SNFC system is investigated for vibration mitigation of a seismically excited large building structure. A Los Angeles (LA) full scale building benchmark control problem (Spencer et al. 1999) and a modified Bouc-Wen MR damper model (Jung et al. 2003) are used for the simulation. The

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performance of the LA building-MR damper system is evaluated under various earthquake excitation sources: El Centro, Kobe, Northridge, and Hachinohe.

This paper is organized as follows. Section 2 describes a MR damper. In Sections 3, a systematic design framework is presented for a MIMO ARX-TS fuzzy modeling framework. In Section 4, a SNFC system design approach is discussed. In Section 5, simulation results are described. Concluding remarks are given in Section 6.

II. Magnetorheological (MR) Damper

A modified Bouc-Wen model (Spencer et al. 1997) and the parameters (Jung et al. 2003) are used to implement the 1000 kN MR dampers into a SNFC system (see Fig. 1).

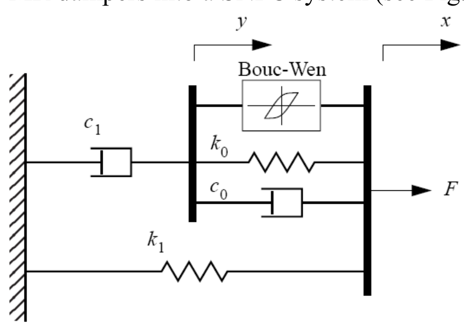

Fig. 1 Modified Bouc-Wen model of the MR damper

The equations of motion of the modified Bouc-Wen model are given by the following equations

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

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

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

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

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

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; 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: If 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. Three signals are feedback to the MR damper: the displacement, velocity, and voltage signal. It should be noted that the displacement and velocity responses of the building-MR damper system cannot be directly controlled. Only a voltage signal is directly controlled by a semiactive control law.

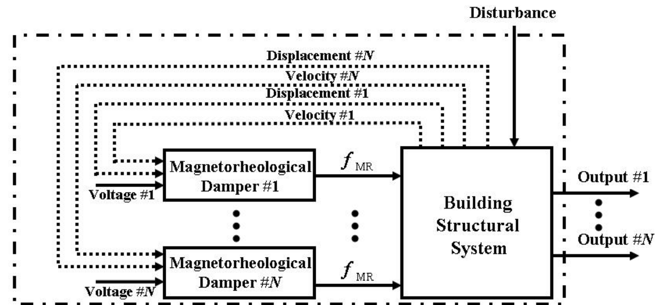

Fig. 2 A building structure employing multiple MR dampers

III. Nonlinear System Identification

A MIMO autoregressive exogenous (ARX) input model-based Takagi-Sugeno (TS) (MIMO ARX-TS) fuzzy model is proposed for identifying nonlinear behavior of the building employing highly nonlinear hysteretic MR dampers.

A. MIMO ARX- fuzzy model

A MIMO nonlinear dynamic model can be described by a set of ARX input based-TS fuzzy models (Johansen 1994)

$$\begin{aligned} &\mathrm{R}_j: \text{If } z_{\mathrm{FZ}}^1 \text{ is } p_{1,j} \text{ and } z_{\mathrm{FZ}}^2 \text{ is } p_{2,j} \text{ and} \ldots \text{and } z_{\mathrm{FZ}}^i \text{ is } p_{i,j} \\ &\quad \text{Then } \underline{y}(k) = \sum_{i=1}^{n} \mathbf{a}_{i,j}\, \underline{y}(k-i) + \sum_{i=1}^{m} \mathbf{b}_{i,j}\, \underline{u}(k-i), \end{aligned} \tag{6}$$

where R_j is the j^{th} fuzzy rule; z_{FZ}^i is a premise vector that can be either a set of dynamic system inputs or outputs; the matrices $\mathbf{a}_{i,j}$ and $\mathbf{b}_{i,j}$ are determined via optimization procedure, i.e.,

$$\mathbf{z}_{\mathrm{FZ}} \in \begin{Bmatrix} y_1(k-1),\ldots,y_1(k-n),\ldots,y_p(k-n), \\ u_1(k-1),\ldots u_1(k-m),\ldots,u_q(k-m) \end{Bmatrix}, \tag{7}$$

$$\underline{y}(k) = \left[y_1(k)\, y_2(k) \cdots y_p(k) \right]^{\mathrm{T}}, \tag{8}$$

$$\underline{u}(k) = \left[u_1(k)\, u_2(k) \cdots u_q(k) \right]^{\mathrm{T}}, \tag{9}$$

$$\mathbf{a}_{i,j} = \begin{bmatrix} a_{i,j}^{1,1} & a_{i,j}^{1,2} & \cdots & a_{i,j}^{1,n-1} & a_{i,j}^{1,n} \\ a_{i,j}^{2,1} & a_{i,j}^{2,2} & & a_{i,j}^{2,n-1} & a_{i,j}^{2,n} \\ \vdots & \vdots & & \vdots & \vdots \\ a_{i,j}^{p-1,1} & a_{i,j}^{p-1,2} & & a_{i,j}^{p-1,n-1} & a_{i,j}^{p-1,n} \\ a_{i,j}^{p,1} & a_{i,j}^{p,2} & \cdots & a_{i,j}^{p,n-1} & a_{i,j}^{p,n} \end{bmatrix}, \tag{10}$$

$$\mathbf{b}_{i,j} = \begin{bmatrix} b_{i,j}^{1,1} & b_{i,j}^{1,2} & \cdots & b_{i,j}^{1,m-1} & b_{i,j}^{1,m} \\ b_{i,j}^{2,1} & b_{i,j}^{2,2} & & b_{i,j}^{2,m-1} & b_{i,j}^{2,m} \\ \vdots & \vdots & & \vdots & \vdots \\ b_{i,j}^{q-1,1} & b_{i,j}^{q-1,2} & & b_{i,j}^{q-1,m-1} & b_{i,j}^{q-1,m} \\ b_{i,j}^{q,1} & b_{i,j}^{q,2} & \cdots & b_{i,j}^{q,m-1} & b_{i,j}^{q,m} \end{bmatrix}, \tag{11}$$

where n is the number of delay steps in the output signals; m is the number of delay steps in the input signals; p is the number of output signals; and q is the number of input signals.

Remark 2: the number of the fuzzy rules, which are associated with the number of the operation regions, corresponds to the number of local ARX models, i.e., m ARX linear dynamic models represent m fuzzy rules that describe behavior of a nonlinear dynamic system.

These ARX local linear models at the specific operating point z^i_{FZ} are blended as an integrated nonlinear dynamic system model via fuzzy logic-based interpolation as follows.

$$\underline{\hat{y}}(k) = \sum_{i=1}^{n}\sum_{j=1}^{N_r} w_j\left(z^i_{\mathrm{FZ}}\right)\mathbf{a}_{i,j}\,\underline{y}(k-i) + \sum_{i=1}^{m}\sum_{j=1}^{N_r} w_j\left(z^i_{\mathrm{FZ}}\right)\mathbf{b}_{i,j}\,\underline{u}(k-i), \tag{12}$$

where $0 \le w_j\left(z^i_{\mathrm{FZ}}\right) \le 1$ is the normalized value of the j^{th} rule,

$$w_j(z^i_{\mathrm{FZ}}) = \prod_{i=1}^{n}\mu_{i,j}(z^i_{\mathrm{FZ}}) \Big/ \sum_{j=1}^{N_r}\prod_{i=1}^{n}\mu_{i,j}(z^i_{\mathrm{FZ}}). \tag{13}$$

Once the multiple ARX-TS fuzzy models are set up, premise parameters $p_{i,j}$ and the consequent parameters $\mathbf{a}_{i,j}$ and $\mathbf{b}_{i,j}$ are determined such that it describes behavior of a nonlinear dynamic system. In this paper, the premise parameters are determined via a clustering technique and the consequent part is optimized using weighted least squares estimation algorithm.

B. MIMO ARX-TS fuzzy model parameter estimation

A fuzzy C-means clustering algorithm has been widely applied to a variety of complicated engineering problems (Wang and Langari 1996). It generates fuzzy sets in an automatic way, while does not require any previous knowledge about the data structure of a given problem. It is formulated as a constraint optimization problem

$$\begin{aligned}&\underset{\sigma_i-\sigma_j\neq 0}{\text{Minimize}}\;\; J(\mathbf{U},\sigma_1,\ldots,\sigma_c) = \sum_{i=1}^{c}\sum_{j=1}^{n_d}\left(\mu_{i,j}\right)^{m_d}\left\|\sigma_i-\sigma_j\right\| \\ &\text{subject to}\;\; \sum_{i=1}^{c}\mu_{i,j} = 1, \quad j = 1,2,\ldots,n_d,\end{aligned} \tag{14}$$

where $\mu_{i,j}$ is membership grades for σ_j in the i^{th} cluster whose values in between 0 and 1; σ_i is the cluster center of each group i; σ_j is j^{th} data point; $m_d > 1$ is a design parameter; $\mathbf{U} = [\mu_{i,j}]$ is the partition matrix with $c \times n_d$ dimension; and c is the number of cluster centers. Using Lagrange multipliers, the constrained optimization can be transformed into an unconstrained optimization problem

$$\begin{aligned}&\bar{J}(\bar{\mathbf{U}},\sigma_1,\ldots,\sigma_c,\lambda_1,\ldots,\lambda_{n_d}) \\ &= \sum_{i=1}^{c}\sum_{j=1}^{n}\left(\mu_{i,j}\right)^{m_d}\left\|\sigma_i-\sigma_j\right\| + \sum_{j=1}^{n_d}\lambda_j\left(\sum_{i=1}^{c}\mu_{i,j}-1\right).\end{aligned} \tag{15}$$

Differentiation of the augmented objective function leads to the necessary conditions

$$\sigma_i = \frac{\sum_{j=1}^{n_d}\left(\mu_{i,j}\right)^{m_d}\sigma_j}{\sum_{j=1}^{n_d}\left(\mu_{i,j}\right)^{m_d}}, \tag{16}$$

$$\mu_{i,j} = \sum_{k=1}^{c}\left(\frac{\left\|\sigma_i-\sigma_j\right\|}{\left\|\sigma_k-\sigma_j\right\|}\right)^{-2/(m_d-1)}. \tag{17}$$

This fuzzy C-means clustering procedure is a simple iterative algorithm: 1) generate the initial MF matrix $\mathbf{U} = [\mu_{i,j}]$ using a random number generator such that the constraint condition is satisfied; 2) calculate a cluster center using Eq. (16); 3) compute the cost function value using Eq. (15) and stop if the iteration stopping criteria is satisfied; and 4) calculate a new MF matrix using Eq. (17) and then go to the second step. Once the premise part is determined using the clustering technique, the consequent parameters can be optimized via the weight least squares algorithm.

$$\boldsymbol{\theta}_j = (\mathbf{H}(k)^{\mathrm{T}} w_j \mathbf{H}(k))^{-1}\mathbf{H}(k)^{\mathrm{T}} w_j\,\underline{\tilde{y}}(k), \tag{18}$$

$$\mathbf{H}(k) = \left[\underline{y}(k-1)^{\mathrm{T}},\ldots,\underline{y}(k-n)^{\mathrm{T}},\underline{u}(k-1)^{\mathrm{T}},\ldots,\underline{u}(k-m)^{\mathrm{T}}\right], \tag{19}$$

$$\boldsymbol{\theta}_j = [\mathbf{a}_{1,j},\ldots,\mathbf{a}_{n,j},\mathbf{b}_{1,j},\ldots,\mathbf{b}_{m,j}]. \tag{20}$$

The MIMO ARX-TS fuzzy model is used for a SNFC system design.

IV. SEMIACTIVE NONLINEAR FUZZY CONTROL (SNFC)

A SNFC system is proposed for vibration control of seismically excited building structure employing MR dampers. 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 et al. 2009).

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)

$$\begin{aligned}&\mathrm{R}_j: \text{If } z^1_{\mathrm{FZ}} \text{ is } p_{1,j} \text{ and} \ldots \text{and } z^n_{\mathrm{FZ}} \text{ is } p_{n,j} \\ &\text{Then } \begin{cases}\dot{\mathbf{x}}(t) = \mathbf{A}_j\mathbf{x}(t) + \mathbf{B}_j\mathbf{u}(t) \\ \mathbf{y}(t) = \mathbf{C}_j\mathbf{x}(t) + \mathbf{D}_j\mathbf{u}(t)\end{cases}, \quad j = 1,2,\ldots,N_r,\end{aligned} \tag{21}$$

where N_r is the number of fuzzy rules; $p_{1,j}$ are fuzzy sets centered at the j^{th} operating point; z^i_{FZ} is are premise variables; $\mathbf{x}(t)$ 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, input, output, and feedthrough matrices, respectively. The rule-based local linear models are blended into a global nonlinear model using a fuzzy interpolation method. The blended TS fuzzy model for any current state vector $\mathbf{x}(t)$ and input vector $\mathbf{u}(t)$ is

$$\dot{\mathbf{x}}(t)=\frac{\sum_{j=1}^{N_r}\prod_{i=1}^{n}\mu_{i,j}(z_{\mathrm{FZ}}^i)\left[\mathbf{A}_j\mathbf{x}(t)+\mathbf{B}_j\mathbf{u}(t)\right]}{\sum_{j=1}^{N_r}\prod_{i=1}^{n}\mu_{i,j}(z_{\mathrm{FZ}}^i)}, \tag{22}$$

where $\mu_{i,j}(z_{\mathrm{FZ}}^i)$ is the grades of membership of z_{FZ}^i. To control responses of the blended TS fuzzy model, an effective control law associated with Eq. (22), i.e., $\mathbf{u}(t)$ is designed: a set of optimum linear controllers using the local 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)

A local j^{th} control rule of an active nonlinear fuzzy control (ANFC) system (Tanaka and Sugeno 1992)

$$\begin{aligned}&\mathrm{R}_j: \text{If } z_{\mathrm{FZ}}^1 \text{ is } p_{1,j} \text{ and} \ldots \text{and } z_{\mathrm{FZ}}^n \text{ is } p_{n,j}\\ &\text{Then} \quad \mathbf{u}_j(t)=\mathbf{K}_j\mathbf{x}(t).\end{aligned} \tag{23}$$

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

$$\mathbf{u}(t)=\frac{\sum_{j=1}^{N_r}\prod_{i=1}^{n}\mu_{i,j}(z_{\mathrm{FZ}}^i)\left[\mathbf{K}_j\mathbf{x}(t)\right]}{\sum_{j=1}^{N_r}\prod_{i=1}^{n}\mu_{i,j}(z_{\mathrm{FZ}}^i)}. \tag{24}$$

By substituting Eq. (24) into Eq. (22), the final closed loop control system is derived

$$\dot{\mathbf{x}}(t)=\frac{\sum_{j}^{N_r}\sum_{q=1}^{N_r}\prod_{i=1}^{n}\mu_{i,j}(z_{\mathrm{FZ}}^i)\prod_{i=1}^{n}\mu_{i,q}(z_{\mathrm{FZ}}^i)\left[\mathbf{A}_j+\mathbf{B}_j\mathbf{K}_q\right]\mathbf{x}(t)}{\sum_{j}^{N_r}\sum_{q=1}^{N_r}\prod_{i=1}^{n}\mu_{i,j}(z_{\mathrm{FZ}}^i)\prod_{i=1}^{n}\mu_{i,q}(z_{\mathrm{FZ}}^i)}. \tag{25}$$

To implement the ANFC system Eq. (25), the next step is to design the multiple state feedback control gains, $\mathbf{K}_j$ $j=1,\ldots,N_r$ such that the controlled building 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 the output feedback system and then are integrated with semiactive converting algorithms to convert the active control system into the semi-active one.

C. Stability LMI formulation

In general, stability conditions of a controlled building are checked after a controller is designed, thus, many trial-and-errors are performed to satisfy the stability of the controlled building. Therefore, it is desirable to formulate the stability checking process as a stabilizing control design procedure in terms of LMIs to minimize the many trial-and-errors (Kim et al. 2009)

$$\mathbf{Q}\mathbf{A}_i^{\mathrm{T}}+\mathbf{A}_i\mathbf{Q}+\mathbf{M}_i^{\mathrm{T}}\mathbf{B}_i^{\mathrm{T}}+\mathbf{B}_i\mathbf{M}_i<0, \quad i=1,2,\ldots,N_r, \tag{26}$$

$$\begin{aligned}&\mathbf{Q}\mathbf{A}_i^{\mathrm{T}}+\mathbf{A}_i\mathbf{Q}+\mathbf{Q}\mathbf{A}_j^{\mathrm{T}}+\mathbf{A}_j\mathbf{Q}+\mathbf{M}_j^{\mathrm{T}}\mathbf{B}_i^{\mathrm{T}}+\\ &\mathbf{B}_i\mathbf{M}_j+\mathbf{M}_i^{\mathrm{T}}\mathbf{B}_j^{\mathrm{T}}+\mathbf{B}_j\mathbf{M}_i<0, \quad i=1,2,\ldots,N_r.\end{aligned} \tag{27}$$

Eq. (26) and Eq. (27) are used to design the stabilizing feedback control gains. However, these stabilizing control formulations do not directly address the performance on transient responses.

D. Pole-placement LMI formulation

The performance on transient responses in the building structure subjected to destructive environmental loadings is also 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

$$\begin{pmatrix}-r_c\mathbf{Q} & q_c\mathbf{Q}+\mathbf{Q}\mathbf{A}_i^{\mathrm{T}}+\mathbf{M}_i^{\mathrm{T}}\mathbf{B}_i^{\mathrm{T}}\\ q_c\mathbf{Q}+\mathbf{A}_i\mathbf{Q}+\mathbf{B}_i\mathbf{M}_i & -r_c\mathbf{Q}\end{pmatrix}<0, \tag{28}$$

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 (28) directly deals with the performance on transient responses of the dynamic system.

LMIs (26), (27), and (28) 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 $\mathbf{P}$

$$\mathbf{K}_i=\mathbf{M}_i\mathbf{Q}^{-1}=\mathbf{M}_i\mathbf{P}, \quad i=1,2,\ldots,N_r. \tag{29}$$

The state feedback controllers are integrated with a Kalman estimator to construct output feedback controllers

$$f_{\mathrm{ANFC}}=\frac{\sum_{j=1}^{N_r}\prod_{i=1}^{n}\mu_{i,j}(z_{\mathrm{FZ}}^i)\left[\mathbf{K}_j\hat{\mathbf{x}}(t)\right]}{\sum_{j=1}^{N_r}\prod_{i=1}^{n}\mu_{i,j}(z_{\mathrm{FZ}}^i)}. \tag{30}$$

Then, the output feedback control system is integrated with an inverse MR damper model to construct a SNFC system as shown in Fig. 3.

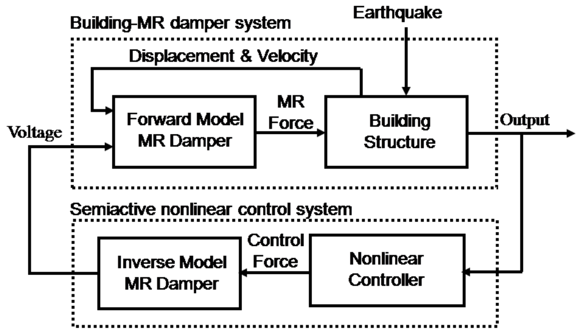

Fig. 3 Semiactive nonlinear fuzzy control implementation

V. SIMULATIONS

As a large-scale 20 story building depicted in Fig. 4 is a moment-resisting frame (MRF), the dimension is 30.48 m by 36.58 m in plane and 80.77 m in height (Spencer et al. 1999). It has five bays in the north-south (N-S) direction while six bays in the east-west (E-W) direction. The dimension of the bay is 6.10 m on center in both N-S and E-W directions. The floor-to-floor height measured from center of beam to center of beam is 3.96 m.

The seismic mass of the structure is: the first floor is 5.32×10^5 kg, the second floor is 5.65×10^5 kg, the third floor to the 20th floor is 5.51×10^5 kg, and the roof level is 5.83×10^5 kg. The total seismic mass of the entire structure is 1.16×10^7 kg. Plane frame elements are used for modeling of the structure whose element contains two nodes in which each node has three degrees-of-freedom (DOFs), i.e., it is an in-plane finite element model of N-S MRF. Therefore, the seismic mass of the structure is modified: the first floor is 2.66×10^5 kg, the second floor is 2.83×10^5 kg, the third floor to the 20th floor is 2.76×10^5 kg, and the roof level is 2.92×10^5 kg.

Each node of the plane frame element includes horizontal, vertical, and rotational DOFs. The total number of nodes and elements is 180 and 284, respectively. The total DOFs is 540 before boundary conditions and subsequent model reduction are applied. After the boundary conditions are applied, the total DOFs are reduced to 526. Assuming the floor slab in each horizontal plane is rigid, the 526 DOF analysis model is reduced to a 106 DOF model. Based on modal damping, the damping matrix is defined using the reduced 106 DOF model: the maximum value of a critical damping is 10 % and the damping in the first mode is assumed to be 2 %. The first ten eigen-frequencies are: 0.29, 0.83, 1.43, 2.01, 2.64, 3.08, 3.30, 3.53, 3.99, and 4.74 Hz. More detailed description is given by Spencer et al. (1999).

Using Eq. (26), Eq. (27) and Eq. (28), 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 $(q_c, r_c) = (50, 45)$. This region puts a lower bound on both the exponential decay rate and the damping ratio of the closed loop response. Note, the proposed SNFC system is a truly nonlinear feedback controller that consists of four linear state feedback controllers, respectively. Fig. 5 shows the real recorded earthquake signals that are used for a disturbance signal of the proposed control systems. Fig. 6 compares maximum responses of the controlled system with uncontrolled one. Further, linear quadratic Gaussian-based control system response is given as a sample controller. The Simulation results indicate that the suggested SNFC system is effective in reducing the vibration of a building structure subjected to various earthquake disturbances.

VI. CONCLUSIONS

In this paper, a MIMO autoregressive exogenous model-based Takagi-Sugeno fuzzy model and a SNFC system are suggested for seismically excited response control of the building structure equipped with the MR damper. The performance of the proposed control system was compared with that of the uncontrolled responses used as the baseline. It was from the simulation demonstrated that the proposed system is very effective in vibration suppression of seismically excited building-MR damper system.

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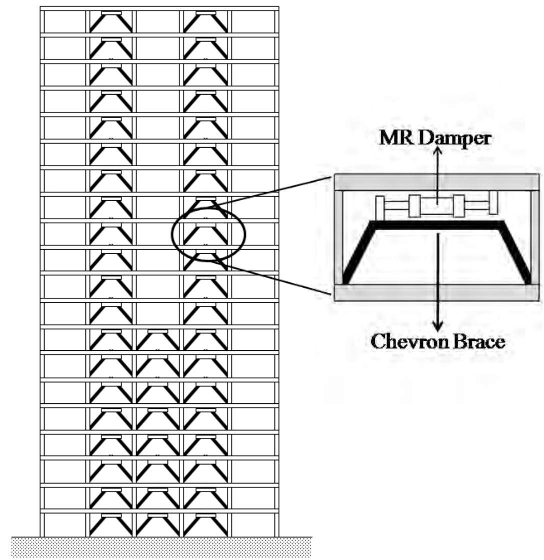

Fig. 4 A 20-story steel building employing MR dampers

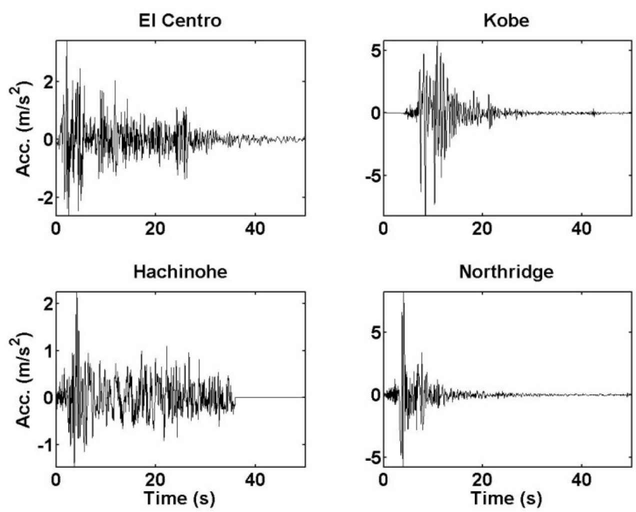

Fig. 5 Earthquake disturbances

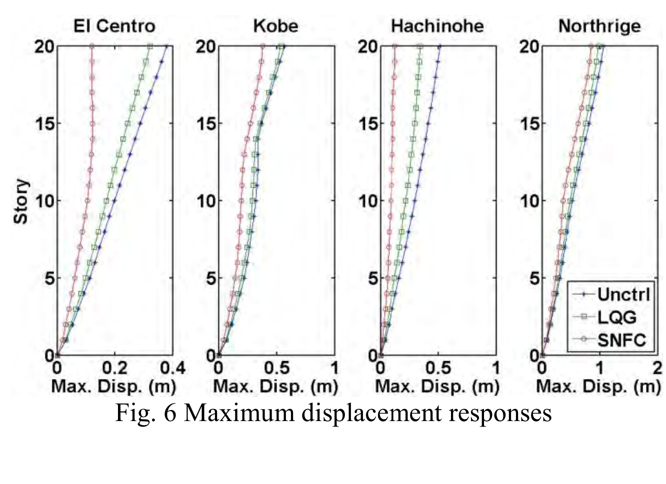

Fig. 6 Maximum displacement responses