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IFAC PapersOnLine 51-13 (2018) 361–365

A method for bidirectional active vibration control of structure using discrete-time sliding mode

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Abstract: In this paper, a novel discrete-time sliding mode control is proposed in order to attenuate structural vibration due to earthquake forces. The analysis is based on the lateral-torsional vibration under the bidirectional waves. The proposed fuzzy modeling based sliding mode control can reduce chattering due to its time-varying gain. In the modeling equation of the structural system, the uncertainty exists in terms of stiffness, damping forces and earthquake. Fuzzy logic model is used to identify and compensate the uncertainty associated with the modeling equation. We prove that the closed-loop system is uniformly stable using Lyapunov stability analysis. The experimental result reveals that discrete-time sliding mode controller offers significant vibration attenuation with active mass damper and torsional actuator.

Keywords: active vibration control, sliding mode control, discrete-time, Lyapunov stability, fuzzy logic.

1. INTRODUCTION

The devastating earthquakes, like 1985 Mexico City, 1994 Northridge, 2008 Chile, and 2012 Emilia, have caused severe damage in civil structures which are evident from the exhaustive research .The control of building structures from the hazardous earthquake waves is an area of great interest for the researchers that is growing rapidly (Fisco and Adeli, 2011). The seismic analysis should be considered bidirectionally in horizon (Lin and Tsai, 2008). The bidirectional movements also induce translation-torsion coupled vibrations in building structure (Chang, 1999; Hochrainer et al., 2000). Magneto-rheological (lMR) damper is combined with the magneto-rheological mass damper (MR-MD) scheme from bidirectional seismic excitations in Yanik et al. (2013). The controller used the mechanism of PD control. In Nigdeli and Boduroglu (2013), the active tendon is used to control torsionally irregular and multistory structures under the grip of near fault ground motion excitation. The problems of existed bidirectional control are: 1) they do not consider the lateral-torsional control mechanism that is only horizontal actuator id used to mitigate the lateral-torsional vibration but a combination of horizontal actuator and torsional actuator are not implemented; 2) they do not analyze the stability of closed-loop system.

If the model of the building structure is unknown, fuzzy logic can be used. Fuzzy logic method is very popular due to its ability to map nonlinearity, simple and robust in nature. There are some applications in structural control due to its simple nature, robustness and nonlinear mapping capability (Choi et al., 2005; Reigles and Syman, 2006). The use of fuzzy logic to mitigate earthquake induced vibrations on structure has multi degree of freedom when utilizing active tuned mass damper (ATMD) (Guclu and Yazici, 2008). In Park et al. (2002), a fuzzy supervisory technique is applied for the active control of earthquake induced building structures. The theory analysis of the above papers are not presented.

The sliding mode control is designed for uncertain nonlinear systems (Utkin, 1992). It is very much effective in terms of robustness against the changes in the parameters and external. . In Iwamoto et al. (2002), it is used to control bending and torsional vibration of a six-story flexible structure. In Soleymani et al. (2016) a robust control system for an active tuned mass damper (AMD) is implemented in a high-rise building. Maria et al. (2016) proposed an active vibration control for a two storeyed flexible structure where the sliding mode controller is designed utilizing LQR approach in order to validate stable motion while undergoing sliding. An approach related to adaptive fuzzy sliding mode in order to eliminate the damage of the nonlinear structure was suggested by Dai (2010). The implementation of computer based control require the system and controller are in the form of discrete-time. Generally, discrete-time control or sampling control is suitable for

Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2018.07.305

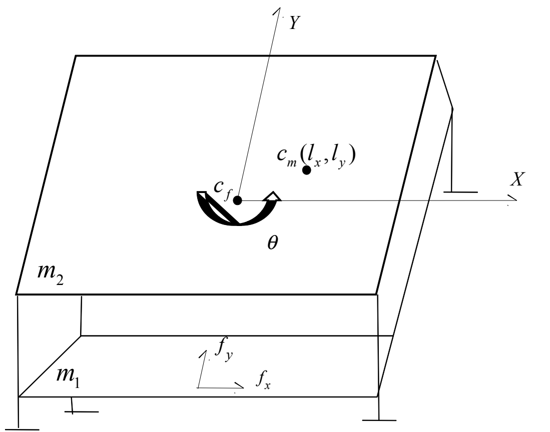

Fig. 1. The torsional oscillation of a two-floor building

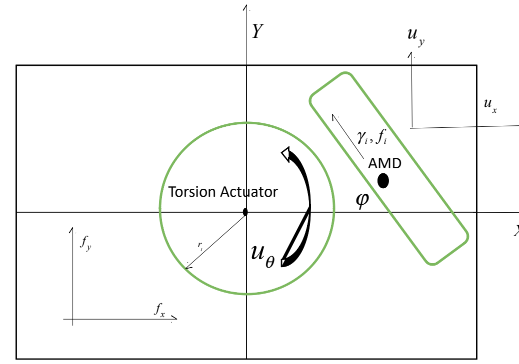

Fig. 2. Bidirectional active control of building structures

the structural control, because the sampling period can be considered the important feature in the performance of the vibration control.

In this paper, we present a fuzzy modeling based discrete-time sliding mode control to minimize the structural vibration under the effect of bidirectional earthquake forces. The active vibration control is based on the lateral-torsional vibration under the bidirectional waves. By introducing time-varying gain to the discrete-time sliding mode control, the chattering is reduced. The stability of the closed-loop system with sliding mode control and fuzzy modeling is given. The experimental results validate the effectiveness of the proposed methods.

2. BIDIRECTIONAL ACTIVE CONTROL OF BUILDING STRUCTURE

For a n-floor building structure, the motion equation with one-direction external force is (Chopra, 2011)

$$M\ddot{\mathbf{x}}(t) + C\dot{\mathbf{x}}(t) + \mathbf{f}_s(\mathbf{x}) = -\mathbf{f}_e \qquad (1)$$

where $M = diag\,(M_x, M_y, J_t) \in \Re^{(3n)\times(3n)}$, $diag\,(\cdot)$ is a diagonal matrix, $M_x = M_y = diag\,(m_1 \cdots m_n)$, m_i is the mass of the i-th floor, $J_t = diag\left(m_1 r_1^2 \cdots m_n r_n^2\right)$ is the polar moment of inertia, $\mathbf{f}_s = [f_{s,1} \cdots f_{s,n}]$ is the structure stiffness force vector and $\mathbf{f}_e$ is the external force vector applied to the structure.

When the external force is in two-direction as in Fig. 1, building structure not only have vibrations in X and Y axes, but also the torsional oscillation. torsional force comes from the asymmetric characteristic of the building, *i.e.*, the physical center (c_f) is different with the mass center (c_m), see Fig. 1.

The bidirectional external forces are expressed as

$$\mathbf{f}_e = [f_x, f_y]^T = \begin{bmatrix} -M_x & 0 \\ 0 & -M_y \\ 0 & 0 \end{bmatrix} \begin{bmatrix} a_x \\ a_y \end{bmatrix}$$

where a_x are a_y are the accelerations of the external force in X and Y directions. The structure stiffness force $\mathbf{f}_s$ is modeled nonlinear model. The displacements of the building structure have three components $\mathbf{x} = [x, y, \theta]^T$, θ is the torsional angle. The damping matrix C is proportional to mass matrix M and stiffness matrix K, $C = aM + bK$.

In order to minimize the vibrations caused by the bidirectional external forces (f_x and f_y), we design two actuators, active mass damper (AMD) and torsion actuator (TA), see Fig. 2. The AMD is placed near the mass centre of the building. The TA is placed on the physical center of the building. The TA is a rotating disc equipped with DC motor and is placed at the center of physical center. The control object of TA is to decrease the torsional response of the building structures due to the bidirectional movements, and the mass center and the physical center being difference.

The control forces have three components, $\mathbf{u} = [u_x, u_y, u_\theta]^T$. The closed-loop system with the control $\mathbf{u}$ is

$$M\ddot{\mathbf{x}}(t) + C\dot{\mathbf{x}}(t) + \mathbf{f}_s(\mathbf{x}) + \mathbf{f}_e(t) = \Gamma[\mathbf{u}(t) - \mathbf{d_u}] \qquad (2)$$

where $\mathbf{u}(t) \in \Re^{3n}$, n is the level number of the building, $\mathbf{d_u}$ is the damping and friction force vector of the dampers, Γ is the location matrix of the dampers. The main role of the AMD is to reduce the response of acceleration of building in X and Y directions whereas the main role of the TA is to minimize the torsional effect on the building. In the closed-loop system (2), $d_\mathbf{u}$ becomes

$$\mathbf{d_u} = \begin{bmatrix} c\dot{x}_{i,x} + \epsilon m_{di} g \tanh\left[\beta \dot{x}_{i,x}\right] \\ c\dot{x}_{i,y} + \epsilon m_{di} g \tanh\left[\beta \dot{x}_{i,y}\right] \\ c\dot{\theta}_t + F_c \tanh(\beta\dot{\theta}_t) \end{bmatrix} \qquad (3)$$

In order to design computer based controller, we use discrete-time model for the building structure. We define $z_\mathbf{1}(t) = \mathbf{x}$ and $z_\mathbf{2}(t) = \dot{\mathbf{x}}$, the model (2) can be transformed into the following state space model

$$\dot{z} = Az + Bu + F_s + f_e \qquad (4)$$

where $z(t) = \begin{bmatrix} z_\mathbf{1}(t) \\ z_\mathbf{2}(t) \end{bmatrix}$, $A = \begin{bmatrix} 0 & 0 \\ 0 & -M^{-1}C \end{bmatrix}$, $B = \begin{bmatrix} 0 \\ M^{-1}\Gamma \end{bmatrix}$, $F_s = M^{-1}\mathbf{f}_s$, $f_e = M^{-1}\mathbf{f}_e$.

Here F_s and f_e can be regarded as the uncertainty parts of the linear system $\dot{z} = Az + Bu$. Obviously, without the external forces, the building structure is stable. It is reasonable to assume that F_s and f_e are bounded, $\|F_s\| \leqslant d_s$, $\|f_e\| \leqslant d_e$. We assume that the control force and the external forces are constant during the sampling period T,

$$u(t) = u(kT), \quad f_e(t) = f_e(kT), \quad kT \leqslant t \leqslant (k+1)T$$

The discrete time model of (2) is (Lu and Zhao, 2001),

$$z(k+1) = A_d z(k) + B_d u(k) + F_{ds}\left[z(k)\right] + f_{de}(k) \qquad (5)$$

where $z(k)$ is a state vector, A_d is a state matrix, $A_d = e^{AT}$, B_d is the input vector, $B_d = \left(\int e^{A\tau} d\tau\right) B$, $u(k)$ is a scalar input, $F_{ds}(k)$ is the model uncertainty matrix and $f_{de}(k)$ is the excitation. Since A_d and B_d are unknown, (5) is written as the following general nonlinear model

$$\begin{array}{l} z(k+1) = f\left[z(k)\right] + g\left[z(k)\right]u(k) + d\left[z(k)\right] \\ f\left[z(k)\right] = A_d z(k), \quad g\left[z(k)\right] = \Gamma_{i,j} B_d, \\ d\left[z(k)\right] = F_{ds}\left[z(k)\right] + f_{de}(k) \end{array} \tag{6}$$

3. FUZZY MODELING AND CONTROL

$f\left[z(k)\right]$ and $g\left[z(k)\right]$ in the model (6) are unknown, in order to design a model based control, we use following fuzzy system to model them. The fuzzy rules have the following form

$$\begin{array}{c} \text{R}^i\text{: IF } (x_i \text{ is } A_{1i}) \text{ and } (y_i \text{ is } A_{2i}) \\ \text{and } (\theta_i \text{ is } A_{3i}) \text{ and } (\dot{x}_i \text{ is } A_{4i}) \text{ and } (\dot{y}_i \text{ is } A_{5i}) \\ \text{and } \left(\dot{\theta}_i \text{ is } A_{6i}\right) \text{ THEN } f\left[z(k)\right] \text{ is } B_{1i} \\ \text{R}^i\text{: IF } (x_i \text{ is } A_{1i}) \text{ and } (y_i \text{ is } A_{2i}) \\ \text{and } (\theta_i \text{ is } A_{3i}) \text{ and } (\dot{x}_i \text{ is } A_{4i}) \text{ and } (\dot{y}_i \text{ is } A_{5i}) \\ \text{and } \left(\dot{\theta}_i \text{ is } A_{6i}\right) \text{ THEN } g\left[z(k)\right] \text{ is } B_{2i} \end{array} \tag{7}$$

By product inference, center-average defuzzification, and a singleton fuzzifier, the output of the fuzzy system is (Wang, 1994)

$$\hat{F}_p = \frac{\left(\sum_{i=1}^{l} w_{pi}[\Pi_{j=1}^{n}\mu_{A_{ji}}]\right)}{\left(\sum_{i=1}^{l}[\Pi_{j=1}^{n}\mu_{A_{ji}}]\right)} = \sum_{i=1}^{l} w_{pi}\sigma_i \tag{8}$$

where $\mu_{A_{ji}}$ is the membership functions of the fuzzy sets A_{ji}, w_{pi} is the point at which $\mu_{\beta_{ji}} = 1$,if we define $\sigma_i = \frac{\Pi_{j=1}^{n}\mu_{A_{ji}}}{\sum_{i=1}^{l}\Pi_{j=1}^{n}\mu_{A_{ji}}}$, the Gaussian functions are chosen as $\mu_{A_{ji}} = \exp\left(-\frac{(x_j - c_{ji})^2}{\rho_{ji}^2}\right)$, c_{ji} and ρ_{ji} are the mean and variance of the Gaussian function, the matrix form of (8) is

$$\hat{F}_p = w(k)\sigma[z(k)] \tag{9}$$

where $w(k) = \begin{bmatrix} w_{11}(k) & & w_{1l}(k) \\ & \ddots & \\ & & \ddots \\ w_{m1}(k) & & w_{ml}(k) \end{bmatrix} \epsilon R^{m\times l}, \sigma[z(k)] = [\sigma_1, \cdots \sigma_l]\epsilon R^{l\times 1}$. So $f\left[z(k)\right]$ and $g\left[z(k)\right]$ are estimated as

$$\hat{f} = w_f(k)\sigma_f[z(k)], \quad \hat{g} = w_g(k)\sigma_g[z(k)] \tag{10}$$

We use the following learning law for the weights in (10),

$$\begin{array}{l} w_f(k+1) = w_f(k) - \eta(k)\sigma_f[z(k)]e_i^T(k) \\ w_g(k+1) = w_g(k) - \eta(k)u(k)\sigma_g[z(k)]e_i^T(k) \end{array} \tag{11}$$

where β is the dead-zone parameter, $\eta(k)$ satisfies

$$\eta(k) = \begin{cases} \dfrac{\eta}{1+\pi(k)} & \text{if } \beta \parallel e_i(k+1) \parallel > \parallel e_i(k) \parallel \\ 0 & \text{if } \beta \parallel e_i(k+1) \parallel < \parallel e_i(k) \parallel \end{cases} \tag{12}$$

$0 < \eta \leq 1$,

$$\pi(k) = \parallel \sigma_f \parallel^2 + \parallel \sigma_g u \parallel^2 \tag{13}$$

$e_i(k)$ is the modeling error

$$e_i(k) = \hat{z}(k) - z(k) \tag{14}$$

$\hat{z}(k)$ is the state of the fuzzy model

$$\beta\hat{z}(k+1) = \hat{f}\left[z(k)\right] + \hat{g}\left[z(k)\right]u(k) \tag{15}$$

where β is a positive constant and $\beta > 1$ which is a design parameter.

In order to analyze the stability of the training algorithm (11), we need the dynamics of the modeling error $e_i(k)$. (15) can be expressed as

$$\beta z(k+1) = w_f^*(k)\sigma_f[z(k)] + w_g^*(k)\sigma_g[z(k)]u(k) + \epsilon_f + \epsilon_g u(k) \tag{16}$$

where w_f^* and w_g^* are unknown optimal weights, ϵ_f are ϵ_g are approximation errors, such as $f = w_f^*(k)\sigma_f[z(k)] + \epsilon_f$, $g = w_g^*(k)\sigma_g[z(k)] + \epsilon_g$. The error dynamics is from (15) and (16),

$$\begin{array}{c} \beta e_i(k+1) = \tilde{w}_f(k)\sigma_f[z(k)] + \tilde{w}_g(k)\sigma_g[z(k)]u(k) \\ +\xi_f + \xi_g u(k) \end{array} \tag{17}$$

where $\tilde{w}_f(k) = w_f(k) - w_f^*(k), \tilde{w}_g(k) = w_g(k) - w_g^*(k), \xi_f = R_f + \epsilon_f$ and $\xi_g = R_g + \epsilon_g$, R_f and R_g are the remainders of the Taylor formula for $\hat{f}$ and $\hat{g}$. The next theorem gives the proof of the stability of the fuzzy modeling.

Theorem 1. If we use fuzzy model (15) to identify nonlinear system (6) with the updating law (11), then the identification error $e_i(k)$ is bounded as

$$\lim_{k\to\infty} \parallel e_i(k) \parallel^2 = \frac{\eta}{\pi(k)}\bar{\zeta} \tag{18}$$

provided that (12) and the dead zone $\beta \parallel e_i(k+1) \parallel > \parallel e_i(k) \parallel$.

For active vibration control, the desired reference should be zero (without vibration), $z^d(k) = 0$. The control error is defined as

$$e(k) = z^d(k) - z(k) = -z(k) \tag{19}$$

We propose the following quasi-sliding mode control

$$u(k) = \frac{1}{\hat{g}}\{-\hat{f} + K^T\mathbf{e}(k) + \sigma sign\left[s(k)\right]\} \tag{20}$$

where $\mathbf{e}(k) = \left[e(k+1-n)\cdots e(k)\right]^T$, $K = \left[k_n \cdots k_1\right]^T \in R^n$ the feedback gain vector, σ is the sliding mode gain, $s(k)$ is switching function which is defined as

$$s(k) = e(k) + K^T\mathbf{e}(k-1) \tag{21}$$

Because $e(k+1) = -K^T\mathbf{e}(k) + s(k+1)$,

$$\mathbf{e}(k+1) = A\mathbf{e}(k) + Bs(k+1) \tag{22}$$

where $A = \begin{bmatrix} 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 \\ \vdots & & \ddots & & \vdots \\ 0 & \cdots & \cdots & 0 & 1 \\ -k_n & \cdots & \cdots & \cdots & -k_1 \end{bmatrix} \in R^{n\times n}$, $B = [0, \cdots 0, 1]^T \in R^{nx1}$. As the proof of (Horn and Johnson, 1985) , $\det(sI - \alpha A) = \alpha^n k_n + \alpha^{n-1}k_{n-1}s + \cdots + \alpha k_1 s^{n-1} + s^n$. We select $K = \left[k_1 \cdots k_n\right]^T$ such that the polynomial $\lambda^n + \sqrt{2}k_1\lambda^{n-1} + \cdots + 2^{\frac{n}{2}}k_n$ is stable, i.e., A is stable. A stable A can assure the following Lyapunov equation have positive definite solutions for P

$$2A^TPA - P = -Q \tag{23}$$

where $Q = Q^T > 0$.

Now we discuss the upper bound of the sliding surface $s(k)$. From (6), (15) and (16), the modeling error satisfies

$$\beta e_i(k+1) = \tilde{f} + \tilde{g}u(k) \tag{24}$$

where $\tilde{f} = \hat{f} - f$, $\tilde{g} = \hat{g} - g$. Substitute the control (20) into the plant (6), the closed-loop system is

$$z(k+1) = \hat{f} - \tilde{f} + \frac{\hat{g} - \tilde{g}}{\hat{g}}\left[-\hat{f} + K^T \mathbf{e}(k) + \sigma sign\left[s(k)\right]\right]$$
$$= -\tilde{f} + K^T e(k) + \sigma sign\left[s(k)\right] - \tilde{g}(k)u(k)$$

Because $s(k+1) = e(k+1) + K^T \mathbf{e}(k) = -z(k+1) + K^T \mathbf{e}(k)$, from (20)

$$e(k+1) + K^T \mathbf{e}(k) = -\sigma sign\left[s(k)\right] + \tilde{f} + \tilde{g}u(k)$$

Use (24),

$$s(k+1) = -\sigma sign\left[s(k)\right] + \beta e_i(k+1) \quad (25)$$

Since $|sign\left[s(k)\right]| \leq 1$ and $|e_i(k+1)| \leq H$

$$|s(k+1)| \leq \sigma + \beta H \quad (26)$$

where H is the upper bound of the modeling error, β is the design parameter of the fuzzy model (15)

The following theorem gives the stability of the discrete-time sliding mode control for building structure.

Theorem 2. If the gain σ of the discrete-time sliding mode controller (20) satisfies

$$\sigma \geq \frac{\beta H}{\|K\|} \quad (27)$$

where H is the upper bound of the modeling error, β is the design parameter of the fuzzy model (15), K salsifies the polynomial $\lambda^n + \sqrt{2}k_1\lambda^{n-1} + \cdots + 2^{\frac{n}{2}}k_n$ is stable, then the closed-loop system is uniformly stable and the upper bound of the tracking error satisfies

$$\lim_{k\to\infty} \frac{1}{T}\sum_{k=1}^{T} \|\mathbf{e}(k)\| \leq \frac{\|P\|}{\lambda_{\min}(Q)}\left(1 + \frac{\beta H}{\sigma}\right) \quad (28)$$

where P and Q are given in (23).

4. EXPERIMENTAL ANALYSIS

To evaluate the theory analysis results, a two-story building prototype is constructed. The building structure is mounted on a shake table which can move in two directions. The bidirectional shake table uses two Quanser one degree of freedom actuators (I-40). The actuator is the hydraulic control system (FEEDBACK EHS 160). The building structure is constructed of aluminum. The active vibration controller AMD is a linear servo motor (STB1108, Copley Controls Corp.), which is mounted on the second floor. The TA actuator is also placed on the second floor. It has a 12V DC motor with an aluminium disc. The entire experimental setup is shown in see Fig. 3.

The moving mass of the damper weights 5% (0.45 kg) of the total building mass. The linear servo mechanism is driven by a digital servo drive (Accelnet Micro Panel, Copley Controls Corp). The control software is in Windows 7 with Matlab R2011a/Simulink. The vibrations are measured by the two-axis accelerometers (XL403A), which are mounted on each floor. The relative acceleration in the second floor is subtracted from the ground floor acceleration. Numerical integrators are used to compute the velocity and position from the accelerometer signal. The gains of the controllers are same as $K_{px} = 1800$, $K_{py} = 2000$, $K_{p\theta} = 2200$, $K_{dx} = 160$, $K_{dy} = 220$, $K_{d\theta} = 300$, $K_{ix} = 2000$, $K_{iy} = 2300$, $K_{i\theta} = 3500$. From Theorem 2, the gain of SMC is: $\sigma = 3$ for the AMD,

Fig. 3. Experimental setup with actuators arrangement

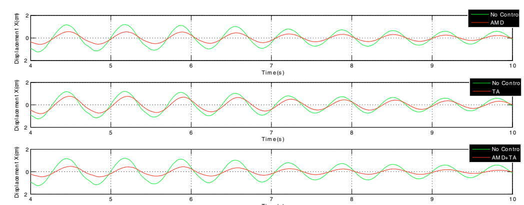

Fig. 4. Discrete sliding mode control of the second floor in the X direction.

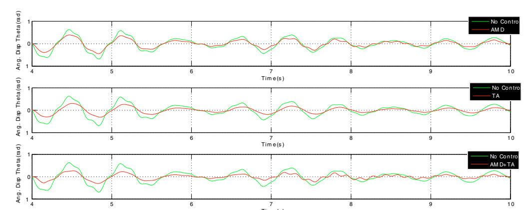

Fig. 5. Discrete sliding mode control of the second floor in the θ direction.

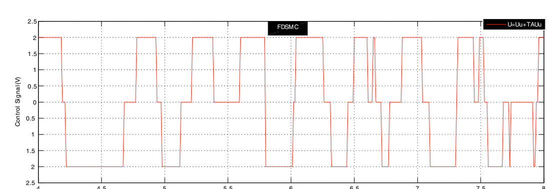

Fig. 6. Control signal of discrete-time sliding mode control

$\sigma = 0.17$ for the TA. The value of $\eta(k)$ is chosen to be 0.9, $z(k) \in [-1, 1]$.For the formulation of fuzzy rules, the FIS variables selected as input variables (position error and velocity error) and output variable (control force). IF-THEN rules are applied. IF and AND conditions are applied between position error and velocity error, whereas THEN conditions gives the required control force. We use six fuzzy rules $\hat{f}$, and four rules for $\hat{g}$. Three membership functions are used to extract the linguistic variables.

We use the Northridge earthquake signal for the shake table. For this prototype, the displacement of the Northridge earthquake is scaled from 16.92cm to 1.50cm, and the time is scaled from 39.98s to 11.91s. The control object is to minimize the relative displacement of each floor in bidirection. The experiments are carried out in three cases: 1) without any active control (No Control); 2) with only TA; 3) with both AMD and TA. The vibration attenuation along X-direction and θ-direction for discrete time sliding mode control are shown in Fig. 4-Fig. 5. The control signal of discrete-time sliding mode control is shown in Fig. 6. For clarity of the results, the vibration responses are displayed for the period of 4s to 10s,whereas the control signals are scaled from the time period of 4s to 8s.The experimental plots validate that discrete-time sliding mode controller successfully attenuate the vibration of the structure due to earthquake forces. The most effective solution is achieved when AMD and TA works in combination as AMD significantly attenuate vibration along X-direction and $Y-$direction whereas TA effect is superior along $\theta-$direction.

5. CONCLUSION

In this paper, we first the model of the controlled building structures. The discrete-time sliding mode control along with fuzzy modeling achieves superior vibration control under bidirectional seismic forces. The time varying gain of SMC helps to reduce the chattering. A two-floor structure associated with AMD and TA is proposed for active vibration control. The stability of the proposed controller has been established using Lyapunov stability theory. The experimental results show that discrete time sliding mode controller works well with AMD and TA. The discrete-time sliding mode controller in combination with both AMD and TA is efficient in mitigation of vibration along X-direction,$Y-$direction, and $\theta-$direction.The advantage of this work is that, the stability of the proposed controller is verified using Lyapunov candidate which is very essential in structural control. Also, the development of TA for torsional control is an important contribution of this research.

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