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Full Length Research Paper

Seismic response control of sliding isolated buildings using adaptive fuzzy sliding mode control

Ken Yeh

Department of Construction Science and Technology, De-Lin Institute of Technology, Tu Cheng, New Taipei City, Taiwan, Republic of China. E-mail: kyeh@dlit.edu.tw.

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The purpose of this paper is to apply adaptive fuzzy sliding mode control for structurally controlling buildings with sliding bearing isolation. Combining fuzzy control and robust control such as sliding mode control, reduces fuzzy rule bases complexity and ensures stability and robustness. We use Lyapunov theory to develop a self-tuning law. Stiffness uncertainty and time delay is used to demonstrate the robustness of our proposed algorithm. The effectiveness of this algorithm is demonstrated by simulation results for the Taiwan Chi Chi earthquake in 1999. Simulations show that adaptive fuzzy sliding mode control achieves satisfactory results in the application of structural control for buildings with sliding bearing isolators.

Key words: Fuzzy control, sliding bearing isolation, robust control.

INTRODUCTION

Several hybrid systems have been shown to effectively reduce damage to structures due to environmental disturbances (such as earthquakes). Hybrid control uses the advantages of active and passive control. Base-isolation reduces ground motion transmitted to a building, whereas active control reduces building response. Base-isolation uncouples the structure from seismic ground motion using replaceable devices placed between the building and ground. The disadvantage of isolators is large lateral displacement that may induce damage. Since the dynamic behavior of base isolation devices, such as frictional-type sliding bearings, is either highly nonlinear or inelastic, such nonlinear systems require nonlinear control. Structural control in civil engineering applications originated in the early 1970s (Yao, 1972). Some of the widely used structural control methods are LQR optimal control (Yang, 1975), pole assignment (Abdel-Rohman et al., 1981), instantaneous optimal control (Yang et al., 1987). Recent H_2 (Suhardjo et al., 1992), H-infinite (Schmitendorf et al., 1994) optimal control, sliding-mode control (Yang et al., 1995), LQG/LTR (Lu et al., 1998) and fuzzy control (Yeh et al., 1996) were introduced for structural control problem. Lately, the applications to structural and mechanical systems are extensively reported using new approaches, such as fuzzy, neural network, genetic algorism, etc (Anisseh et al., 2011; Banga et al., 2011; Bingol et al., 2010; Chen, 2006; Chen et al., 2007; Chen, 2009; Chen et al., 2009; Chen, 2009; Chen et al., 2010; Chen, 2010; Chen et al., 2010; Chen and Chen, 2010; Nataraja et al., 2006; Pamučar et al., 2011; Tusat, 2011).

This paper applies adaptive fuzzy sliding mode control for structural control of buildings with sliding bearing isolation. In industry, systems with complex mechanism, nonlinear, and/or ill-defined are difficult to model mathematically, but an operator can control and operate the system adequately. Operator control strategy is based on intuition and experiences, such as, assuming a set of heuristic decision rules. The theory of fuzzy logic and algorithms evaluates and implements these imprecise linguistic statements directly and effectively, but difficulties exist in fuzzy control design: (1) the huge amount of fuzzy rules for a high-order system makes the analysis complex; (2) suitable parameters of membership functions must be given by time-consuming trial and error procedure and (3) stability analysis tools cannot be applied to fuzzy control (Lo et al., 1998). In order to solve these problems (Chen, 2006; Hsiao et al., 2005; Liu et al., 2010) proposed a stability condition for a nonlinear structural system based on both linear matrix inequality

(LMI) transformation and the T-S fuzzy model. Although the controller design problem can be transformed into a solvable LMI problem, the control approach has to be enhanced to be effective for real engineering applications. Here, we consider adaptive fuzzy sliding mode control (AFSMC) strategies for a real building structure with a sliding bearing isolation hybrid protective system.

System parameters are generally difficult to determine precisely, but bounds on uncertainty is known. For unmodeled dynamics, robust control such as sliding mode control is a useful strategy (Hui et al., 1992) that provides a systematic approach to solving the problem of maintaining stability and consistent performance. Yager et al. (1994) determined fuzzy rules based on the sliding mode condition. The sliding surface can dominate dynamic control behavior and reduce the numbers of fuzzy rule base rules. Palm demonstrated that fuzzy control can be considered as an extension of the conventional sliding mode controller with a boundary layer (Palm, 1992). Adaptive fuzzy control (Wang, 1993, 1994) used a linear combination of fuzzy basic functions and tuned consequent parameters adaptively. The adaptive law for the method of adaptive fuzzy sliding mode control presented in this study is derived from the Lyapunov theory. The adaptive law is used to tune the centers of the consequences of the membership functions. A stable adaptive fuzzy sliding mode control is developed for affine highly nonlinear systems (Hwang et al., 2001). The desired control behavior is achieved by developing an equivalent control using the unknown part of the system dynamics and the fuzzy learning model. Lhee et al. (2002) described sliding mode-like fuzzy logic control with fast self-tuning of the dead-zone parameters given parameter variations in the controlled system. Fischle et al. (1999) extended the method of stable adaptive fuzzy control to a broader group of nonlinear plants. They achieved this by using an improved controller structure adopted from the neural network domain. Their controllers (Palm, 1992; Lhee et al., 2002; Fischle et al., 1999) were designed for application to a high order single output system. However, since civil structures are multi-output systems, the response information from sensors may include a wide variety of data such as displacements, velocities and accelerations.

The coefficients of the sliding surface (Palm, 1992; Hwang et al., 2001; Lhee et al., 2002; Fischle et al., 1999) are selected so that s(t)=0 is Hurwitz. In this study, the optimal sliding mode method is used to determine the sliding surface. The controller’s sliding surface (Palm, 1992; Hwang et al., 2001; Lhee et al., 2002; Fischle et al., 1999) can ensure system stability. Notably, the optimal sliding mode method not only ensures system stability, but can also adjust the weighting matrices according to the control objective. The method discussed in this paper is more efficient than other types of controllers ((Palm, 1992; Hwang et al., 2001; Lhee et al., 2002; Fischle et al., 1999; Liu et al., 2010).

The aim of this study is thus to develop a systematic AFSMC design procedure capable of controlling the behavior of seismically excited buildings constructed with sliding bearing isolation systems. The effectiveness of the developed algorithm is illustrated using several examples applied to sliding bearing isolated buildings.

STRUCTURAL DYNAMICS

Assume that the equation of motion for a base-isolated building controlled by actuators and subjected to ground excitation $\ddot{x}_g$ is written as follows:

$$\begin{bmatrix} M & Ml \\ l^T M & l^T Ml+m_b \end{bmatrix} \begin{pmatrix} \ddot{\bar{x}}(t) \\ \ddot{x}_b(t) \end{pmatrix} + \begin{bmatrix} C & 0 \\ 0 & c_b \end{bmatrix} \begin{pmatrix} \dot{\bar{x}}(t) \\ \dot{x}_b(t) \end{pmatrix} + \begin{bmatrix} K & 0 \\ 0 & k_b \end{bmatrix} \begin{pmatrix} \bar{x}(t) \\ x_b(t) \end{pmatrix} = -\begin{pmatrix} Ml \\ l^T Ml + m_b \end{pmatrix} \ddot{x}_g(t) + \begin{pmatrix} 0 \\ 1 \end{pmatrix} (U(t)-f(t)) \quad (1)$$

or Equation 1 is represented as follows:

$$M^* \ddot{\bar{X}}(t) + C^* \dot{\bar{X}}(t) + K^* \bar{X}(t) = b(U(t)-f(t)) - \bar{M}\ddot{x}_g \quad (2)$$

where $\bar{x} = [\bar{\bar{x}}_1, \bar{\bar{x}}_2 .... \bar{\bar{x}}_r]^T \in R^r$ = r-vector with $\bar{\bar{x}}_i$ denoting the ith floor displacement relative to base; x_b = base displacement relative to the ground. Matrices M, C and K = r $\times$ r mass, damping and stiffness matrices, respectively, for the superstructure; l= r-vector denoting the influence of the earthquake excitation; m_b, c_b and k_b are base mass, damping and stiffness matrices, respectively; U(t) corresponds to the actuator forces (generated via active tendon system or an active mass damper) and f(t) is the forces from the isolators; this is only a static model, neglecting the dynamic equations of actuators. The frictional force of the sliding bearings is given as:

$$f(t) = \mu\, mgv(t) \quad (3)$$

in which mg = the weight of the structural system above the sliding bearing and μ is the coefficient of friction. Generally, the coefficient of friction μ is velocity-dependent. An approximate model for the frictional coefficient μ of sliding bearings using Teflon/strainless-steel plates is obtained experimentally (Mokha et al., 1990a, b):

$$\mu = \mu_m - \mu_f e^{-a_\mu |\dot{x}_b|} \quad (4)$$

in which μ_m, μ_f and a_μ are constants to be obtained experimentally using curve-fitting procedures; and x_b is the relative displacement of the sliding system. The constants $\mu_{m,}$ μ_f and a_μ depend on the surface condition and the pressure of sliding bearings.

v(t) is the hysteretic component of the sliding bearings governed by the equation as follows:

$$\dot{v}(t) = D_y^{-1}(\alpha\dot{x}_b - \beta|\dot{x}_b|\|v|^{\eta-1}v - \gamma\dot{x}_b|v|^{\eta}) \quad (5)$$

where D_y is the yield deformation and α, β, γ and η are the parameters defining the characteristics of the hysteresis loop of the frictional force.

For controller design, the standard first-order state equation corresponding to Equation 2 is given as:

$$\dot{X}(t)=AX(t) + B(U(t) - f(t)) + E\ddot{x}_g \quad (6)$$

where X^T =[$\overline{X}^T$ $\dot{\overline{X}}^T$]=2(r + 1) vector and

$$A=\begin{bmatrix} 0 & I \\ -(M^*)^{-1}K^* & -(M^*)^{-1}C^* \end{bmatrix},\ B=\begin{bmatrix} 0 \\ (M^*)^{-1}b \end{bmatrix},$$

$$E=\begin{bmatrix} 0 \\ -(M^*)^{-1}\overline{M} \end{bmatrix} \quad (7)$$

ADAPTIVE FUZZY SLIDING MODE CONTROL

For a complete account of robust control such as sliding mode control theory, the reader can consult the references (Decarlo et al., 1988; Utkin, 1992). The basic concept is that the controller changes its structures according to the position of the state trajectory with respect to a chosen sliding surface. The control is designed to force the state trajectory of the system onto the sliding surface and to maintain it there. This is accomplished by a high speed switching law. The design of a sliding mode controller consists of two steps: (1) The design of the sliding surface (2) The design of the control strategy to steer the state trajectory to the sliding surface.

The design of the sliding surface is described in the following. Consider the equation of system has the form:

$$\dot{X} = AX + BU + BH + F + W \quad (8)$$

where X(t) is a n state vector, n=2(r + 1), A is a n$\times$n system matrix, B is a n$\times$m matrix, H is a n vector which contains the uncertainty and nonlinear of a system and satisfy matching condition , F is an n vector which contains the uncertainty and nonlinear of the system, but F do not satisfy matching condition. W is an n excitation vector.

Suppose { x | S(X) = 0 } is the chosen sliding surface, the we have:

$$S(X)= PX \quad (9)$$

Consider the nominal system as:

$$\dot{X} = AX + BU \quad (10)$$

The optimal sliding modes method (Yang et al., 1995; Utkin, 1992) is used for the determination of P. The sliding surface is obtained by minimizing the integral of the quadratic function of the state vector as:

$$I= \int_0^\infty X^T QX dt \quad (11)$$

where Q is a (n$\times$ n) positive definite weighting matrix.

The second step is the design of the controller. The controllers are designed to drive the state trajectory into the sliding surface S=0.

Define a Lyapunov function V as:

$$V=0.5S^T S \quad (12)$$

In Equation 8, F is an n vector which contains the uncertainty and nonlinear of the system, W is an n excitation vector. Generally, system parameters are difficult to be known exactly, but the bounds on the uncertainty can be known.

$$\|F\| \le \delta_F \ , \ \|W\| \le \delta_W \quad (13)$$

Let

$$U = U_{eq} -(\gamma + \eta)\mathrm{sgn}(S^T PB)^T \quad (14)$$

where U_{eq} = - $(PB)^{-1}PAX$, $\gamma = \frac{\delta}{\|B\|}$, $\delta = \delta_F + \delta_W$

Let K= η + γ , $\overline{S}$ =$(S^TPB)^T$, Equation 14 control force U =U_{eq} –Ksgn($\overline{S}$), stability can be obtained when the following holds:

$$K \ge \eta + \frac{\delta}{\|B\|} \quad (15)$$

$\| \ \|$ denotes the Euclidean norm.

A drawback to the control law given in Equation 14 is that, it is discontinuous and tends to excite high frequency modes of the plant. The problem can be alleviated with the insertion of a boundary layer about the sliding surface. The characteristic U= f ($\overline{S}$) of the sliding mode controller with boundary layer is linear, but the one of fuzzy sliding mode controller is nonlinear.

A fuzzy sliding mode controller is proposed, in which a fuzzy inference mechanism is used to estimate the second part of Equation 14, that is u_f . The range of u_f is [-K , K] . The fuzzy rule is as follows:

If $\overline{S}$ is PB and $\dot{\overline{S}}$ is PB then u_f is NB.

Fuzzy output u_f can be calculated by the center of area defuzzification:

$$u_f = \frac{\sum_{i=1}^{l} w_i c_i}{\sum_{i=1}^{l} w_i} = \frac{[c_1 \ldots c_l]\begin{bmatrix} w_1 \\ \vdots \\ w_l \end{bmatrix}}{\sum_{i=1}^{l} w_i} = v^T \Psi \quad (16)$$

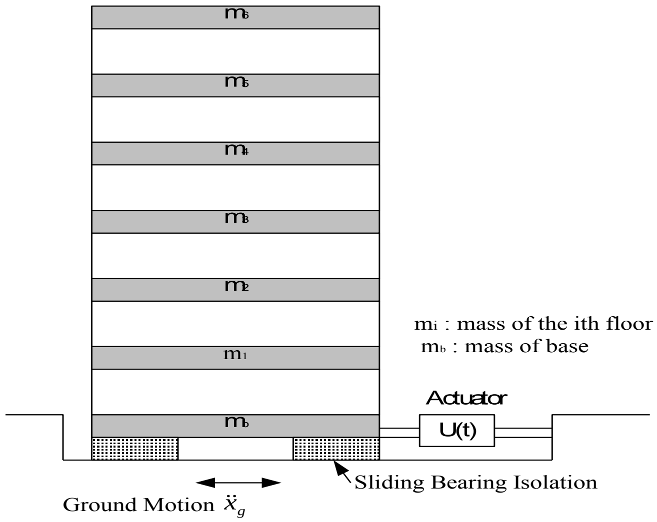

Figure 1. A base-isolated six floor building.

where v=$[c_1....c_l]^T$ is a adjustable parameter vector, c_i is the center of membership function and $\Psi = \frac{[w_1....w_l]^T}{\sum_{i=1}^{l} w_i}$ is a firing strength vector.

Assume u_f exists a specific $\hat{u}_f$ which achieves minimum control cost. $\hat{u}_f$ satisfies the sliding mode condition. From Equation 16, $\hat{u}_f$ can be written as follows:

$$\hat{u}_f = \hat{v}^T \Psi \tag{17}$$

where $\hat{v}$ is the optimal vector which achieves the minimum control cost.

Define the parameter vector as:

$$\tilde{v} = v - \hat{v} \tag{18}$$

Let the Lyapunov function for each controller be:

$$V = \frac{1}{2}(s^2 + \frac{1}{\alpha}\tilde{v}^T\tilde{v}) \tag{19}$$

where α is a positive constant.

Finally, the adaptive law (Yeh, 2011) is obtained as:

$$\dot{v} = -\alpha s P b_i \Psi \tag{20}$$

The adaptive law adjusts the centers of the membership function. From the earlier discussed, it can be seen that the traditional fuzzy sliding mode controller requires the upper bound of uncertainty. While the uncertainty increases, the control cost increases as well. But the optimal value of uncertainty can not be obtained exactly owing to the unknown of structure or system complexity. Adaptive fuzzy sliding mode control proposed in this paper can deal with the problem and estimate the minimum control cost. The characteristics of this approach is that the controller can be designed so that it estimates some uncertainty within the system, then automatically designs a controller for the uncertainty. In this way the control system uses information gathered on-line to reduce uncertainty, that is, to figure out exactly what the real environments are at the current time so that good control can be achieved.

In this work some examples are used to illustrate the adaptive fuzzy sliding mode control in isolated buildings.

NUMERICAL SIMULATION AND RESULTS

The fuzzy sliding mode controller is used to control building with sliding bearing isolations. Figure 1 shows a base-isolated six floors building. The nominal value of each floor mass is 345600 kg, base mass is 450000 kg, stiffness of each floor is 3.1×10^8 Nt/m, damping ratio is 0.02. The coefficient of friction μ for Teflon /strainless-steel bearings is given by Equation 3 with μ_m=0.1, μ_f=0.05, a_μ=20 s/m. The parameter values for Equation 4 are α =1.0, β =0.5, η =2, γ =0.5 and $D_y=1.2\times10^{-4}$ m. Firstly, the 1999 Taiwan Chi Chi earthquake (ew direction) whose peak ground acceleration is over 1 g is used as input excitation. Figure 2 is the time history of Chi Chi earthquake.

The optimal sliding mode method is used to determine the sliding surface with a diagonal weighting matrix Q; Q_{77}=1, $Q_{ii} = 5 \times 10^3$, for i= 1, 2,...6 and Q_{ii} = 1, for i= 8, 9,...14. Figures 3 and 4 show the structural responses of uncontrolled and fuzzy sliding mode control systems such as the base and the top floor displacement during

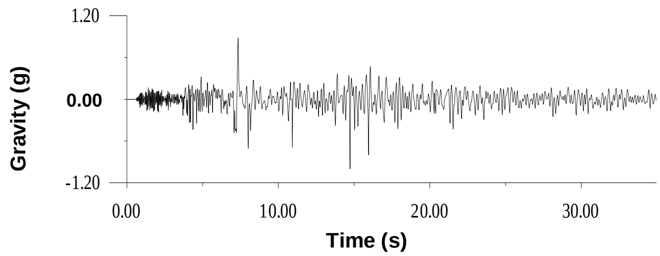

Figure 2. The Chi Chi earthquake.

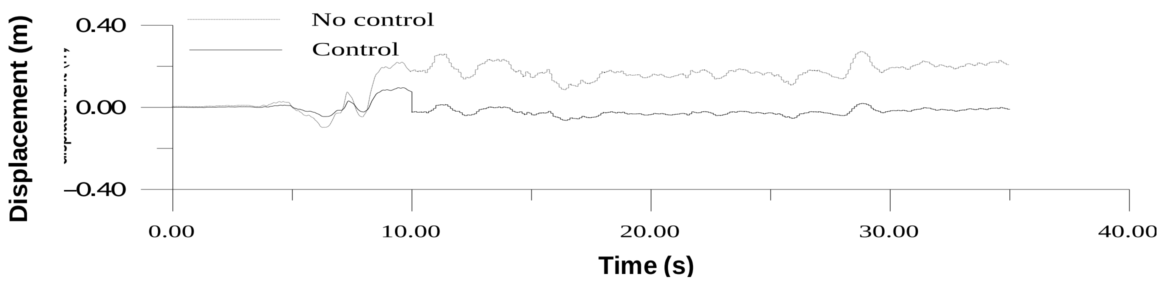

Figure 3. The base displacement history of building with sliding bearing.

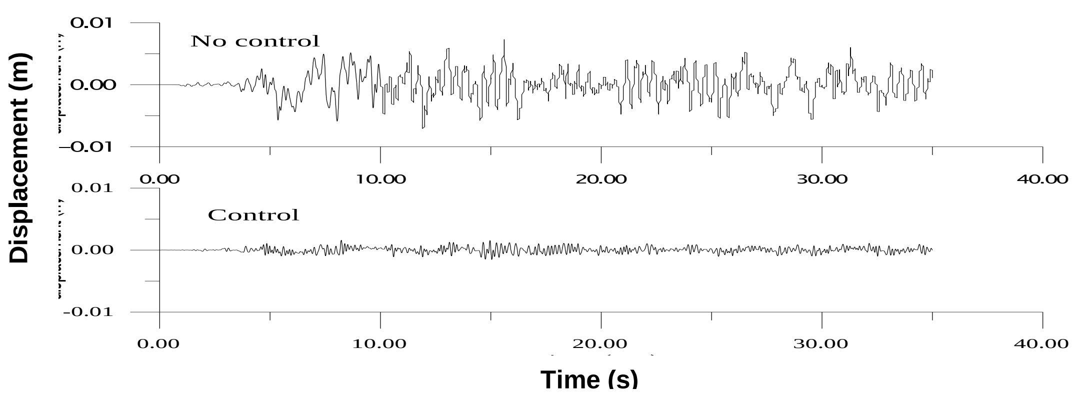

Figure 4. The top floor displacement history of building with sliding bearing.

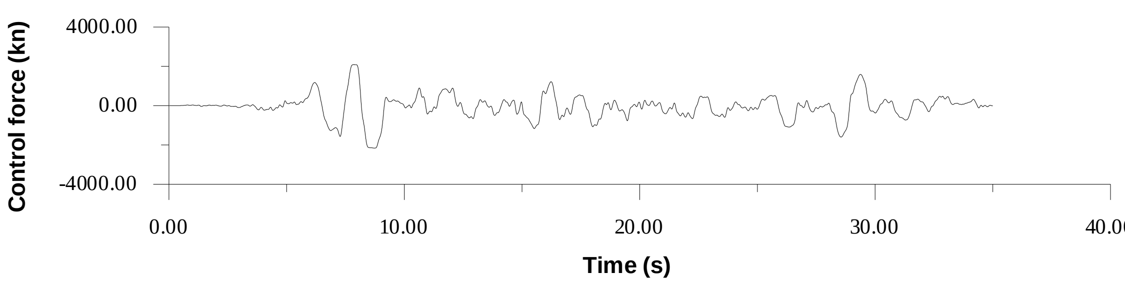

Figure 5. The control force history of fuzzy sliding mode control.

Chi Chi earthquakes. As seen from the figures, as compared to the case without control, the base and the top-floor displacement responses are reduced significantly. Figure 5 shows the control force sent to

Table 1. Maximum response quantities of building with sliding bearing.

Floor	No control U_{max}=0 kN		Control no error U_{max}=2174 kN		Stiffness +40% U_{max}=2174 kN		Stiffness -40% U_{max}=2174 kN		Time delay 30 ms U_{max}=2174 kN	
	x_i (m)	$\ddot{x}_i$ (m/s^2)	x_i (m)	$\ddot{x}_i$ (m/s^2)	x_i (m)	$\ddot{x}_i$ (m/s^2)	x_i (m)	$\ddot{x}_i$ (m/s^2)	x_i (m)	$\ddot{x}_i$ (m/s^2)
B	2.68E-01	11.066	1.19E-01	8.7792	1.56E-01	8.7266	1.41E-01	7.9341	2.02E-01	8.8813
1	7.77E-03	5.0928	2.89E-03	4.6607	3.61E-03	4.747	3.27E-03	4.9528	4.54E-03	5.0426
2	7.98E-03	6.7986	2.53E-03	4.9707	3.54E-03	5.0731	2.76E-03	5.0102	4.73E-03	5.2476
3	7.29E-03	6.7512	2.09E-03	3.6555	3.33E-03	4.5918	3.06E-03	4.4755	3.89E-03	5.1132
4	6.83E-03	6.0155	2.38E-03	3.7513	3.25E-03	4.1997	4.07E-03	3.5907	3.50E-03	4.0271
5	6.07E-03	5.4851	1.80E-03	3.5419	2.42E-03	4.163	3.75E-03	3.6777	2.74E-03	4.3466
6	4.63E-03	6.7718	1.60E-03	3.4441	1.84E-03	3.7724	2.71E-03	4.1679	2.77E-03	4.4257

(B: Base, i = 1,2,3,…..,6, the ith floor.

building due to the Chi Chi earthquake. Therefore, it is verified that the proposed s fuzzy sliding mode controller could significantly reduce the isolated-building structural response due to earthquake.

To examine the robustness of the self-tuning fuzzy robust control, we vary the stiffness of all the floor of the building by $\pm$40% in design controller and suppose 30 ms time delay. All maximum response quantities of building with sliding bearing are shown in Table 1. x_i, $\ddot{x}_i$, and U_{max}, are the interstory deformation of each floor or base , the absolute acceleration of each floor or base and maximum control force, respectively. Table 1 shows that the fuzzy sliding mode control can not only reduce the deformation of base, but the response of the superstructure and the amplitude of floor's acceleration also decreased. Notice that the performance results of the fuzzy sliding mode controller are still effective in reducing the building structural responses under stiffness uncertainty and time delay conditions. This means that the fuzzy sliding mode controller is robust. The maximum control forces of s fuzzy sliding mode control are rather low. They are all small than 9% weight of the superstructure.

CONCLUSIONS

It is shown that buildings equipped with isolation can reduce the interfloor drift and floor absolute acceleration from the simulations. The proposed fuzzy sliding mode control l not only reduces the base displacement, but all the above response quantities.

The maximum control forces of fuzzy sliding mode control are rather low. They are all small than 9% of the superstructure weight. Table 1 demonstrates this control method can work well in estimation error and time delay. It is robust, it can be used for structural control with nonlinear, uncertainty and time delay. It can be used in practical application.

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