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Fuzzy Sliding Surface Control of Wind-Induced Vibration

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Abstract— **Although normal fuzzy sliding mode controllers can reduce the chattering problem in building structure control, there are some problems such as they need the equivalent control and the upper bounds of the uncertainties. In this paper, we use fuzzy logic to approximate the sliding surface for the sliding mode control. The stability of the proposed controller is established. A six-story building prototype equipped with an active mass damper is used to demonstrate the effectiveness of the proposed controller towards the wind-induced vibration.**

I. Introduction

In order to protect the buildings from the earthquake and wind-induced vibrations, a passive or active control could be added to the building structure. Structural vibration can be generally controlled by using smart materials in the buildings [9] or by adding controlling devices like dampers or actuators to the building [8]. Different control devices and algorithms were proposed and implemented in the last few decades [18]. Many active control devices were designed for structural control applications. Active Mass Damper (AMD) is a popular actuator, which utilizes a moving mass of about 2% of the total building mass without a spring and dashpot. In this paper, we use AMD for the active vibration control.

The objective of structural control is to reduce the vibration of a building due to earthquakes or large winds through an external control force. Many attempts have been made to introduce advanced controllers for the active vibration control of building structures. One of the main challenges in the structural control is to design a robust control with respect to the uncertainties in the building structure. Some model-free controllers, such as Sliding Mode Control (SMC) [20], [3], neural network control [10], and fuzzy control [7] were employed for vibration attenuation. While SMC is one of the most popular robust controllers, because it is more simple than the other controllers and the behavior of SMC is similar to the vibration motion. A modal space SMC method is proposed in [2], where only the dominant frequency mode is considered in the design. Another SMC based on the modal analysis is presented in [3], which considers the first six modes. A decentralized system with SMC is presented in [14], where the reaching laws were derived, with and without considering actuator saturations.

Due to the imperfection in the high-frequency discontinuous switching, the direct implementation of the SMC will result in chattering effect, which may cause damage to the mechanical components like the actuators [22]. The tracking error of SMC converges to zero if its gain is bigger than the upper bound of the unknown nonlinear parts. The chattering mainly occurs due to the two facts: 1) SMC changes its sign very quickly near the sliding surface; 2) The gain of SMC is very big. There are many methods to reduce the chattering. Boundary layer method avoids chattering near the sliding surface. However, the control inside the boundary layer is not so efficient [16]. Higher order SMC preserves the features of the first order SMC and further improves its chattering reduction and convergence speed [13]. However, this SMC becomes complex and it requires the system knowledge about its uncertainty bounds. Many structural vibration control via SMC also needs the equivalent control [2], [4]. But it is difficult in the case of structural control because we do not have the complete building parameters. In [6], a low-pass filter is used to estimate the equivalent control. However, the filter parameters are difficult to tune and adds delay to the closed-loop system. SMC with gain adaptation have not yet been discussed in structural vibration control. In this paper, we use fuzzy logic technique, and do not need the equivalent control to avoid chattering.

Neural networks and fuzzy logic are the most popular intelligent control techniques used to modify SMC [22]. In [20], a neural network compensation with SMC is applied for the active control of seismically excited building structures, where the slope of the sliding surface is moved within a stable region. In [12], a radial basis function (RBF) neural network is used to obtain a chattering free SMC, while a genetic algorithm is applied during the training process. As SMC provides a stable and fast controller and the fuzzy logic provides the ability to handle a nonlinear system, many research works are carried out in designing SMC with fuzzy logic, called FSMC [11], [24]. The chattering problem is avoided in most of these FSMC systems. A genetic algorithm based FSMC is presented in [23], where the genetic algorithm is used to find the optimal rules and membership functions. References [3], [6], [1], [21] discuss the design of chattering free SMCs for structural vibration control.

In this paper, an AMD is used for attenuating the wind-induced vibrations in tall buildings. In order to avoid the chattering phenomenon with respect to the unknown building uncertainty bounds, we modify the sliding surface by using a fuzzy system. The modification successfully overcomes the problems of the other fuzzy SMC, such as the necessity of the equivalent control and the knowledge of the upper bounds of the uncertainties and moreover the stability is assured. An active vibration control system for a six-story building structure equipped with an AMD is constructed for the experimental study. The experimental results are compared with the other controller results and the effectiveness of the

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proposed algorithms is demonstrated.

II. Structural Control of Wind-Induced Vibration

A building structure can be modeled by using three components [5]: mass component m, damping component c, and stiffness component k. Among these three components the stiffness component k can be modeled either as linear (elastic) or nonlinear (inelastic). When an external force f_e is applied to the structure, it produces changes in its displacement $x(t)$, velocity $\dot{x}(t)$, and acceleration $\ddot{x}(t)$. Each floor is regarded as a single-degree-of-freedom structure, which can be modeled by

$$m\ddot{x} + c\dot{x} + kx = f_e \tag{1}$$

A n-floor building structure excited by an external force (e.g. wind force) can be expressed as

$$M\ddot{x}(t) + C\dot{x}(t) + F_s = -F_e \tag{2}$$

where $M = \begin{bmatrix} m_1 & 0 & \cdots & 0 \\ 0 & m_2 & \cdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & m_n \end{bmatrix}$, $C = \begin{bmatrix} c_1+c_2 & -c_2 & \cdots & 0 & 0 \\ -c_2 & c_2+c_3 & \cdots & \vdots & \vdots \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \vdots & \vdots & \cdots & c_{n-1}+c_n & -c_n \\ 0 & 0 & \cdots & -c_n & c_n \end{bmatrix}$, $M \in \Re^{n\times n}$ and $C \in \Re^{n\times n}$ are the mass and damping matrices, $F_e \in \Re^{n\times 1}$ is the external force vector acting on the structure, such as the earthquake or wind forces, and F_s is the structure stiffness. In (1), F_s is linear with respect to x,

$$F_s = Kx(t) \tag{3}$$

where $K = \begin{bmatrix} k_1+k_2 & -k_2 & \cdots & 0 & 0 \\ -k_2 & k_2+k_3 & \cdots & \vdots & \vdots \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \vdots & \vdots & \cdots & k_{n-1}+k_n & -k_n \\ 0 & 0 & \cdots & -k_n & k_n \end{bmatrix} \in \Re^{n\times n}$. In the case of real building structures, the relationship between the lateral force F_s and x is nonlinear. Then the stiffness component is inelastic. This happens when the structure is excited by a very strong force, which deforms the structure beyond its limit of linear elastic behavior. Then, the nonlinear force F_s in (2) can be represented using Bouc-Wen model [25] as

$$F_s = F_s(x, \dot{x}) = \tilde{\alpha}kx + (1-\tilde{\alpha})k\tilde{\eta}f_r \tag{4}$$

where $\tilde{\alpha}, k,$ and $\tilde{\eta}$ are positive numbers and f_r is the nonlinear restoring force that satisfies

$$\dot{f}_r = \frac{\tilde{\delta}\dot{x} - \tilde{\beta}|\dot{x}||f_r|^{p-1}f_r + \tilde{\gamma}\dot{x}|f_r|^p}{\tilde{\eta}} \tag{5}$$

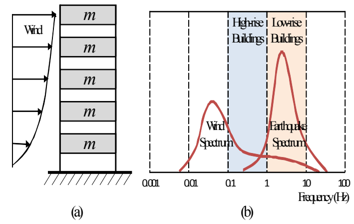

Fig. 1. (a) Wind excitation (b) Frequency spectrum of excitations.

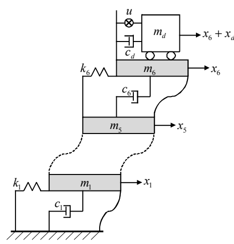

Fig. 2. Building structure equipped with AMD.

where $\tilde{\delta}, \tilde{\beta},$ and $\tilde{\gamma}$ are positive numbers and p is an odd number.

The wind force acts on a building in the form of an external pressure, see Figure 1 (a). The frequency range of wind force is usually lesser than that of the earthquake forces, see Figure 1 (b). For that reason the high-rise buildings are more effected by these wind forces. If the wind-induced vibration exceeds more than $0.15\,\mathrm{m}/\mathrm{s}^2$, humans may feel uncomfortable and the fragile items in the building may be damaged [17]. The main objective of structural control against the high wind forces is to reduce the relative movement of the building into a comfortable level.

In order to attenuate the vibrations caused by the external wind force, an AMD is installed in the structure, see Figure 2. The force exerted by the AMD on the structure is

$$F_d = m_d(\ddot{x}_r + \ddot{x}_d) = u - d \tag{6}$$

where m_d is the mass of the damper, $\ddot{x}_r$ is the acceleration of r-th floor on which the damper is installed, $\ddot{x}_d$ is the acceleration of the damper, u is the control signal to the damper generated by a control algorithm, and

$$d = c_d\dot{x}_d + \epsilon m_d g \,\mathrm{sign}\left[\dot{x}_d\right]$$

where c_d and $\dot{x}_d$ are the damping coefficient and velocity of the damper respectively, g is the acceleration due to gravity, and ϵ is the friction coefficient between the damper and the floor on which it is attached.

The closed-loop system with AMD is

$$M\ddot{x}(t) + C\dot{x}(t) + F_s + F_e = \Gamma u \tag{7}$$

where $u \in \Re^{n\times 1}$ is the control signal applied to the damper, $\Gamma \in \Re^{n\times n}$ is the location matrix of the dampers

$$\Gamma_{i,j} = \begin{cases} 1 & i = j = r \\ 0 & i \neq j \neq r \end{cases}, \forall i, j \in \{1, ..., n\}, r \subseteq \{1, ..., n\}$$

where r are the floors on which the dampers are installed. In the case of a two-story building, if the damper is placed on the second floor, $r = \{2\}$, $\Gamma_{2,2} = 1$. If the damper is placed on both the first and second floor, then $r = \{1, 2\}$, $\Gamma_{2\times 2} = I_{2\times 2}$.

Obviously, the building structures are stable when there is no external force, $F_e = 0$. In this case, the active control is not needed, hence $u = 0$. The ideal active control is $\Gamma u = F_e$. However, it is impossible because F_e is not always measurable and $F_e \gg F_d$. Depending on the size of the building, the power requirements of these actuators vary from kilowatts to several megawatts. The objective of the active control is to maintain the vibration as small as possible and to keep the energy requirement as minimum as possible, for example to avoid the actuator saturation.

The structure model (7) can be rewritten in state-space form as

$$\begin{aligned} \dot{z}_1 &= z_2 \\ \dot{z}_2 &= f(z) + \widetilde{\Gamma} u \end{aligned} \tag{8}$$

where $z_1 = x$, $z_2 = \dot{x}$, $f(z) = -M^{-1}\left[Cz_2 + F_s + F_e\right]$, $\widetilde{\Gamma} = M^{-1}\Gamma$. The output can be defined as $y = C_y z$, where C_y is a known matrix.

One of the most important approach for dealing the model uncertainty is the robust control. Equation (8) can be written as

$$\dot{z} = Az + Bf_0(z) + B\Delta f + B\widetilde{\Gamma} u \tag{9}$$

where f_0 is the nominal structure dynamics, Δf is the uncertainty part, $A = \begin{bmatrix} 0 & I \\ 0 & 0 \end{bmatrix} \in \Re^{2n\times 2n}$, $B = [0, I]^T$, $z = \left[z_1^T, z_2^T\right]^T$. We assume that the uncertainty, $\Delta f = f(z) - f_0(z)$ is bounded as

$$\|\Delta f\| \leq \bar{f}_d \tag{10}$$

If the parameters of $f(z)$ is completely unknown, then we assume that $f(z)$ is also bounded.

$$\|f(z)\| \leq \bar{f} \tag{11}$$

This assumption is practically reasonable, because in the absence of external forces the building structure is stable and also the big input excitation forces are bounded, $\|F_e\| \leq \bar{F}_e$.

A. Sliding Mode Control with Fuzzy Sliding Surface

In recent years, increasing attention has been given to the systems with discontinuous control actions. By intelligent selection of control actions, the state trajectories may be changed correspondingly to give the desired properties to the processes in the system under control. The control design problem in such systems with discontinuous control actions (sliding mode control) can be reduced to the convergence problem to a special surface in the corresponding phase space (sliding surface).

A general class of discontinuous structural control is defined by the following relationships

$$u = -\eta \mathrm{sign}(s) = \begin{cases} -\eta & \text{if } s > 0 \\ 0 & \text{if } s = 0 \\ \eta & \text{if } s < 0 \end{cases}, \quad \eta > 0 \tag{12}$$

where s is the sliding surface and $\mathrm{sign}(s) = \left[\mathrm{sign}(s_1), \ldots, \mathrm{sign}(s_{2n})\right]^T$. The sliding surface can be a function of the regulation error $e = z - z^d$, where z^d is the desired state. If we use $s = e$, then the objective of the SMC is to drive the regulation error to zero in the presence of disturbance. In active vibration control of building structures, the references are defined as $z^d = \left[x^d, \dot{x}^d\right]^T = 0$, then $s = \left[x^T, \dot{x}^T\right]^T \in \Re^{2n\times 1}$ and $\dot{s} = \dot{z}$.

Consider the positive definite quadratic form

$$V_1 = s^T P s, \quad P = P^T > 0 \tag{13}$$

Finding the time derivative of the function (13) on the trajectory of system (9), we get

$$\dot{V}_1 = z^T\left(A^T P + PA\right)z + 2z^T PBf + 2z^T PB\widetilde{\Gamma} u \tag{14}$$

Since, A is a stable matrix, there exits $Q = Q^T > 0$, such that $A^T P + PA = -Q$. Using (11), (12), and $PB\widetilde{\Gamma} > 0$

$$\dot{V}_1 \leq -\|z\|_Q^2 + 2\bar{f}\,\|PB\|\,\|z\| + 2z^T PB\widetilde{\Gamma}\eta\mathrm{sign}(z) \tag{15}$$

Using the property $z^T\mathrm{sign}(z) = \|z\|$ we can write

$$\begin{aligned} \dot{V}_1 &\leq -\|z\|_Q^2 + 2\bar{f}\,\|PB\|\,\|z\| - 2\eta\,\|PB\|\left\|\widetilde{\Gamma}\right\|\|z\| \\ &= -\|z\|_Q^2 + 2\,\|PB\|\,\|z\|\left(\bar{f} - \eta\left\|\widetilde{\Gamma}\right\|\right) \\ &\leq 2\,\|PB\|\,\|z\|\left(\bar{f} - \eta\left\|\widetilde{\Gamma}\right\|\right) \end{aligned} \tag{16}$$

Obviously, if the gain of the sliding mode control satisfies the following condition

$$\eta \geq \frac{\bar{f}}{\left\|\widetilde{\Gamma}\right\|}$$

then $\dot{V}_1 \leq 0$. From [15] we know that the $s = e$ will converge to zero.

Since, $\bar{f}$ in (11) is unknown, we have to select a very big η in (12). This may amplify the chattering effect, where the control signal switches in a high-frequency within a tight neighborhood of the sliding surface. In structural control, this is also caused by the unmodelled parasitic dynamics present in the system. This high frequency switching can damage mechanical systems like the actuators. Although, the huge dampers with big time constants in the structural vibration control can be regarded as a second order low-pass filter and do not respond to high frequency commands, the chattering control signal may damage the motor mechanism of the AMD.

Many strategies were proposed to reduce the chattering phenomenon. The boundary layer method approximates the sign function in (12) using a saturation function.

$$u = -\eta \mathrm{sat}(s) = \begin{cases} -\eta & \text{if } s > \delta \\ \frac{s}{\delta}\eta & \text{if } \delta \geq s \geq -\delta \\ \eta & \text{if } s < -\delta \end{cases}, \quad \eta > 0 \tag{17}$$

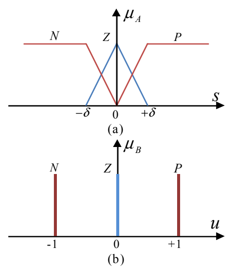

Fig. 3. Membership functions: (a) input set (b) output set.

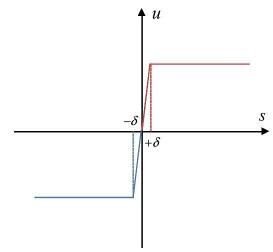

Fig. 4. FSMC switching.

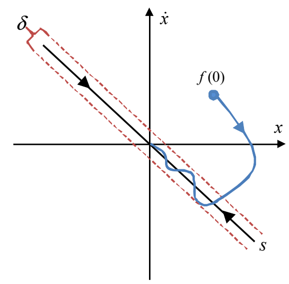

Fig. 5. Concept of real sliding surface.

where δ is a positive constant and 2δ is the thickness of the boundary layer. In general, the bigger the boundary layer thickness, the smoother the control signal, and the bigger the residual set to which s will converge. The boundary layer method smooths the control signal with a loss of control accuracy.

In this paper, we use a fuzzy system to smooth the sliding surface s. We use the following three fuzzy rules

R^1: IF s is “Positive" P THEN u is “Negative” $-\eta$
R^2: IF s is “Zero" Z THEN u is “Zero” Z
R^3: IF s is “Negative" N THEN u is “Positive” η

The membership function of the input linguistic variable s is defined as μ_A, the membership function of the output linguistic variable u is defined as μ_B. We use triangle functions as the membership functions, see Figure 3.

By using product inference, center-average, and singleton fuzzifier, the output of the fuzzy logic system can be expressed as

$$u = \eta \frac{w_1 \mu_{A_P}(s) + w_2 \mu_{A_Z}(s) + w_3 \mu_{A_N}(s)}{\mu_{A_P}(s) + \mu_{A_Z}(s) + \mu_{A_N}(s)} \tag{18}$$

where μ_{A_P}, μ_{A_Z}, and μ_{A_N} are membership functions of “Positive”, “Zero”, and “Negative” of the input s and w_i, $i = 1 \cdots 3$, are the points at which $\mu_B = 1$. From Figure 3 (b) $w_1 = -1$, $w_2 = 0$, $w_3 = 1$, then (18) becomes

$$u = \frac{\mu_{A_N}(s) - \mu_{A_P}(s)}{\mu_{A_P}(s) + \mu_{A_Z}(s) + \mu_{A_N}(s)} \tag{19}$$

We can see that, when $s > \delta$, $\mu_{A_P}(s) = 1$, $\mu_{A_Z}(s) = 0$, $\mu_{A_N}(s) = 0$, then $u = -\eta$; and when $s < -\delta$, $\mu_{A_P}(s) = 0$, $\mu_{A_Z}(s) = 0$, $\mu_{A_N}(s) = 1$, then $u = \eta$. Finally, the sliding mode control with fuzzy sliding surface is

$$u = \begin{cases} -\eta \text{ sign}(s) & \text{if } \|s\| > \delta \\ \eta \frac{\mu_{A_N}(s) - \mu_{A_P}(s)}{\mu_{A_P}(s) + \mu_{A_Z}(s) + \mu_{A_N}(s)} & \text{if } \|s\| \leq \delta \end{cases}, \quad \eta > 0 \tag{20}$$

The fuzzy switching is shown in Figure 4.

The stability of the fuzzy sliding mode control (20) is proved by using the same Lyapunov function (13). We substitute the fuzzy sliding mode control (20) into (14), which is the time derivative of the function (13). We consider two cases

1) When $\|s\| > \delta$, $u = -\eta \text{sign}(s)$. It is the same as (16), if $\eta \geq \frac{\bar{f}}{\|\Gamma\|}$, $\dot{V}_1 \leq 0$, hence s decreases.

2) When $\|s\| \leq \delta$, $u = \eta \frac{\mu_{A_N}(s) - \mu_{A_P}(s)}{\mu_{A_P}(s) + \mu_{A_Z}(s) + \mu_{A_N}(s)}$. Then s is bounded in the residential set δ.

From 1) and 2), we know that s is bounded and the total time during which $\|s\| > \delta$ is finite. Let T_j denotes the time interval during which $\|s\| > \delta$. (a) If only finite times that s stay outside the circle of radius δ (and then reenter), s will eventually stay inside this circle. (b) If s leave the circle infinite times, since the total time s leave the circle is finite,

$$\sum_{j=1}^{\infty} T_j < \infty, \quad \lim_{j \to \infty} T_j = 0 \tag{21}$$

So s is bounded via an invariant set argument. Let $s(k)$ denotes the largest tracking error during the T_j interval. Then (21) and bounded $s(k)$ imply that

$$\lim_{k \to \infty} [-s(k) + \delta] = 0$$

So $s(k)$ will converge to δ. From these discussions one can say that the implementation of (20) can only assures a “real sliding surface” [**?**], which guarantees the state trajectories will slide within a domain (δ), see Figure 5.

III. Experimental Results

To illustrate the theory analysis results of this paper, a six-story building prototype is constructed which is mounted on a shaking table, see Figure 6. The building structure is constructed of aluminum. The shaking table is actuated using a hydraulic control system (FEEDBACK EHS 160), which is used to generate the excitation signals. The AMD is a linear servo actuator (STB1104, Copley Controls Corp.), which is mounted on the sixth `floor`. The moving mass of the damper weights 3% of the total building mass. The linear servo mechanism is driven by a digital servo drive (Accelnet

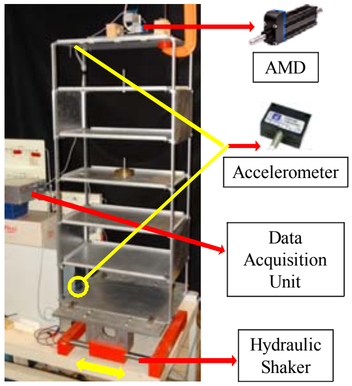

Fig. 6. Experimental setup.

Micro Panel, Copley Controls Corp). ServoToGo II I/O board is used for the data acquisition purpose.

The control programs are operated in Windows XP with Matlab 7.2/Simulink. All the control actions are employed at a sampling frequency of $1.0\,\text{kHz}$. The control signal generated by the control algorithm is fed as voltage input to the amplifier. The amplifier converts its voltage to a corresponding current output. The AMD operation is realized by current control loop. The force constant of the AMD is $5.42\,\text{N}\,/\,\text{A}$.

The structure displacement under the wind-induced vibration can be referred in three ways: a) absolute or total displacement $x_a(t)$, b) ground displacement $x_g(t)$, and c) relative displacement $x(t)$ between the floor mass and the ground. The relationship between these three displacements is

$$x_a(t) = x_g(t) + x(t) \tag{22}$$

In the case of wind excitation, $x_g = 0$. The proposed controller needs the structure position and velocity data. Two accelerometers (Summit Instruments 13203B) are used to measure the ground and the top floor accelerations. The ground acceleration is then subtracted from the top floor acceleration to get the relative floor movement. The relative velocity and position data are then estimated using the numerical integrator proposed in [19].

The proposed SMC with fuzzy sliding surface (FSMC) is compared with a classic PID controller and normal SMC. All of these controllers are designed to work within the normal operation range of the AMD. The PID control has the following form

$$u = -K_p x - K_d \dot{x} - K_i \int_0^t x(\tau)\, d\tau \tag{23}$$

where $k_p = 425$, $k_i = 50$, $k_d = 55$, are the proportional, integral, and derivative gains. The SMC has a fixed switching gain of $\eta = 0.8$. The FSMC parameters are $\bar{\eta} = 50$, $\eta_{t=0} = 0.8$, $\delta = 0.02$, and $\mu = 0.001$. These parameters are selected in such a way that a satisfactory chattering and vibration attenuation is achieved.

The control performance is evaluated in the sense of reducing relative displacement of each floor. The wind

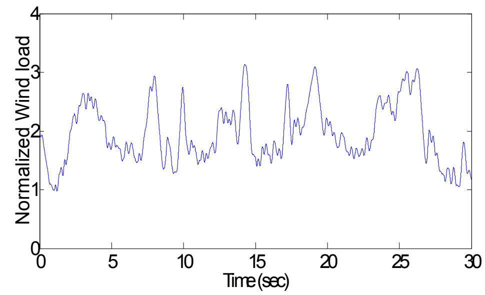

Fig. 7. Wind excitation signal.

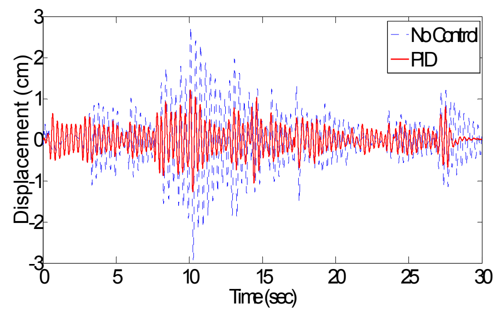

Fig. 8. Uncontrolled and controlled displacements of the top floor using PID controller.

force signal used to excite the building prototype is shown in Figure 7. Figures 8–10 show the time responses of the sixth floor displacement for both the controlled and uncontrolled cases. The control algorithm output is shown in Figure 11.

We can see that the response time of the PID controller is slower than the normal SMC. The PID controller produces peak control signals. For normal SMC, increasing η beyond 0.8 results unwanted vibration in certain points due to the chattering. To avoid this, the gain is kept as 0.8. Among these three controllers, FSMC produces the best result. For FSMC, the adaptive algorithm significantly reduces the switching gain when the vibration decreases. Therefore, the control energy is adjusted to a better value such that the AMD power requirement is also reduced. The control signal becomes continues during the interval $[0, 2.5]$ and $[22, 23.5]$, because $\|s\| \leq \delta$.

IV. Conclusion

The selection of SMC switching gain is crucial in the controller design. In this paper, adaptive and fuzzy control techniques are combined to overcome the chattering problem of SMC. The SMC gain is updated online. The stability of the proposed controller is established using Lyapunov-like theory. The technical advance of this paper is that a systematic tuning method of SMC gain and sliding surface is proposed based on the stability analysis. The above new approaches are successfully applied to a six-story building prototype.

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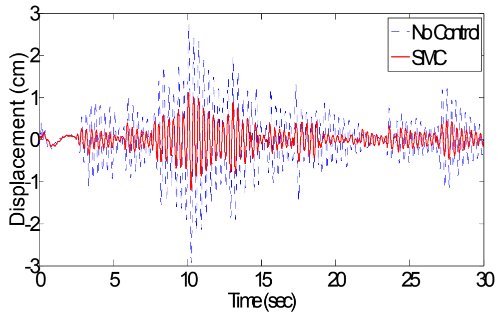

Fig. 9. Uncontrolled and controlled displacements of the top floor using SMC controller.

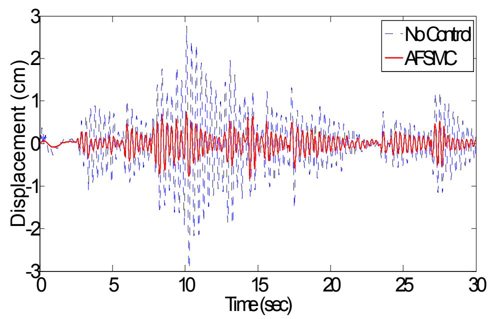

Fig. 10. Uncontrolled and controlled displacements of the top floor using FSMC controller.

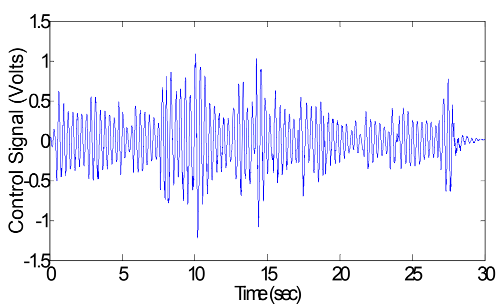

Fig. 11. Control signal from PID controller.

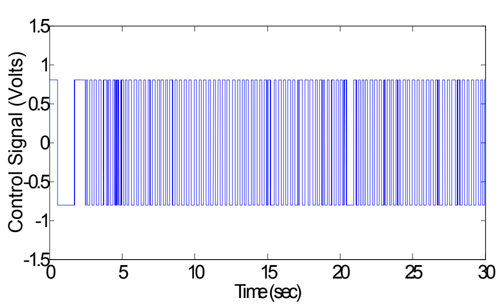

Fig. 12. Control signal from SMC controller.

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