대형구조물의 진동 감소를 위한 슬라이딩 모드 퍼지 제어기의 설계

Design of Sliding Mode Fuzzy Controller for Vibration Reduction of Large Structures

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국문요약

대형구조물의 진동감소를 위한 슬라이딩 모드 퍼지 제어기 (Sliding Mode Fuzzy Control, SMFC)에 대하여 연구하였다. 본 제어기에 사용된 퍼지 추론기의 규칙은 비선형 제어기법의 하나인 슬라이딩 모드 제어기를 기반으로 하여 구성되었다. 그 결과, 제어기의 퍼지성은 제어 시스템을 시스템 계수의 불확실성과 구조물에 작용되는 외부하중의 불확실성에 대하여 강인한 성질을 갖게 하였으며, 제어 규칙의 비선형성으로 인하여 제어기는 선형제어기에 비하여 보다 효율적이 되었다. 복잡한 수학 해석에 기반한 종래의 제어기법에 비하여 퍼지 이론에 기반한 본 제어기법은 제어기의 설계절차가 매우 편리하다는 장점을 갖게 된다. 제안된 제어기법의 검증을 위하여 미국 토목학회 산하 구조제어 위원회(ASCE Committee on Structural Control)에서 주도한 벤치마크 문제에 대하여 적용시켜 보았다. 본 연구의 제어결과를 다른 연구자들에 의하여 발표된 $H_{mixed\ 2/\infty}$, optimal polynomial control, neural networks control, 슬라이딩 모드 제어의 벤치마크 결과와 비교하였으며, 그 결과 제안된 제어기법이 구조물의 진동을 매우 효율적으로 감소시키며, 제어기의 설계절차가 쉽고 편리함을 확인할 수 있었다.

주요어 : 진동제어, 퍼지, 지진 피해 감소, 강인제어

ABSTRACT

A sliding mode fuzzy control (SMFC) algorithm is presented for vibration reduction of large structures. Rule-base of the fuzzy inference engine is constructed based on the sliding mode control, which is one of the nonlinear control algorithms. Fuzziness of the controller makes the control system robust against the uncertainties in the system parameters and the input excitation. Non-linearity of the control rule makes the controller more effective than linear controllers. Design procedure based on the present fuzzy control is more convenient than those of the conventional algorithms based on complex mathematical analysis, such as linear quadratic regulator and sliding mode control (SMC). Robustness of presented controller is illustrated by examining the loop transfer function. For verification of the present algorithm, a numerical study is carried out on the benchmark problem initiated by the ASCE Committee on Structural Control. To achieve a high level of realism, various aspects are considered such as actuator-structure interaction, modeling error, sensor noise, actuator time delay, precision of the A/D and D/A converters, magnitude of control force, and order of control model. Performance of the SMFC is examined in comparison with those of other control algorithms such as $H_{mixed\ 2/\infty}$, optimal polynomial control, neural networks control, and SMC, which were reported by other researchers. The results indicate that the present SMFC is an efficient and attractive control method, since the vibration responses of the structure can be reduced very effectively and the design procedure is simple and convenient.

Key words *: vibration control, fuzzy control, sliding mode fuzzy control, earthquake, robust control, benchmark problem*

1. Introduction

Vibration control is one of the effective methods to reduce the excessive vibration by installing additional control devices. Many researchers have suggested various control methods. Most of them are based on the ordinary linear optimal theory.$^{(1),(2)}$ However, recently developed control devices such as

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본 논문에 대한 토의를 12월 31일까지 학회로 보내 주시면 그 결과를 게재하겠습니다.

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hybrid systems and semi-active systems have inherent nonlinear properties. Moreover, in current design practice, structures are assumed to behave non-linearly under severe loading conditions. Hence it is necessary to develop nonlinear control methods. Sliding mode control (SMC) technique[(3)] is one of the non-linear algorithms, which is recently introduced to vibration control of civil engineering structures. The technique can handle the nonlinear systems and may suppress the vibration more effectively than the linear control algorithms. It can also avoid the saturation of the actuator and utilize the measured external environmental loads explicitly. It is generally robust against uncertainties in the structural parameters.

The present sliding mode fuzzy control (SMFC) algorithm is a fuzzified sliding mode control. Overall structure of the controller is similar to the sliding mode control. However, the control rule is fuzzified, then modified reflecting the control designer's experience.[(4)] By incorporating the fuzzy logic, the SMFC can be more effective and more robust against the uncertainties in the system parameters and the input excitations than the SMC. Moreover, in most of the algorithms based on the complex mathematical models, it is very difficult to design the controllers. Designers must select the design parameters, such as weighting matrices in LQR, convergence factor and weighting matrix in SMC, and weighted sensitivity functions in robust control.[(5),(6)] Many iterative simulations based on experience are generally needed to obtain the appropriate design parameters. However, the SMFC may be designed very intuitively by scaling the input and output fuzzy numbers.

In this paper, theory and verification of the SMFC are presented. Validity and applicability of the suggested algorithm are examined through a numerical study on the benchmark problem initiated by the ASCE Committee on Structural Control.[(7)] Comparison with the results obtained by other algorithm[(3),(7),(8)] shows the effectiveness of the SMFC.

2. Model of control system

Consider a structure subjected to an earthquake excitation and controlled by an actuator system. Then the system dynamics can be represented by an n_χ - order augmented state space model, taking into account the interactions between the structure and the control devices as[(3)]

$$\dot{\mathbf{x}}_a(t) = \mathbf{A}_a\mathbf{x}_a(t) + \mathbf{B}_{au}\mathbf{u}_c(t) + \mathbf{B}_{ag}\ddot{y}_g(t) \tag{1}$$

where $\mathbf{x}_a(t)$=augmented state vector considering the structure and the actuators; $\mathbf{u}_c(t)$= control command signal; $\ddot{y}_g(t)$=ground acceleration; and $\mathbf{A}_a, \mathbf{B}_{au}, \mathbf{B}_{ag}$=augmented system matrices. The augmented measurement equation can be written as

$$\mathbf{y}_{ma}(t) = \mathbf{C}_{ma}\mathbf{x}_a(t) + \mathbf{D}_{mau}\mathbf{u}_c(t) + \mathbf{D}_{mag}\ddot{y}_g(t) \tag{2}$$

where $\mathbf{y}_{ma}(t) = \left\{ \ddot{\mathbf{y}}_{sa}(t)^T \quad \mathbf{y}_p(t)^T \quad \mathbf{u}_s(t)^T \quad \ddot{y}_g(t)^T \right\}^T$; $\ddot{\mathbf{y}}_{sa}(t)$=absolute acceleration of structure; $\mathbf{y}_p(t)$ and $\dot{\mathbf{y}}_p(t)$=displacement and velocity of the actuator piston relative to the floor; $\mathbf{u}_s(t)$= control force vector; and $\mathbf{C}_{ma}$, $\mathbf{D}_{mau}$, and $\mathbf{D}_{mag}$ =measurement system matrices. The control equation is obtained as

$$\mathbf{y}_{ca}(t) = \mathbf{C}_{ca}\mathbf{x}_a(t) + \mathbf{D}_{cau}\mathbf{u}_c(t) + \mathbf{D}_{cag}\ddot{y}_g(t) \tag{3}$$

where $\mathbf{y}_{ca}(t) = \{\mathbf{y}_s(t)^T \quad \dot{\mathbf{y}}_s(t)^T \quad \ddot{\mathbf{y}}_{sa}(t)^T \quad y_p(t)^T$

$\dot{y}_p(t)^T \quad \mathbf{u}_s(t)^T\}^T$ = augmented control signal; $\mathbf{y}_s(t)$ =displacement of structure relative to the ground; and $\mathbf{C}_{ma}$, $\mathbf{D}_{mau}$ and $\mathbf{D}_{mag}$ = measurement system matrices.

For the computational efficiency, the control law is designed based on the reduced model using the balanced truncation method.(9) Then the state space system is transformed into a balanced system, of which the controllability and the observability Gramians are diagonal and identical. Taking the largest n_r ($\leq n_x$) Hankel singular values, the following reduced-order system incorporating the modeling error and the measurement noise can be obtained as

$$\begin{aligned}
\dot{\mathbf{x}}_r(t) &= \mathbf{A}_r\mathbf{x}_r(t) + \mathbf{B}_{ru}\mathbf{u}_c(t) + \mathbf{B}_{rg}\ddot{y}_{gm}(t) - \mathbf{B}_{rg}v_g(t) + \mathbf{B}_{rw}\mathbf{w}_r(t) \\
\mathbf{y}_{mr}(t) &= \mathbf{C}_{mr}\mathbf{x}_r(t) + \mathbf{D}_{mru}\mathbf{u}_c(t) + \mathbf{D}_{mrg}\ddot{y}_{gm}(t) - \mathbf{D}_{mrg}v_g(t) + \\
&\qquad + \mathbf{D}_{mrw}\mathbf{w}_r(t) + \mathbf{v}_r(t) \\
\mathbf{y}_{cr}(t) &= \mathbf{C}_{cr}\mathbf{x}_r(t) + \mathbf{D}_{cru}\mathbf{u}_c(t) + \mathbf{D}_{crg}\ddot{y}_{gm}(t) - \mathbf{D}_{crg}v_g(t) + \mathbf{D}_{crw}\mathbf{w}_r
\end{aligned} \tag{4}$$

where $\mathbf{y}_{mr}(t)$, and $\mathbf{y}_{cr}(t)$= measured signal and control signal of the reduced system, whose components are identical to those of $\mathbf{y}_{ma}(t)$ and $\mathbf{y}_{ca}(t)$; $\mathbf{x}_r(t)$=state variable for the reduced system; $\ddot{y}_{gm}(t)$=measured ground acceleration; $v_g(t)$ = noise in measured ground acceleration; $\mathbf{w}_r(t)$ = modeling error; and $\mathbf{v}_r(t)$ =noise in measured signal.

To estimate the reduced state from the measured signal, Kalman-Bucy filter is used as(10)-(13)

$$\begin{aligned}
\dot{\mathbf{x}}_{rE}(t) &= \mathbf{A}_r\mathbf{x}_{rE}(t) + \mathbf{B}_{ru}\mathbf{u}_c(t) + \mathbf{B}_{rg}\ddot{y}_{gm}(t) \\
&\quad + \mathbf{L}_{ob}(\mathbf{y}_{mr}(t) - \mathbf{C}_{mr}\mathbf{x}_{rE}(t) - \mathbf{D}_{mru}\mathbf{u}_c(t) - \mathbf{D}_{mrg}\ddot{y}_{gm}(t))
\end{aligned} \tag{5}$$

where $\mathbf{x}_{rE}(t)$=estimated state vector; and $\mathbf{L}_{ob} = \left(\mathbf{P}_{ob}\mathbf{C}_{mr}^T + \mathbf{B}_{rgw}\mathbf{S}_{ob}\right)\mathbf{R}_{ob}^{-1}$ =observer gain matrix.

Overall structure of the structure-control system is shown in Fig 1.

3. Design of sliding mode fuzzy control

As in the sliding mode control (SMC), the basic strategy of the sliding mode fuzzy control (SMFC) is forcing the state of the system to stay in some region, so called the sliding surface, whereas the response of the system on the sliding surface can be reduced rapidly.(3),(14)-(25) Using the Lyapunov's direct method, the structure of the SMFC can be constructed as(17),(20),(23),(26),(27)

$$\begin{aligned}
\mathbf{u}_c(t) &= -(\mathbf{PB}_{ru})^{-1}\left(\mathbf{PA}_r + \begin{bmatrix} \ddots & & \\ & \eta & \\ & & \ddots \end{bmatrix}\mathbf{P}\right)\mathbf{x}_{rE}(t) \\
&\quad - (\mathbf{PB}_{ru})^{-1}\mathbf{PB}_{rg}\ddot{y}_{gm}(t)
\end{aligned} \tag{6}$$

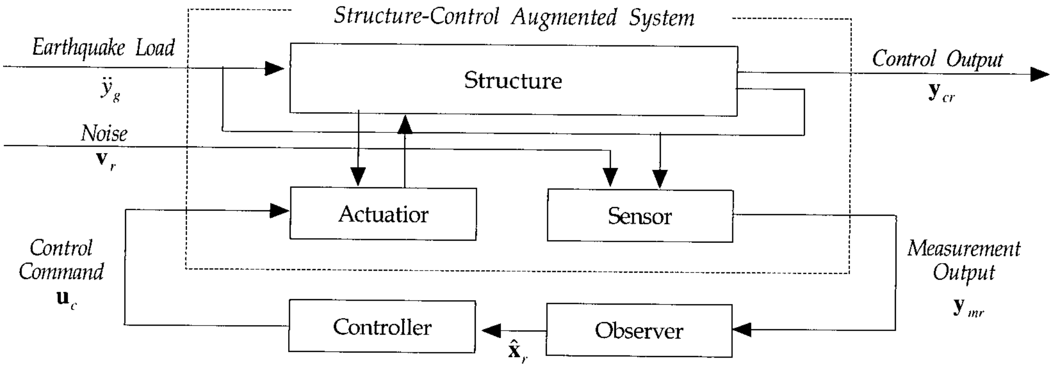


Fig. 1 Schematic diagram for structure-control system

where $\mathbf{P}=\left[P_1 \ \cdots \ P_{n_u}\right]^T$; P_i=direction vector of the sliding surface for the i-th control force.

Converting the above control law into a fuzzy form, a SMFC can be obtained. The present fuzzy controller consists of 5 modules : (1) Normalization, (2) Fuzzification, (3) Inference Engine, (4) De-Fuzzification, and (5) De-Normalization.(4),(28),(29)

In the first module named *Normalization*, the observed signal are normalized as

$$\mathbf{s}_n(t)=\alpha_n\mathbf{K}_n\mathbf{x}_{rE}(t),\ \ \mathbf{s}_t(t)=\alpha_t\mathbf{K}_t\mathbf{x}_{rE}(t),$$
$$\mathbf{s}_y(t)=\alpha_y\mathbf{K}_y\ddot{y}_{gm}(t) \tag{7}$$

where $\mathbf{K}_n=(\mathbf{PB}_{ru})^{-1}\left(\mathbf{PA}_r+\left[\ddots\eta\ddots\right]\mathbf{P}\right)$, $\mathbf{K}_t=\dfrac{\|\mathbf{K}_n\|}{\|\mathbf{B}_{ru}\|}\mathbf{B}_{ru}^T-\dfrac{\mathbf{K}_n\mathbf{B}_{ru}}{\|\mathbf{K}_n\|\|\mathbf{B}_{ru}\|}\mathbf{K}_n$, $\mathbf{K}_y=-(\mathbf{PB}_{ru})^{-1}\mathbf{PB}_{rg}$ and $\mathbf{s}_n(t)$ and $\mathbf{s}_t(t)$=normal and tangential components of the state vectors with respect to the transformed sliding surface; $\mathbf{s}_y(t)$=auxiliary state representing the feed-forward control force; and α_n, α_t and α_y are scale factors.

Fuzzification module converts the scaled crisp values to the fuzzy numbers with singleton membership functions as follows

$$\mu_{\tilde{\mathbf{s}}_n^I}(s)=\begin{cases}1 & if\ \ s=\mathbf{s}_n\\ 0 & otherwise\end{cases},\quad \mu_{\tilde{\mathbf{s}}_t^I}(s)=\begin{cases}1 & if\ \ s=\mathbf{s}_t\\ 0 & otherwise\end{cases}$$
$$\mu_{\tilde{\mathbf{s}}_y^I}(s)=\begin{cases}1 & if\ \ s=\mathbf{s}_y\\ 0 & otherwise\end{cases} \tag{8}$$

where $s\in$R.

Fuzzy Rule Base is constructed based on the SMC as shown in Table 1.(30),(31) In this study, the implication of the fuzzy relation from If-then rule is conducted by Mamdani's method and for each fuzzy number, triangular membership functions are used as in Fig. 2. Aggregation for several fuzzy relations is conducted by disjunction.

In the module of *Inference Engine*, approximate reasoning is conducted using generalized modus ponens. Finally the fuzzy control force can be obtained as

$$\tilde{\mathbf{u}}=\tilde{\mathbf{u}}_{FB}^o\oplus\tilde{\mathbf{s}}_y^I \tag{9}$$

where $\oplus$is the operator represents the fuzzy sum whose membership function is given as

$$\mu_{\tilde{x}\oplus\tilde{y}}(z)=\sup_{\substack{x,y\\ z=x+y}}\min(\mu_{\tilde{x}}(x),\mu_{\tilde{y}}(y)) \tag{10}$$

In the module of *De-Fuzzification*, the fuzzy control force is transformed to the form of the crisp number by the center of gravity method.

Table 1 Rule Table for $\tilde{\mathbf{u}}_{FB}$

$\tilde{\mathbf{s}}_t$ \ $\tilde{\mathbf{s}}_n$	NB	NM	NS	Z	PS	PM	PB
PB	Z		NS		NM		NB
PM		Z		NS		NM	
PS	PS		Z		NS		NM
Z		PS		Z		NS	
NS	PM		PS		Z		NS
NM		PM		PS		Z	
NB	PB		PM		PS		Z

Note : The first character in the fuzzy number denotes negative or positive, and the second character denotes big, medium, or small. Z means zero

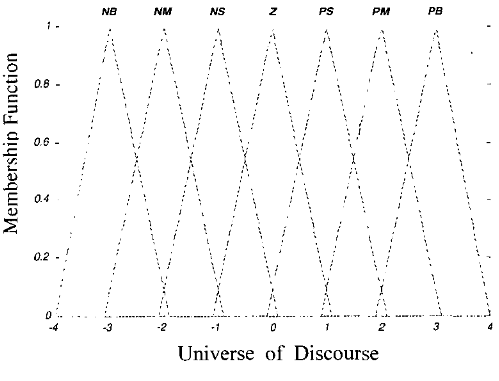


Fig. 2 Triangular membership functions

4. Numerical study on benchmark problem

Numerical studies have been performed using the proposed SMFC on the benchmark problem initiated by the ASCE Committee on Structural Control.(7) The structure of the benchmark problem is a scaled 3-story building model as in Fig. 3. Active tendons are located between the base and the first floors to transmit the control force. A model having 20-dimensional states was given by the problem organizer to evaluate the control performance. It is required to develop control algorithms based on a reduced model, which has no more than 12 dimensional states. To consider the capacity of the actuator, the root-mean-square (RMS) and maximum constraints for control command ($\mathbf{u}_c$), control force ($\mathbf{u}_s$) and actuator piston displacement ($\mathbf{y}_p$) are given as $\sigma_{\mathbf{u}_c} \le 1volt$, $\sigma_{\mathbf{u}_s} \le 4kN$, $\sigma_{\mathbf{y}_p} \le 1cm$, $\max_t |\mathbf{u}_c(t)| \le 3volt$, $\max_t |\mathbf{u}_f(t)| \le 12kN$ and $\max_t |\mathbf{y}_p(t)| \le 3cm$ The measurements are relative displacement of the actuator piston, absolute accelerations at three floors, control force in the active tendon, and ground acceleration. The AD/DA converter has 12-bit precision, ±3 *volt* span, and 1*kHz* sampling time. Each of the measured signal contains an RMS noise of 0.01 volt, which is approximately 0.3% in RMS of the full span of the A/D converter and modeled as Gaussian rectangular pulse processes with a pulse width of 0.001 second. The time delay of the controller is taken as 200μsec.(8),(32)-(40)

Evaluation of the control performance is carried out using the following 10 performance criteria : J_1-J_5 on the RMS responses for a simulated stationary random excitation and J_6-J_{10} on the peak responses for El Centro and Hachinohe earthquake excitations as

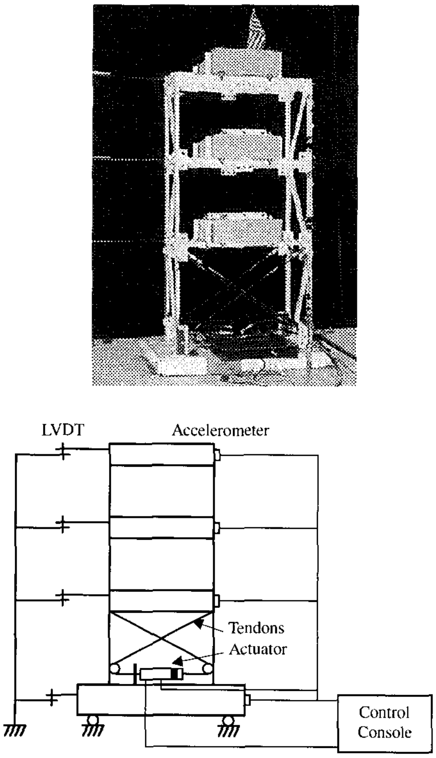


Fig. 3 3-story test structure (Spencer, et al. 1997)

$$J_1 = \max_{i=1,3}\left\{\frac{\sigma_{y_{sd,i}}}{\sigma_{y^o_{s,3}}}\right\} \quad J_2 = \max_{i=1,3}\left\{\frac{\sigma_{\ddot{y}_{sa,i}}}{\sigma_{\ddot{y}^o_{sa,3}}}\right\} \quad J_3 = \max\left\{\frac{\sigma_{y_p}}{\sigma_{y^o_{s,3}}}\right\}$$

$$J_4 = \max\left\{\frac{\sigma_{\dot{y}_p}}{\sigma_{\dot{y}^o_{s,3}}}\right\} \; J_5 = \max\left\{\frac{\sigma_{\mathbf{u}_s}}{W}\right\} \; J_6 = \max_{\substack{t \\ i=1,3 \\ \text{El Centro} \\ \text{Hachinohe}}}\left\{\frac{|y_{sd,i}(t)|}{y^o_{s,3}}\right\}$$

$$J_7 = \max_{\substack{t \\ i=1,3 \\ \text{El Centro} \\ \text{Hachinohe}}}\left\{\frac{|\ddot{y}_{sd,i}(t)|}{\ddot{y}^o_{s,3}}\right\} \quad J_8 = \max_{\substack{t \\ i=1,3 \\ \text{El Centro} \\ \text{Hachinohe}}}\left\{\frac{|y_p(t)|}{y^o_{s,3}}\right\}$$

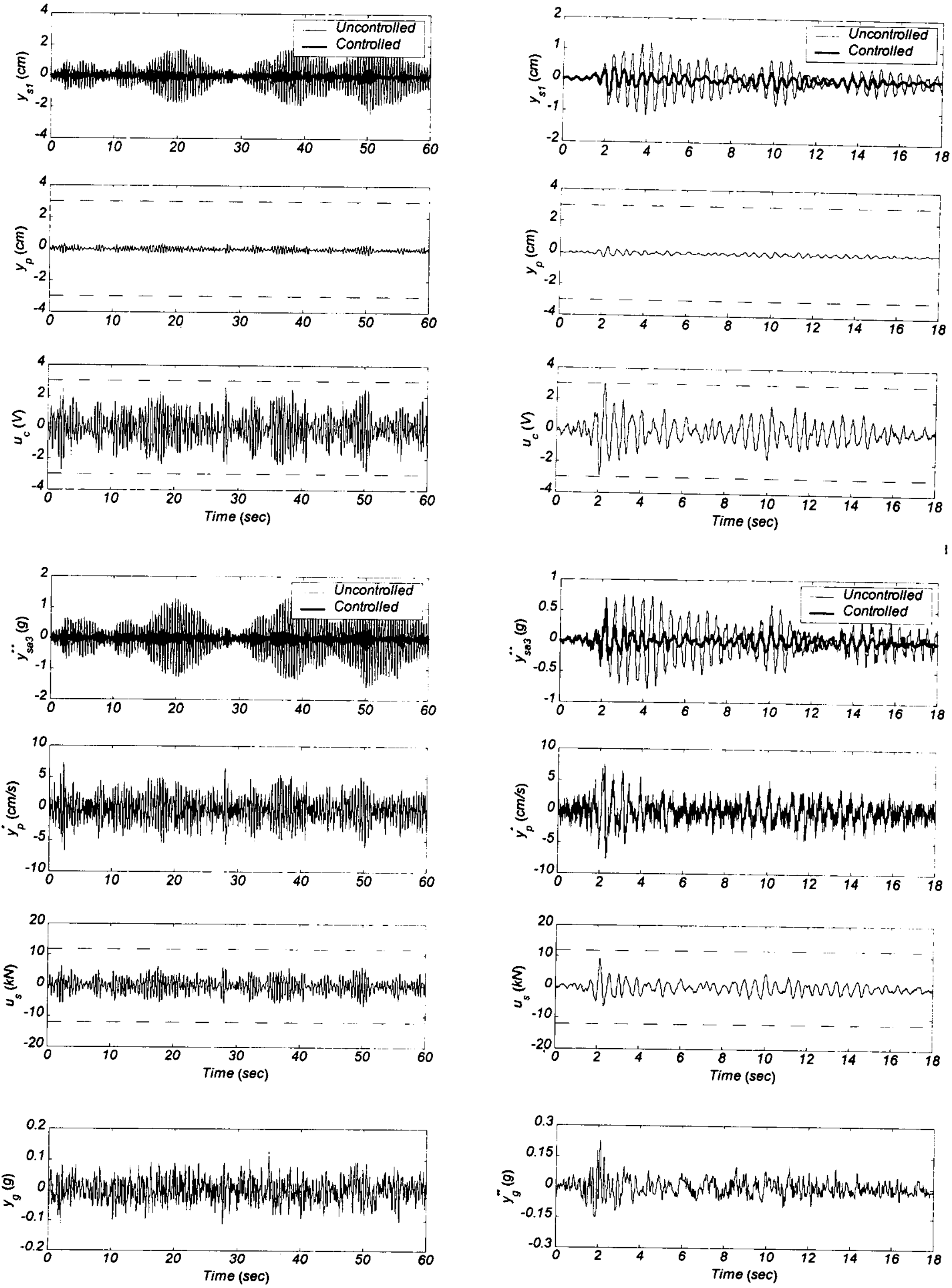
$$J_9 = \max_{\substack{i=1,3 \\ \text{El Centro} \\ \text{Hachinohe}}}\left\{\frac{|\dot{y}_p(t)|}{\dot{y}^o_{s,3}}\right\} \quad J_{10} = \max_{\substack{t \\ \text{El Centro} \\ \text{Hachinohe}}}\left\{\frac{|\mathbf{u}_s(t)|}{W}\right\} \tag{11}$$

where $\sigma_{y_{sd,i}}$ and $\sigma_{\ddot{y}_{sa,i}}$ are the stationary RMS displacement and absolute acceleration of the i-th floor of the controlled building subjected to a stationary random excitation simulated from Kanai-Tajimi spectrum; $\sigma_{y^o_{s,3}}$ and $\sigma_{\ddot{y}^o_{sa,3}}$ are those of the third floor of the uncontrolled building; σ_{y_p} and $\sigma_{\dot{y}_p}$ are the stationary RMS displacement and velocity of the actuator piston; $\sigma_{\dot{y}^o_{s,3}}$ is the stationary RMS velocity of the third floor of the controlled building; W is the weight of the building; $y^o_{s,3}$, $\dot{y}^o_{s,3}$ and $\ddot{y}^o_{sa,3}$ are the uncontrolled peak of the third floor responses under two earthquake excitations.

The controlled responses using the SMFC are shown along with the uncontrolled responses in Table 2 and Fig. 4. Compared with the uncontrolled responses, the story drifts of the first floor are reduced to 26-42% levels in the peak values and to 19-32% levels in the RMS values under three earthquake excitations. The absolute accelerations of the third floor are reduced to 27-70% level in the peak values and to 20-32% levels in the RMS values. The performance of the SMFC is compared with those by other methods, such as optimal polynomial control, neural networks control, multiobjective optimal control ($H_{mixed\ 2/\infty}$), fixed order mixed norm control ($H_{mixed\ 2/\infty}$), and contiuous sliding mode control with compensators (CSMC&C) in Table 3, which were obtained using the same constraint conditions by other researchers.(3),(7),(8) The present results for J_1, J_2, J_6, and J_7 representing the responses of the structure are found to be in the range of 41.5%-68.8% of the other results, while J_5 and J_{10} representing the levels of the control force are in the range of 73.3%-88.5%. However, the present J_3, J_4, and J_9 representing the actuator piston responses are found to be generally larger than those by other methods.

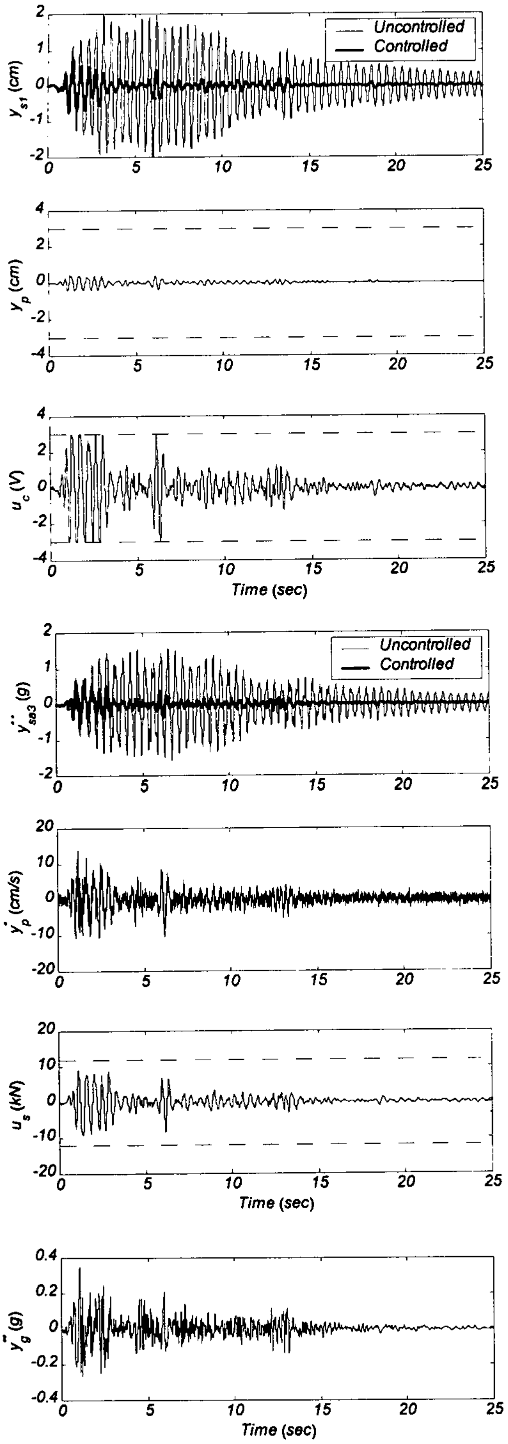
Table 2 Comparisons of controlled and uncontrolled responses

		Simulated Kanai-Tajimi Spectrum		El Centro Earthquake		Hachinohe Earthquake		Constraints
Maximum Responses		Uncontr.	Contr.	Uncontr.	Contr.	Uncontr.	Contr.	
Story Drifts (cm)	1	2.518	0.665	1.981	0.826	1.194	0.380	-
	2	4.004	0.981	3.088	1.192	1.766	0.619	-
	3	2.182	0.579	1.804	0.760	0.950	0.381	-
Absolute Floor Accelerations (g)	1	0.617	0.216	1.052	0.412	0.405	0.359	-
	2	1.326	0.329	1.277	0.416	0.646	0.414	-
	3	1.756	0.468	1.559	0.682	0.760	0.530	-
Piston Displacement (cm)		-	0.393	-	0.419	-	0.397	3.0
Piston Velocity (cm/s)		-	8.333	-	13.977	-	7.665	-
Control Force (kN)		-	8.138	-	9.186	-	9.141	12.0
Control Command (V)		-	3.000	-	3.000	-	3.000	3.0
RMS Responses		Uncontr.	Contr.	Uncontr.	Contr.	Uncontr.	Contr.	
Story Drifts (cm)	1	0.697	0.153	0.768	0.143	0.392	0.127	-
	2	1.104	0.222	1.212	0.215	0.617	0.182	-
	3	0.597	0.123	0.670	0.128	0.337	0.104	-
Absolute Floor Accelerations (g)	1	0.151	0.041	0.263	0.063	0.120	0.054	-
	2	0.367	0.076	0.432	0.080	0.215	0.066	-
	3	0.488	0.103	0.556	0.111	0.278	0.089	-
Piston Displacement (cm)		-	0.110	-	0.104	-	0.088	1.0
Piston Velocity (cm/s)		-	1.879	-	2.167	-	1.680	-
Control Force (kN)		-	2.158	-	2.081	-	1.740	4.0
Control Command (V)		-	0.888	-	0.839	-	0.706	1.0



(a) Simulated earthquake

(b) El Centro earthquake



(c) Hachinohe earthquake

Fig. 4 Controlled and uncontrolled responses of structure and control system
(- - : Maximum constraints given by the organizer)

The total sums of the performance criteria of two intelligent control methods, i.e. the SMFC and the neural networks control, are found to be considerably smaller than those by other methods, which shows the overall performance of the controllers.

5. Conclusions

A sliding mode fuzzy control algorithm is presented for vibration reduction of civil engineering structures. It is a kind of intelligent and nonlinear algorithm, so the design procedure is simple and the limitations of linear algorithm can be overcome. To verify the proposed algorithm, a numerical study is conducted on a benchmark problem. Model reduction and state estimation are carried out to take into account the conditions in real applications to the structures with many degrees of freedom. The results show the adequacy of the reduced model and the state observer. The numerical results indicate that the present sliding mode fuzzy control can reduce the vibration of the structure very effectively. Comparison with the results by other algorithms shows that the overall performance of the present method is very good.

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Table 3 Performance criteria compared with other methods

	SMFC	Optimal Polynomial Control*	Neural Networks*	Multiobjective Optimal Control*	Fixed Order Mixed Norm*	CSMC&C*	Earthquake Input
J_1	0.0745	0.1795	0.1454	0.1673	0.1226	0.1727	Simulated Kanai-Tajimi Spectrum
J_2	0.1774	0.3850	0.3121	0.3597	0.2734	0.3669	
J_3	0.0612	0.0270	0.0410	0.0259	0.0395	0.0317	
J_4	0.0734	0.0289	0.0360	0.0372	0.0436	0.0307	
J_5	0.0077	0.0105	0.0087	0.0101	0.0087	0.0097	
J_6	0.1940	0.3319	0.3011	0.2990	0.2818	0.3245	El Centro or Hachinohe Earthquake
J_7	0.5205	0.8900	0.7731	0.7712	0.7902	0.8097	
J_8	0.0690	0.0749	0.0708	0.0571	0.1030	0.0611	
J_9	0.2331	0.0757	0.0708	0.1849	0.2112	0.0549	
J_{10}	0.0327	0.0373	0.0374	0.0400	0.0396	0.0382	
J	1.4435	2.0407	1.7964	1.9524	1.9136	1.9001	

* : Results presented in the special issue for the benchmark problem in the journal of earthquake engineering and structural dynamics 27(11) 1998

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