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Application of robust fuzzy sliding-mode controller with fuzzy moving sliding surfaces for earthquake-excited structures

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Abstract. This study shows a fuzzy tuning scheme to fuzzy sliding mode controller (FSMC) for seismic isolation of earthquake-excited structures. The sliding surface can rotate in the phase plane in such a direction that the seismic isolation can be improved. Since ideal sliding mode control requires very fast switch on the input, which can not be provided by real actuators, some modifications to the conventional sliding-mode controller have been proposed based on fuzzy logic. A superior control performance has been obtained with FSMC to deal with problems of uncertainty, imprecision and time delay. Furthermore, using the fuzzy moving sliding surface, the excellent system response is obtained if comparing with the conventional sliding mode controller (SMC), as well as reducing chattering effect. For simulation validation of the proposed seismic response control, 16-floor tall building has been considered. Simulations for six different seismic events, Elcentro (1940), Hyogoken (1995), Northridge (1994), Takochi-oki (1968), the east-west acceleration component of Düzce and Bolu records of 1999 Düzce-Bolu earthquake in Turkey, have been performed for assessing the effectiveness of the proposed control approach. Then, the simulations have been presented with figures and tables. As a result, the performance of the proposed controller has been quite remarkable, compared with that of conventional SMC.

Keywords: fuzzy; moving sliding mode; control; seismic isolation; structures.

1. Introduction

In recent years, constructions of taller and more flexible structures have been increasing because of development of light and high strength materials. However, these structures are very susceptible against earthquake and wind loads. Hence, control methods for vibration suppression must be considered to prevent the degradation of safety of the flexible structure due to excessive vibration. Further, the necessity of semi active and active control systems is understood due to the lack of adaptability of passive control systems against varying dynamic effects and base isolation systems that are generally capable of applying only for short buildings. For this reason, the active and especially semi-active control systems are fields of increasing interest due to increase in flexibility and height of buildings (Soong and Constantinou 1994, Singh and Matheu 1997).

Sliding mode technique is one of the well known active control approaches studied by many

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authors for civil engineering structures (Adhikari and Yamaguchi 1997, Wu and Yang 1998, Zhao *et al.* 2000). The popularity of SMC comes from its outstanding robustness properties against parametric uncertainties and external disturbances. Furthermore, recently developed control devices in the field of active control make this method more attractive.

The basic concept of SMC is that the controller adapts itself according to the position of the state trajectory in the state space with respect to a defined sliding surface (switching surface). SMC is designed to drive the state trajectory of the system on the sliding surface and to stay it there. This is achieved by a high speed switching law. That's why the selection of the sliding surface and a nonlinear switched feedback control law to steer the state trajectory to the sliding surface are two steps of designing SMC. There are two main advantages of SMC: a) the dynamic behavior of the system may be tailored by the chosen switching function, and b) the closed loop response becomes totally insensitive to a particular class of uncertainty.

The main drawback of the conventional SMC is severe chattering, which is too many switches in the control bounds. Hence, time histories of control forces can not be realized by the real controllers. Moreover, the chattering phenomenon tends to excite high frequency modes of the system. This problem can be alleviated with the insertion of a boundary layer about the sliding surface. However, these kinds of approaches are known to degrade robustness (Slotine and Li 1991, Utkin *et al.* 1999).

The theory of Fuzzy logic (FL) and fuzzy sets introduced by Zadeh in 1970's have been extensively studied in various fields of engineering. However, the most important researches about FL application have been presented in the field of control engineering. One of the most prominent usages of fuzzy logic control (FLC) is active structural control applications in the field of structural engineering (Battaini *et al.* 1998, Yue *et al.* 1997, Symans and Kelly 1999, Hung and Lai 2001, Ahlawat and Ramaswamy 2002).

A linguistic FLC can be designed for an active control of complex structural systems by incorporating human experiences and the classical control theories into the fuzzy IF-THEN rules. However, there are still several drawbacks in the FLC: a large number of fuzzy rules for a high order system, time consuming trial and error procedure for obtaining the suitable parameters of membership functions and no stability analysis for FLC algorithms.

The above drawbacks of FLC and the chattering of actuators in SMC can be compensated by combining FLC and SMC. Al and Re (2003) applied FSMC algorithm for structures subjected to seismic activity. The optimized semi-active controllers were utilized in their study. The structure was controlled through a controllable electromagnetic damper. The parameters of the controller were optimized using a global stochastic search based on the Metropolis simulated annealing algorithm. The integration of FLC and SMC that formed FSMC has become a new control method (Li *et al.* 1997, Palm 1994). The main intention of integration is to utilize FLC method to improve robustness of the SMC and avoid chattering phenomenon. It can be shown that FSMC is quite effective in reducing the number of switches in the control bounds without degrading the other system performances. Forming linguistic fuzzy control rule base, the state trajectory can be moved towards the desired sliding surface (plane) by applying a large or small control force while the state trajectory is leaving from the desired sliding surface.

The main focus of this paper is to apply fuzzy tuning to moving sliding surfaces for fast and robust control for a seismic isolation of earthquake-excited structure. A moving sliding surface, proposed in Choi and Park (1994) and (Choi *et al.* 1994) for fast tracking with rotating or shifting surface, is adaptable to arbitrary initial condition (Ha *et al.* 1999). The system representative point is no longer on the surface after each movement since the sliding surface is rotated instantaneously in the proposed method. Using the fuzzy moving sliding surface, it is shown that the system performance is improved remarkably in terms of fast damping, robustness and reducing chattering effect.

In this study, to verify the performance of the proposed controller, we consider a sixteen story shear building installing an active tendon system. The realistic earthquake data, which are the acceleration records of Elcentro (1940), Hyogoken (1995), Northridge (1994), Takochi-oki (1968) and east-west acceleration components of Düzce and Bolu records of 1999 Düzce-Bolu earthquake (Alli and Yakut 2005), have been used as a seismic activity (Fig. 1). Then, the methodology and design of SMC and FSMC addressed by Alli and Yakut (2005) have been summarized in section 3 and 4. The proposed FSMC with fuzzy moving sliding surface has been presented in section 4. For comparing the simulation results of the mentioned control algorithms, their simulink models have been developed. To illustrate the robustness of FSMC with fuzzy moving sliding surface against the parametric and structural uncertainties, the numerical simulation of the proposed method has been also presented at the ±30% deviations of the mass and stiffness value. In addition, the robustness of the proposed control algorithm with respect to time delay has been studied. Finally, the conclusions have been given in section 6.

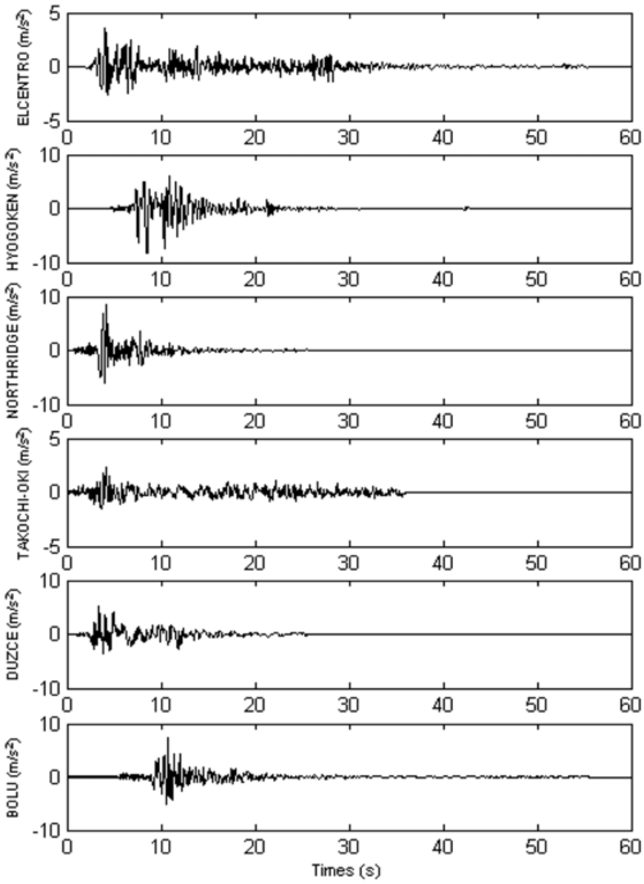

Fig. 1 The acceleration records of Elcentro (1940), Hyogoken (1995), Northridge (1994), Takochi-oki (1968), Düzce and Bolu earthquakes (1999)

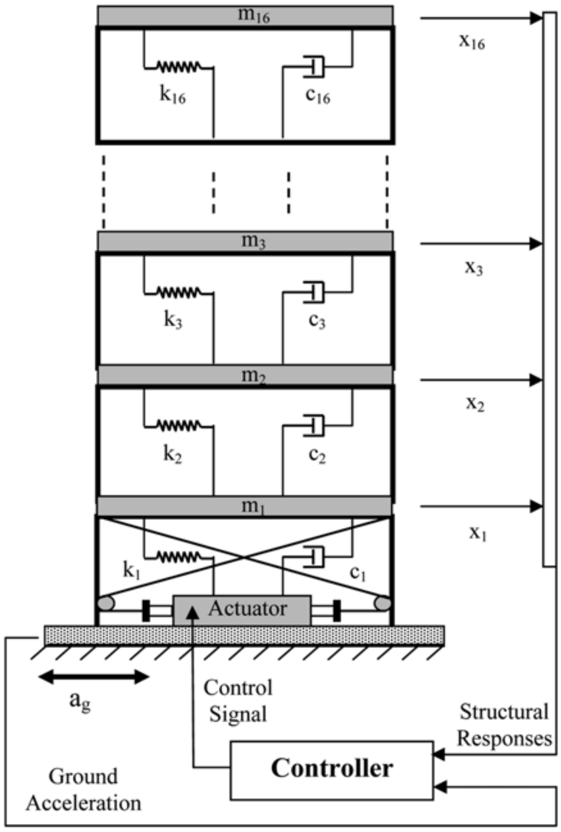

Fig. 2 An idealized model of 16-story building with the active tendon system

2. The dynamics of the structural system

A schema of the sixteen-story shear building with the active tendon system placed in the ground flour is shown in Fig. 2.

The equation of motion of the considered structural system subjected to one dimensional scalar ground acceleration $a_g(t)$ and the active control force $u(t)$ can be written in matrix notation (Alli and Yakut 2005) as

$$\mathbf{M}\ddot{\mathbf{x}}(t) + \mathbf{C}\dot{\mathbf{x}}(t) + \mathbf{K}\mathbf{x}(t) = \mathbf{B}u(t) + \mathbf{H}a_g(t) \quad (1)$$

where constant matrices M, C and K are respectively the mass, damping and stiffness matrices with $(N \times N)$ dimensions, $\ddot{x}$, $\dot{x}$ and x describe the $(N \times 1)$ dimensional relative acceleration, velocity and displacement vector, respectively. Moreover, B is a $(N \times 1)$ dimensional control location vector and $H = -M\delta$ is the external force location vector of size $(N \times 1)$, where δ is a $(N \times 1)$ dimensional earthquake influence vector whose terms are all equal to one.

Table 1 gives the mass, damping and stiffness properties of the considered building (Liu *et al.* 2003).

Table 1 The mass, stiffness and damping properties of the 16-storey building

Store number	Mass values (kg)	Stiffness values (kN/m)	Damping values (kNs/m)
1	672300	256000	27
2-13	568400	256000	27
14-16	555900	174000	27

Eq. (1) can be rewritten in a state form as

$$\dot{\mathbf{z}}(t) = \mathbf{A}\mathbf{z}(t) + \mathbf{D}_1 u(t) + \mathbf{D}_2 a_g(t) \tag{2}$$

where

$$\mathbf{A} = \begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix}_{2N \times 2N}, \quad \mathbf{D}_1 = \begin{bmatrix} 0 \\ M^{-1}B \end{bmatrix}_{2N \times 1}, \quad \mathbf{D}_2 = \begin{bmatrix} 0 \\ M^{-1}H \end{bmatrix}_{2N \times 1}, \quad \mathbf{z}(t) = \begin{bmatrix} x(t) \\ \dot{x}(t) \end{bmatrix}_{2N \times 1} \tag{3}$$

A is a $(2N \times 2N)$ dimensional system matrix, D_1 is a $(2N \times 1)$ dimensional controller location vector, D_2 is a $(2N \times 1)$ dimensional the excitation influence matrix and z is a $(2N \times 1)$ dimensional state vector.

3. Conventional sliding-mode control

The reader can be advised to consult the references (Slotine and Li 1991, Utkin *et al.* 1999) for more detail of a complete theory of SMC. SMC, based on the theory of variable structure control, drives the trajectory of the structure from any initial state onto a specified-user-chosen surface in the state space. Once the sliding surface has been reached, than the system states remain on the sliding surface for all time and move along it to the origin. This condition is achieved through high-

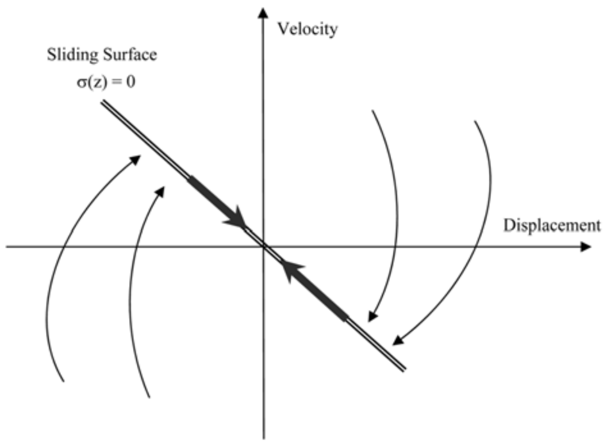

Fig. 3 The sliding surface in the phase plane

frequency switching. The feature of robustness against structural uncertainties, unmodeled dynamics and disturbances is the main advantage of SMC approach (Slotine and Li 1991).

The sliding surface is defined as

$$\sigma = \{z : \sigma(z) = 0\} \tag{4}$$

shown in Fig. 3. In order to satisfy the above condition, the nonlinear control force in the SMC is defined as (Alli and Yakut 2005)

$$u(z, t) = u_{eq}(z, t) - \eta \mathrm{sgn}(\sigma(z)) \tag{5}$$

where u_{eq} defines the linear part of the control force so called the equivalent control force, η is a constant design parameter and sgn is signum function.

The Utkin-Drazenovic method of equivalent control (Utkin *et al.* 1999) has been used to obtain the equivalent control force, which guarantees that once the system trajectory enters the sliding surface, it will move along the sliding surface since $\sigma(\mathbf{z}) = 0$ and $\dot{\sigma}(\mathbf{z}) = 0$.

The sliding surface is defined as

$$\sigma(\mathbf{z}) = \mathbf{S}\,\mathbf{z} \tag{6}$$

where S is a $(1 \times 2N)$ dimensional sliding surface coefficient matrix, usually constant and $\sigma(\mathbf{z})$ is chosen to be a linear function of the system-states, satisfying

$$\sigma(\mathbf{z}) = 0 \quad \text{and} \quad \dot{\sigma}(\mathbf{z}) = 0 \tag{7}$$

then, the equivalent control force can be obtained as (Alli and Yakut 2005)

$$u_{eq}(\mathbf{z}, t) = -(\mathbf{SD}_1)^{-1}[\,\mathbf{SAz}(t) + \mathbf{SD}_2 a_g(t)] \tag{8}$$

The control law defined in Eq. (8) can not be synthesized explicitly because $a_g(t)$ is not previously known. However, the control law can be realized via discontinuous control defined in terms of the known system parameters and under appropriate conditions. Therefore $a_g(t)$ is neglected and a proper η parameter is alternatively chosen to compensate for the uncertainties in the external excitation. However, η must be chosen in such a way that the existence and the reachability of the sliding-mode are guaranteed. This sliding condition can be stated as

$$\sigma(\mathbf{z})\dot{\sigma}(\mathbf{z}) < 0 \tag{9}$$

The above condition yields (Alli and Yakut 2005)

$$\eta \geq \left|(SD_1)^{-1} SD_2 \hat{a}(t)\right| \tag{10}$$

where $\hat{a}(t)$ is the maximum absolute value of ground acceleration.

The block diagram of the SMC algorithm is indicated in Fig. 4 (Alli and Yakut 2005).

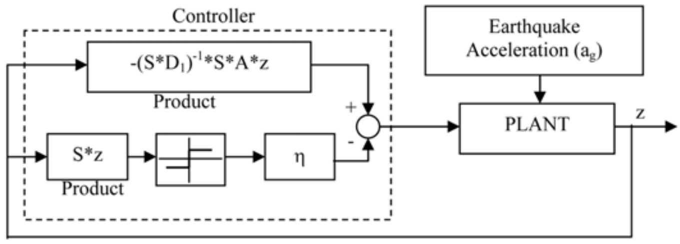

Fig. 4 The block diagram of the SMC algorithm

4. Application of fuzzy sliding-mode controller with fuzzy moving sliding surfaces

The main advantage of FLC is to require only a linguistic description of the control law with fuzzy rules and it does not require a detailed analytical description of the structure. The fuzzy control rules are generally elicited from domain experts. The general structure of FL is

$$\text{IF } x_i \text{ THEN } y_o$$

where x_i is input and y_o is output.

In this study, the switching variable σ and the variation of σ ($\Delta\sigma$) are the input variables while the control variable u is the output variable. If the trajectory in the phase plane leaves from the switching surface with a large angle ($\Delta\sigma$ is big) and σ is large, then the control variable u will become large. However, if the trajectory leaves from the switching surface with a small angle, the trajectory will need a small control force to return the switching surface. Finally, if the trajectory is on the switching surface, there is no need to apply the control force to the system. The states of the control variable u are shown in Table 2 according to the conditions of σ and $\Delta\sigma$.

The control variable not only depends on s but also $\Delta\sigma$ unlike SMC. If $\Delta\sigma$ is big, a large value is assigned to the control variable. For this reason, vibration can be diminished rapidly. If $\Delta\sigma$ is small,

Table 2 The rule base

u		$\Delta\sigma$		
		CσN	*CσZ*	*CσP*
σ	*σN*	*NB*	*NB*	*NM*
	σZ	*NS*	*Z*	*PS*
	σP	*PM*	*PB*	*PB*

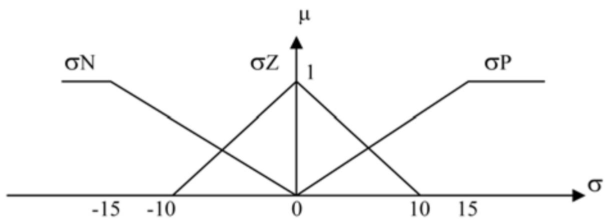

Fig. 5 The membership function for the input σ

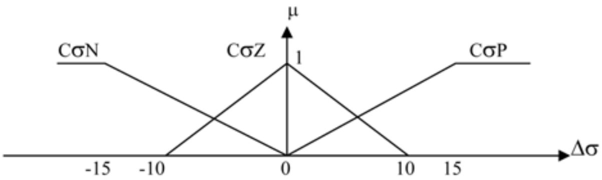

Fig. 6 The membership function for the input $\Delta\sigma$

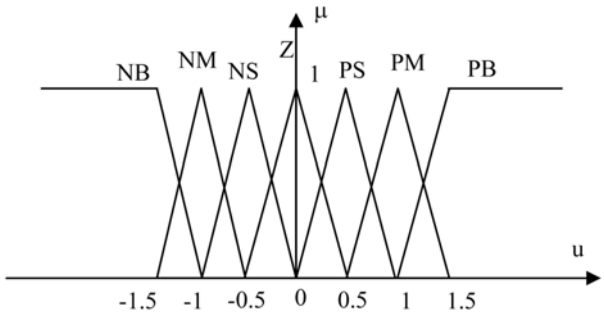

Fig. 7 The membership function for the output u

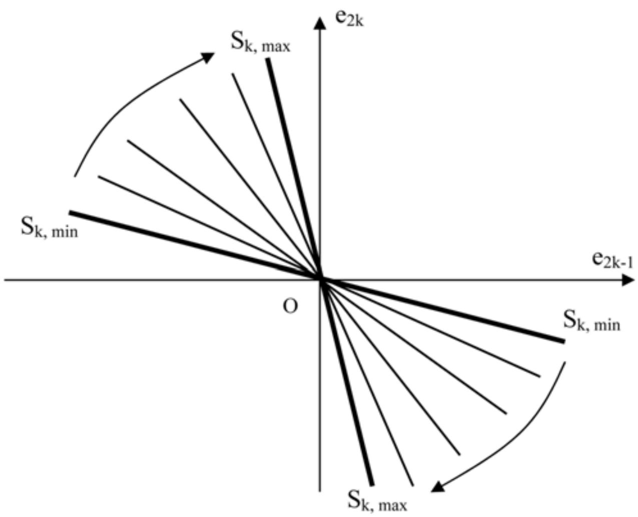

Fig. 8 Rotating sliding surface

a small value is assigned to the control variable. Hence, domestic change of control variable (chattering, the most disadvantage of SMC) can be prevented.

In this work, we establish the fuzzy system in FSMC using the graphical user interface tools provided by the Fuzzy Logic Toolbox in MATLAB (Alli and Yakut 2005).

Once we define the rule base, we now need to determine the membership functions for σ and $\Delta\sigma$ shown in Figs. 5 and 6. Based on our experiences and trial and error approach, three triangular membership functions were used. Furthermore, based on the control rules and the look-up table, the membership function for the control variable u is established and shown in Fig. 7.

Due to the usage of linguistic expression, it is not easy to guarantee the stability and robustness of the fuzzy control system. To achieve the stability and robustness properties of the fuzzy control system, FSMC technique is proposed in the spirit of SMC strategy. It is well known that the stability and robustness properties of SMC can be easily proven by using Lyapunov stability theorem. The theoretical justification of FSMC may be performed in the same way. For more detail of this justification, the reader can consult (Alli and Yakut 2005).

Considering the studies of Ha *et al.* (1999), we adapt fuzzy tuning methods to continuously move sliding surfaces such that better response is obtained. The sliding surface slopes, S_k are bounded by a maximum value, $S_{k,\max}$, and a minimum value, $S_{k,\min}$. Fig. 8 indicates the region for possible slopes of rotating sliding surface in the stable region of the phase plane (e_{2k-1} (relative displacement error), e_{2k} (relative velocity error)) (the second and fourth quadrants). The system performance is sensitive to the sliding surface slope S_k. If big values of S_k are available, the system will be more stable but the response accuracy may be degraded because of a longer reaching time of the representative point to the surface σ_k.

However, the convergence speed on the sliding surface itself will be slow, leading to longer tracking times if small values of S_k are chosen. If a larger value for S_k results in a longer reaching time, S_k will decrease when $|e_{2k-1}|$ is large, and vice versa. Therefore, the fuzzy rule for tuning S_k can be determined as

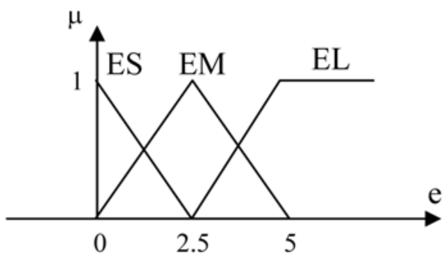

Fig. 9 The membership function for the input error(e)

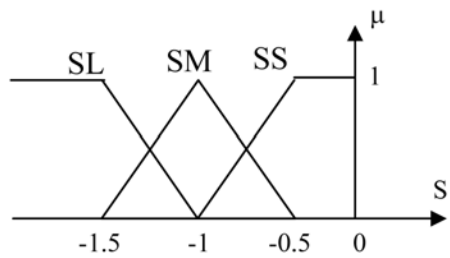

Fig. 10 The membership function for the output *S*

Table 3 The rule base

e_{2k-1}	S_k
EL	SS
EM	SM
ES	SL

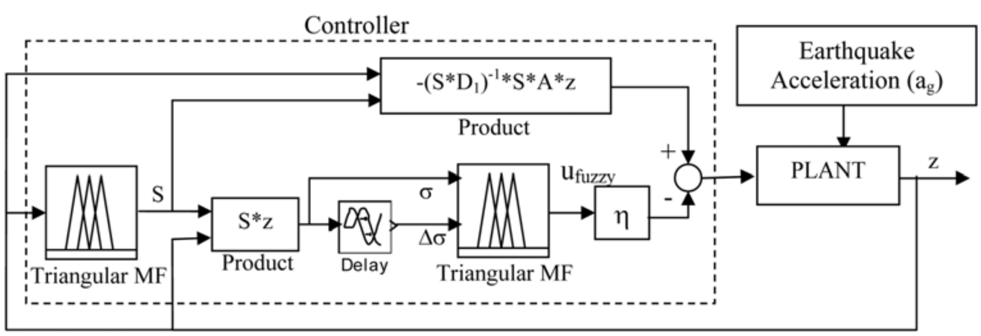

Fig. 11 The block diagram of the FSMC with moving sliding surfaces algorithm

If error is large (EL) then slope is small (SS).
If error is middle (EM) then slope is middle (SM).
If error is small (ES) then slope is large (SL).

Based on satisfying the above statements, the fuzzy rule for tuning S_k automatically determines $S_{k,\min}$ and $S_{k,\max}$ in the second and fourth quadrants (stable region).

The membership functions for error(e) and S shown in Figs. 9 and 10.

The states of the slope are shown in Table 3 according to conditions of the errors of the system states. We used the graphical user interface tools provided by the Fuzzy Logic Toolbox in MATLAB, as we designed the fuzzy system for FSMC before. The only difference of this section is that the Gaussian membership function is used for the input and output based on trial and error approach to obtain better performance.

The block diagram of the FSMC with moving sliding surfaces algorithm is indicated in Fig. 11.

5. Numerical simulation and results

Figs. 12, 13, 14, 15, 16 and 17 indicate the displacement and acceleration of the base and sixteenth floor and the time histories of the applied control force of the considered building applied SMC and FSMC with fuzzy moving sliding surfaces and excited by the acceleration records of Elcentro (1940), Hyogoken (1995), Northridge (1994), Takochi-oki (1968), Düzce and Bolu

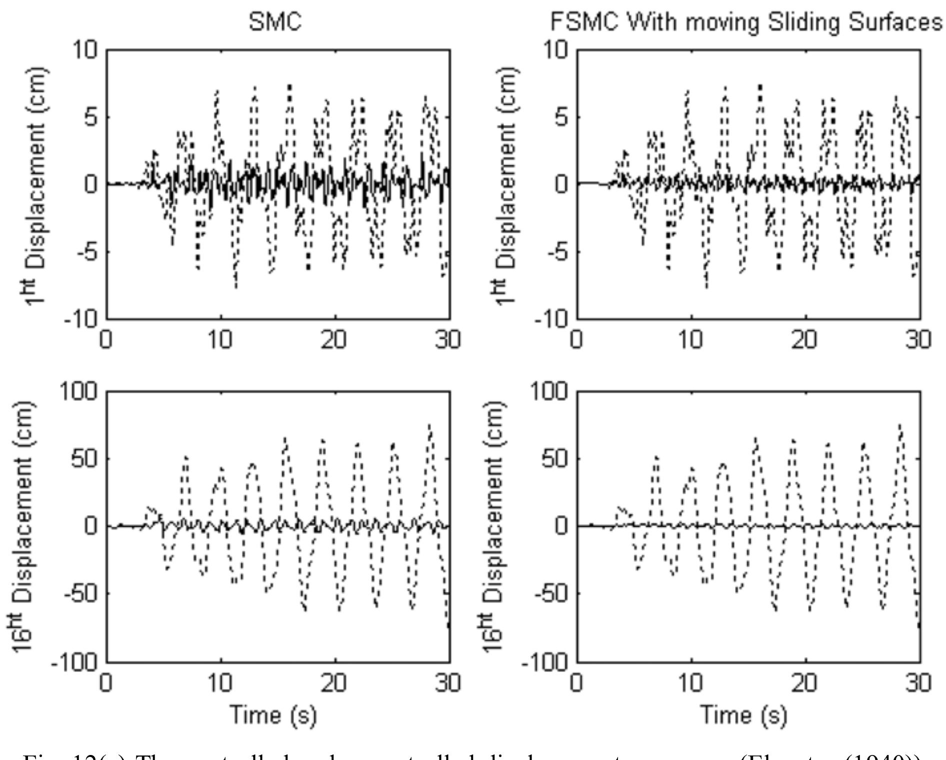

Fig. 12(a) The controlled and uncontrolled displacement responses (Elcentro (1940))

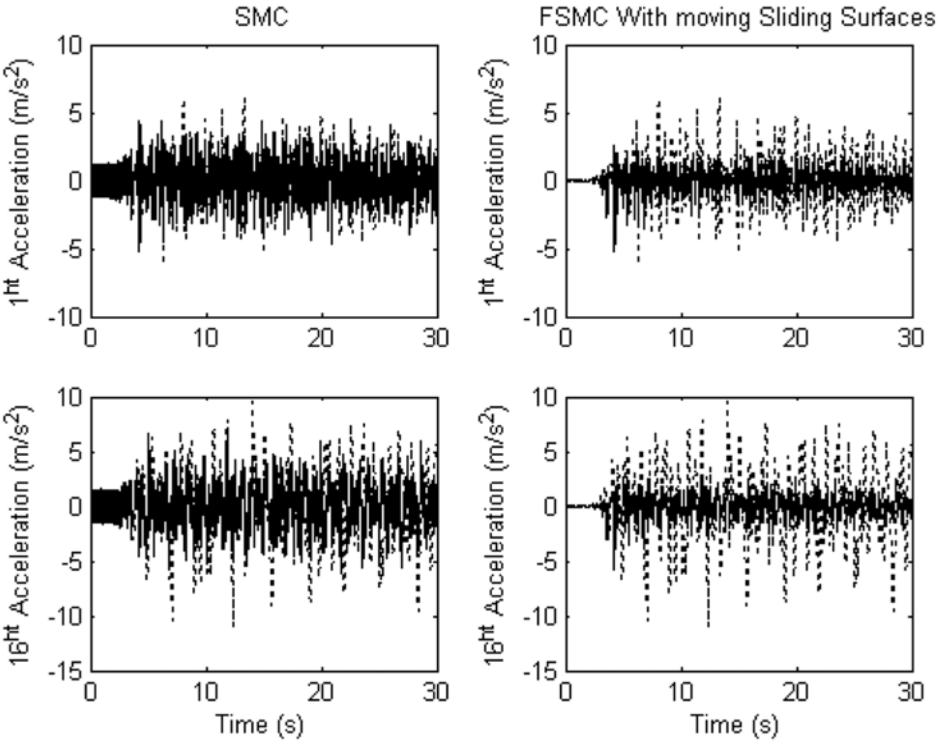

Fig. 12(b) The controlled and uncontrolled acceleration responses (Elcentro (1940))

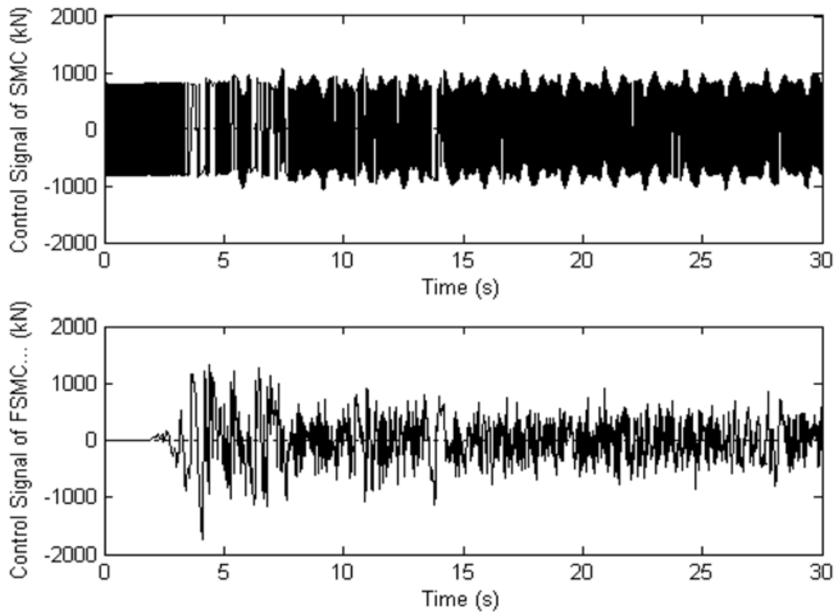

Fig. 12(c) The time histories of the control force (Elcentro (1940))

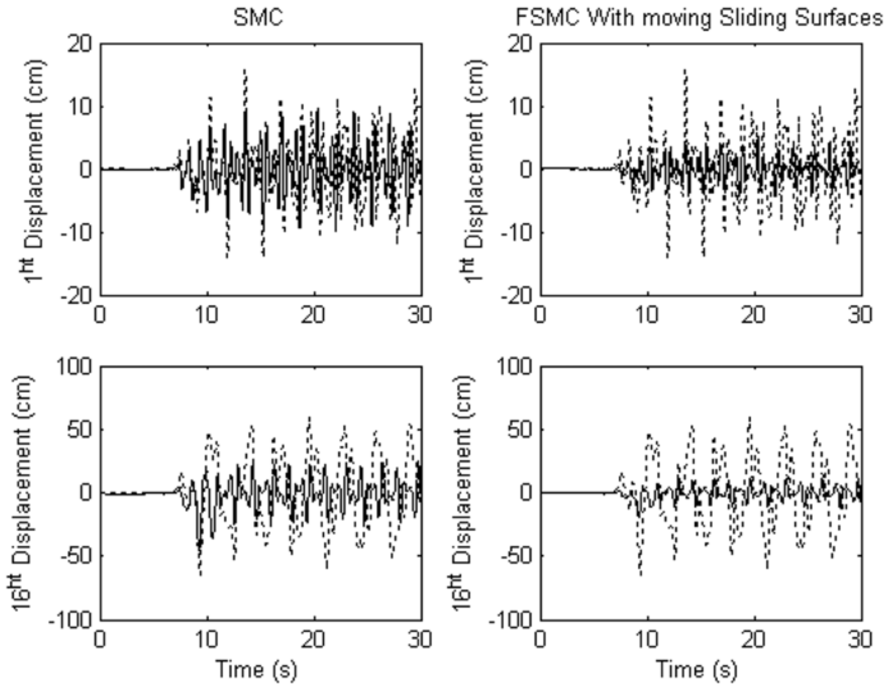

Fig. 13(a) The controlled and uncontrolled displacement responses (Hyogoken (1995))

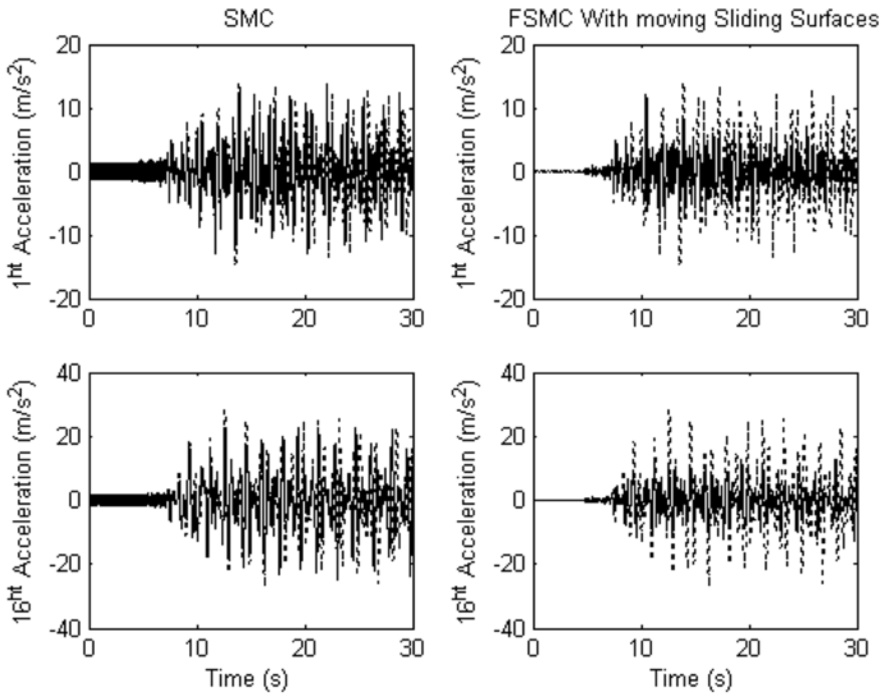

Fig. 13(b) The controlled and uncontrolled acceleration responses (Hyogoken (1995))

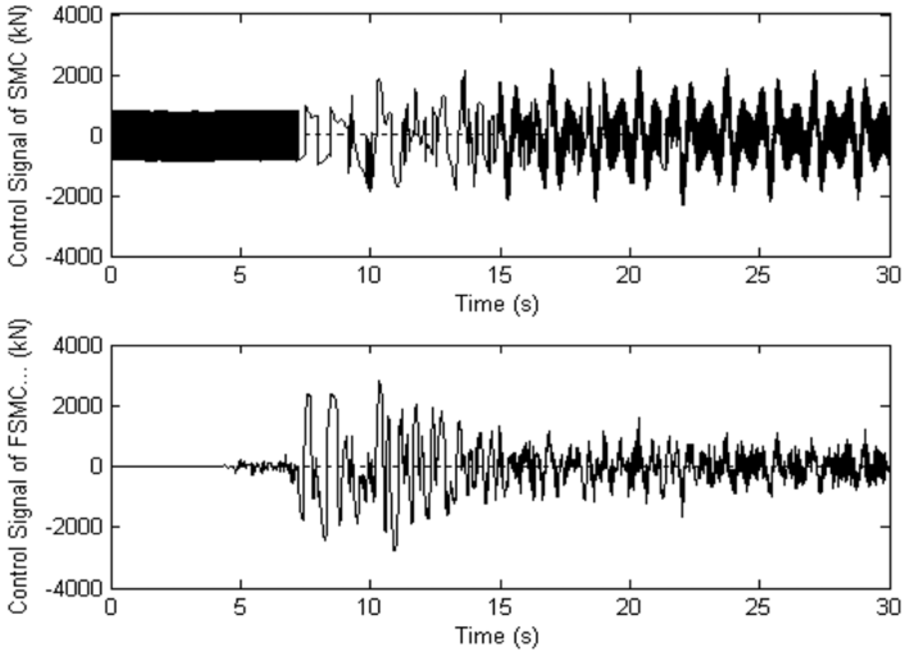

Fig. 13(c) The time histories of the control force (Hyogoken (1995))

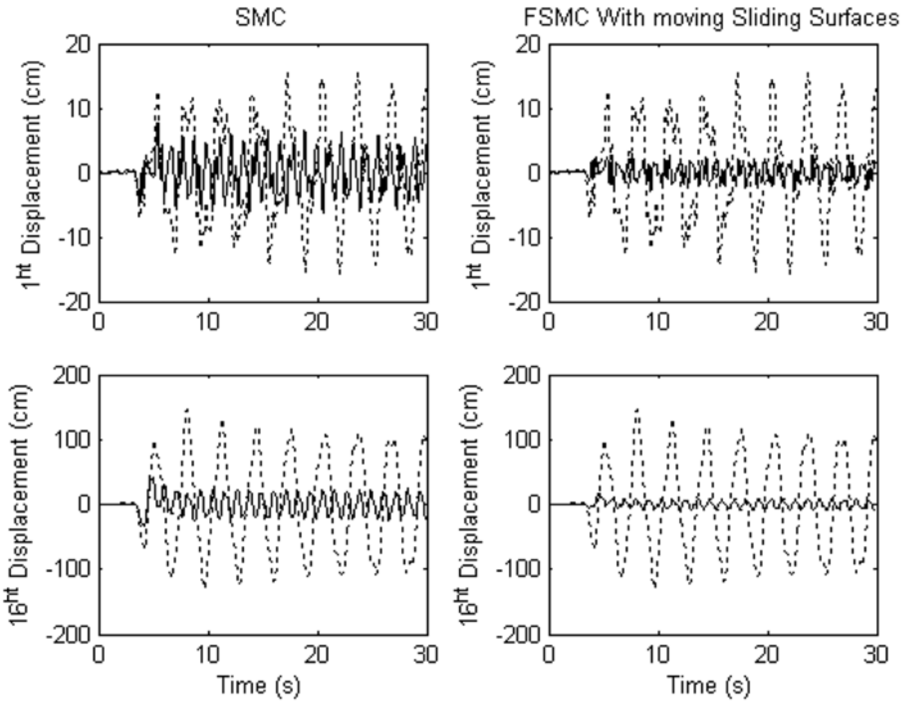

Fig. 14(a) The controlled and uncontrolled displacement responses (Northridge (1994))

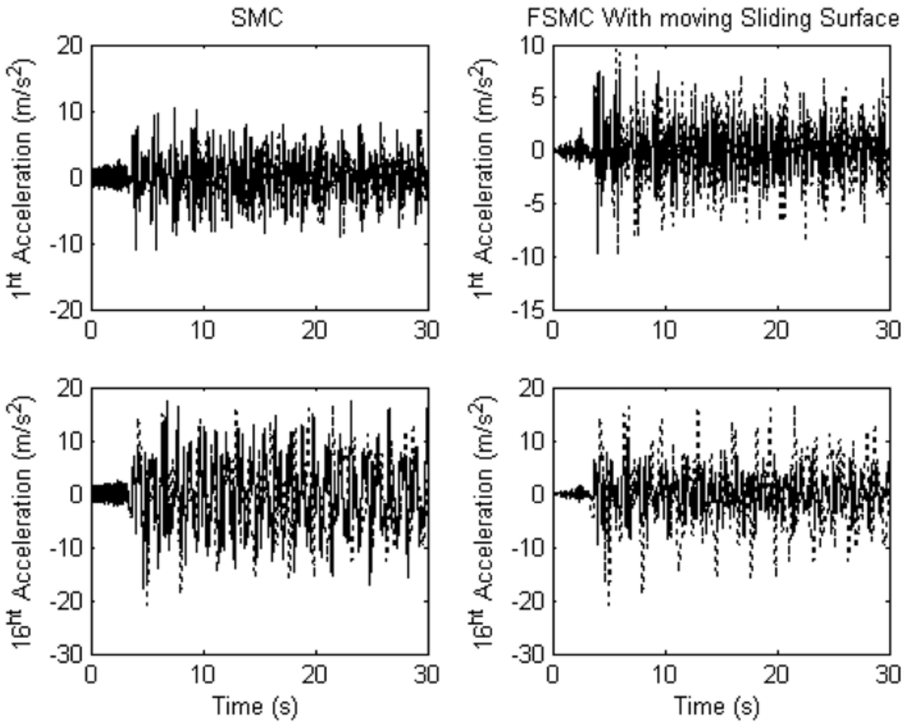

Fig. 14(b) The controlled and uncontrolled acceleration responses (Northridge (1994))

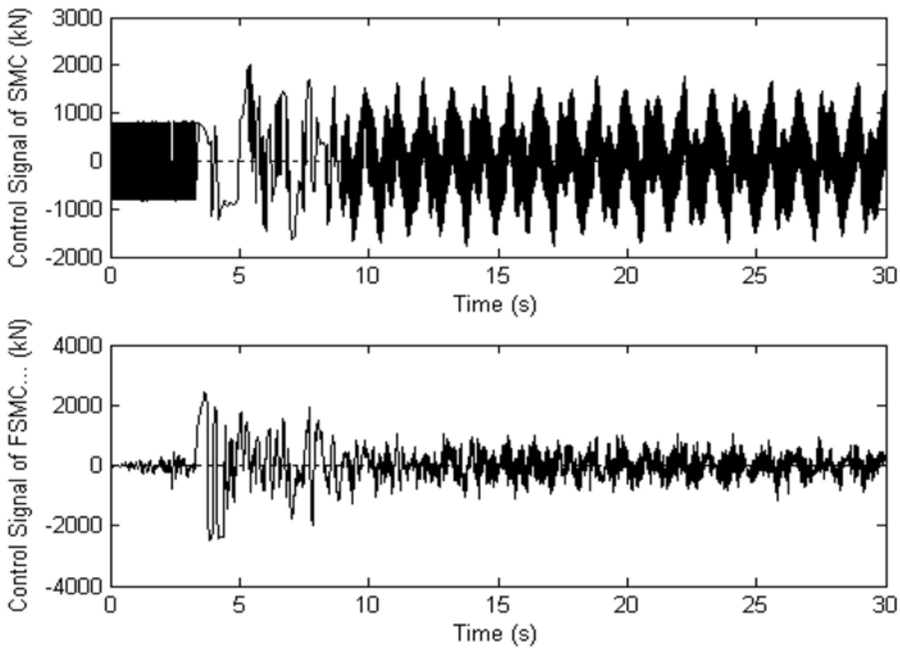

Fig. 14(c) The time histories of the control force (Northridge (1994))

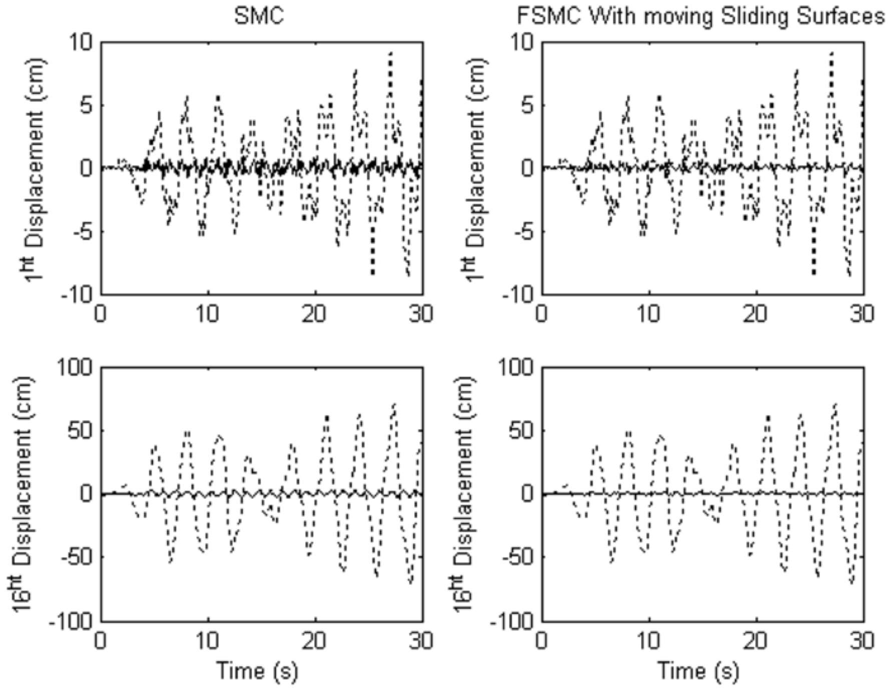

Fig. 15(a) The controlled and uncontrolled displacement responses (Takochi-oki (1968))

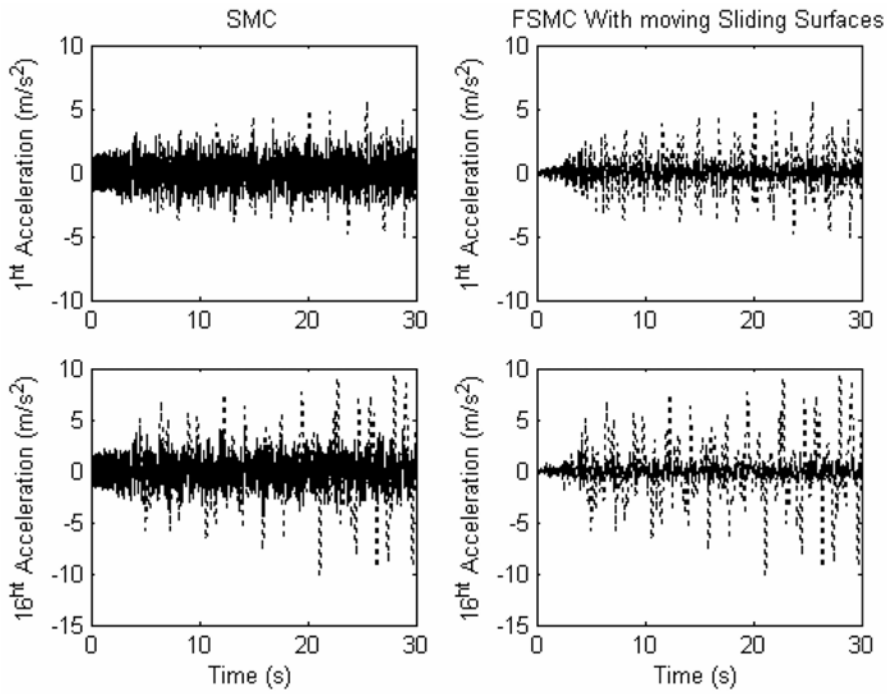

Fig. 15(b) The controlled and uncontrolled acceleration responses (Takochi-oki (1968))

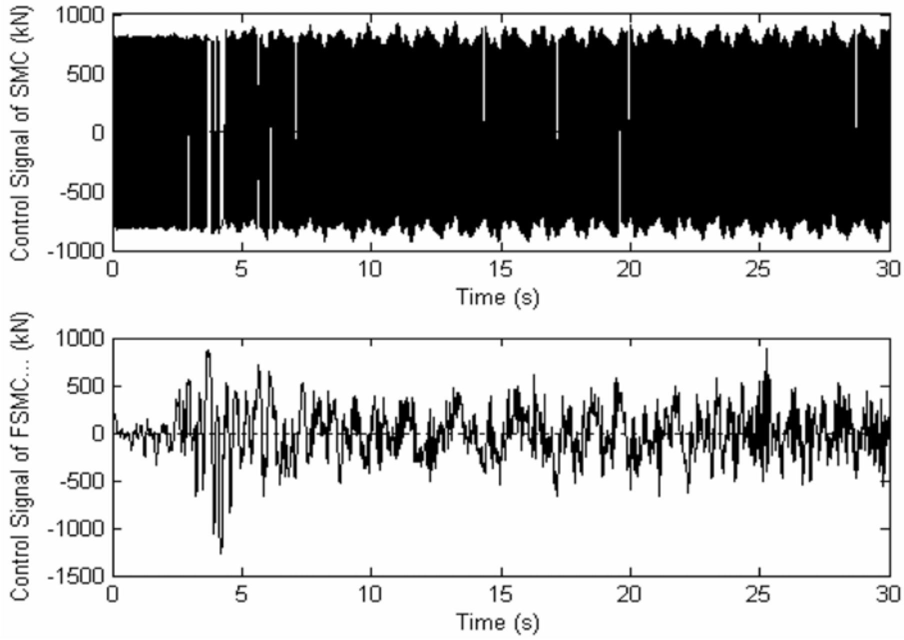

Fig. 15(c) The time histories of the control force (Takochi-oki (1968))

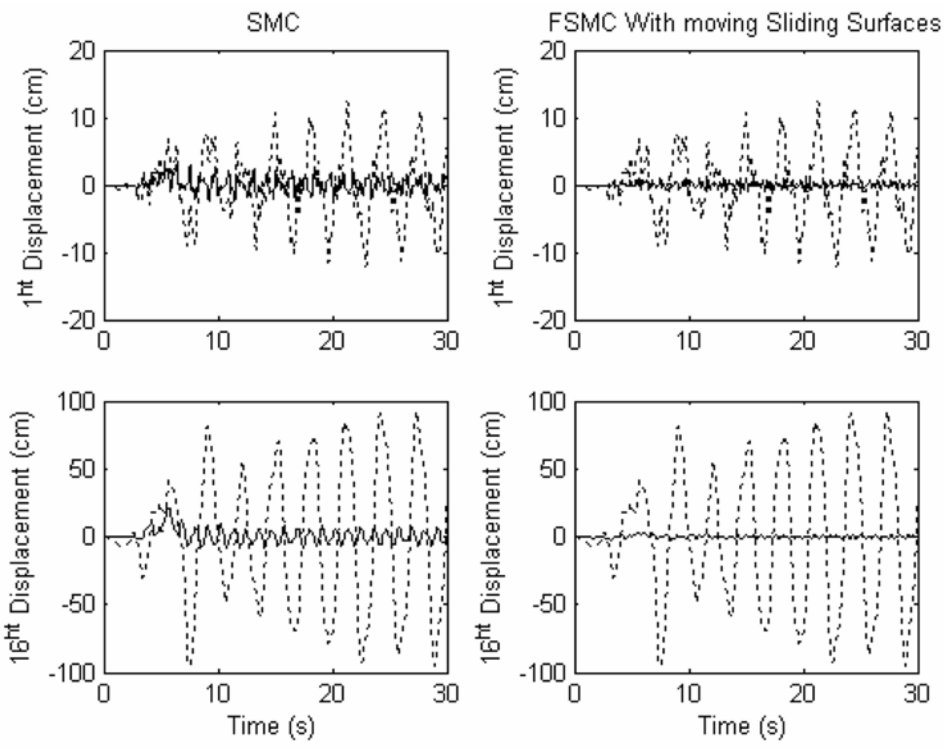

Fig. 16(a) The controlled and uncontrolled displacement responses (Düzce (1999))

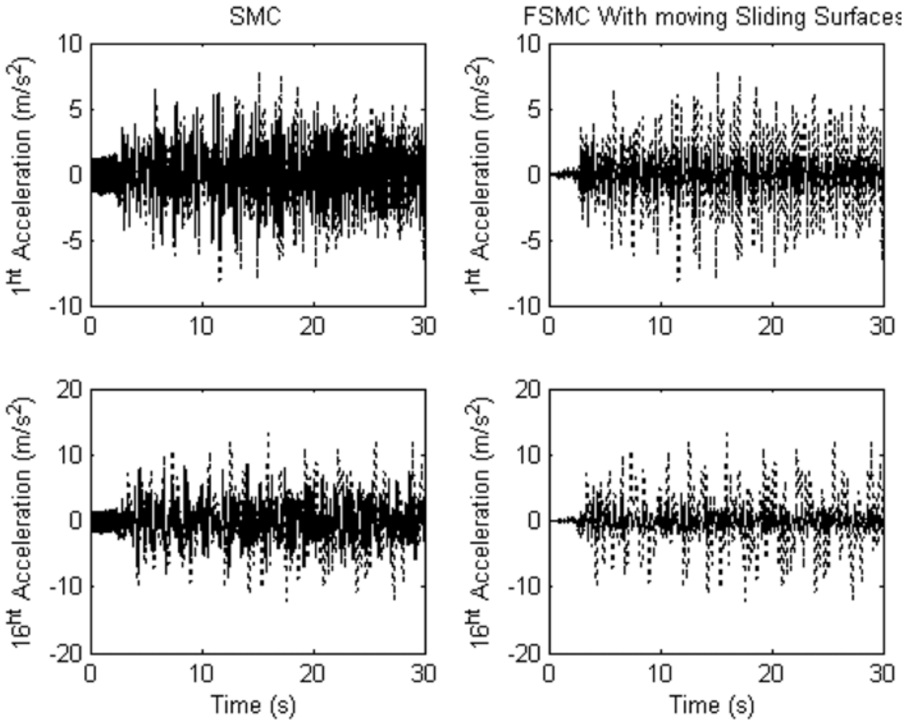

Fig. 16(b) The controlled and uncontrolled acceleration responses (Düzce (1999))

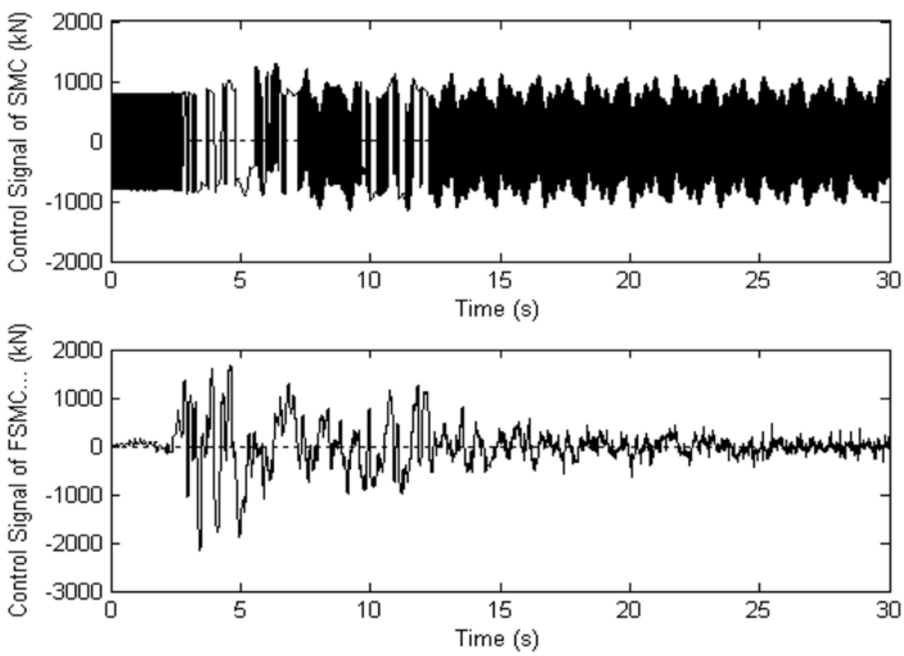

Fig. 16(c) The time histories of the control force (Düzce (1999))

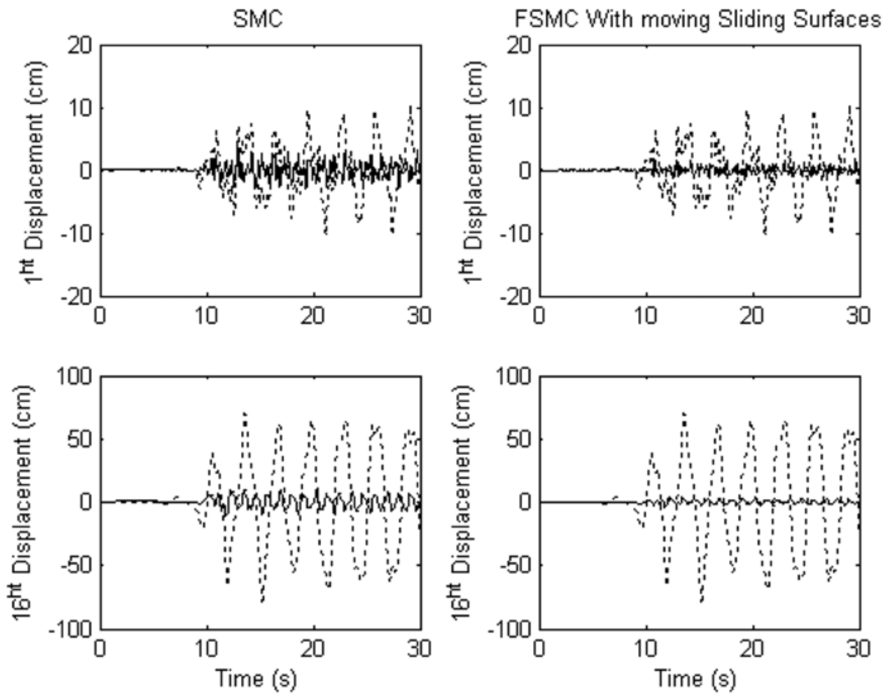

Fig. 17(a) The controlled and uncontrolled displacement responses (Bolu (1999))

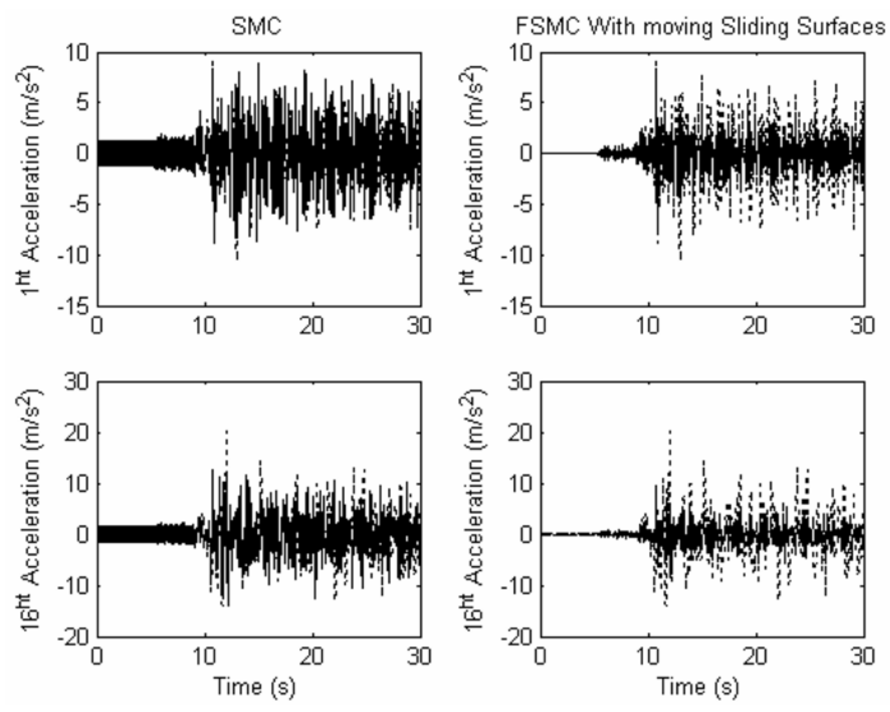

Fig. 17(b) The controlled and uncontrolled acceleration responses (Bolu (1999))

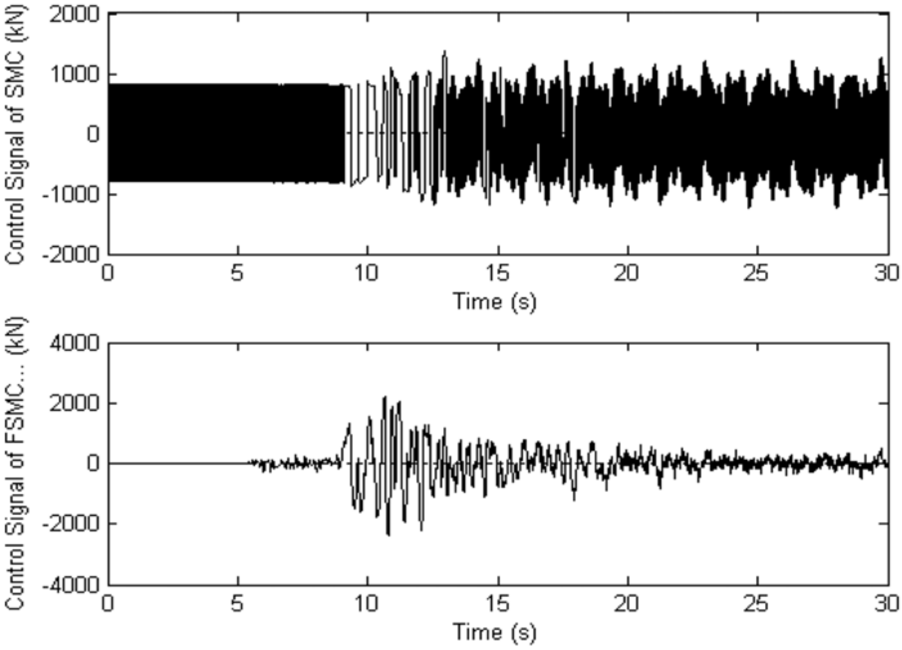

Fig. 17(c) The time histories of the control force (Bolu (1999))

Table 4 The maximum displacement and acceleration responses of the considered building with and without the controllers

Earthquakes	Stores	Max. Displacements (cm)			Max. Accelerations (m/s^2)		
		Uncontrolled	SMC	Move with FSMC	Uncontrolled	SMC	Move with FSMC
Elcentro	16th Store	76,7685	5,8413	2,1456	10,9045	7,0835	5,8248
	1th Store	7,7698	1,8978	0,8121	6,1656	5,2528	4,9476
Hyogo-ken	16th Store	64,2914	45,3224	19,262	28,3552	24,9705	12,9467
	1th Store	15,5953	9,8496	4,6357	14,9466	13,6122	11,9557
Northridge	16th Store	145,8908	40,8541	17,1857	20,7386	17,852	10,1954
	1th Store	15,7276	7,6791	3,0125	10,0144	10,9647	9,3546
Takochi-oki	16th Store	71,2969	3,1301	1,4978	10,0494	4,3233	2,1701
	1th Store	9,0505	0,893	0,5002	5,6249	3,3561	1,64
Düzce	16th Store	95,588	21,9742	3,1091	13,1486	8,5738	4,3006
	1th Store	12,3936	3,0435	1,0741	8,1721	6,4844	3,6074
Bolu	16th Store	79,1271	10,8716	4,011	20,1432	14,1245	8,7562
	1th Store	10,5383	3,7313	1,5735	10,6175	8,8985	8,0323

earthquakes (1999), respectively.

As shown in these figures, the earthquake induced vibrations are suppressed by the both proposed controllers, meanwhile, the FSMC with fuzzy moving sliding surfaces does not have chattering

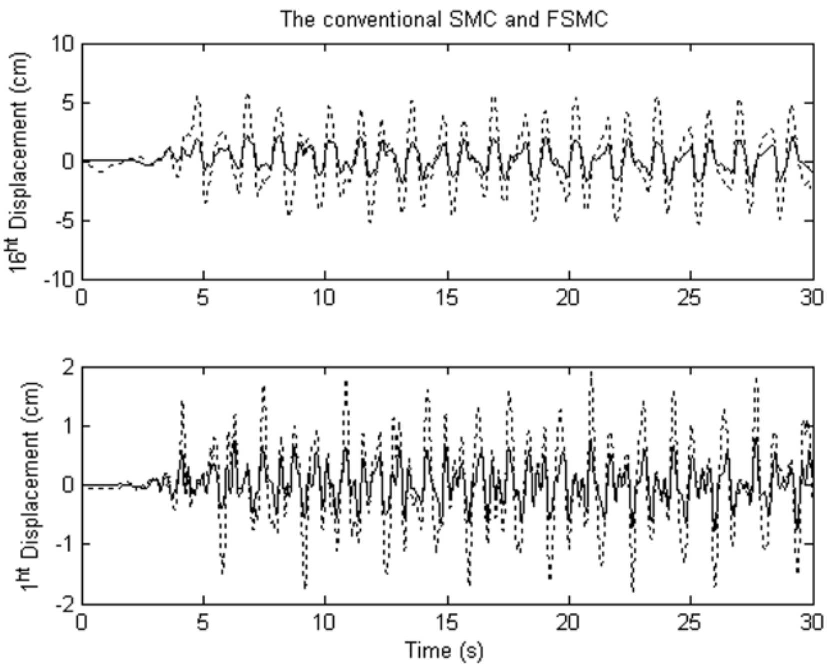

Fig. 18(a) The comparison of system response of the conventional SMC (…) and FSMC with moving sliding surface (—) (Elcentro (1940))

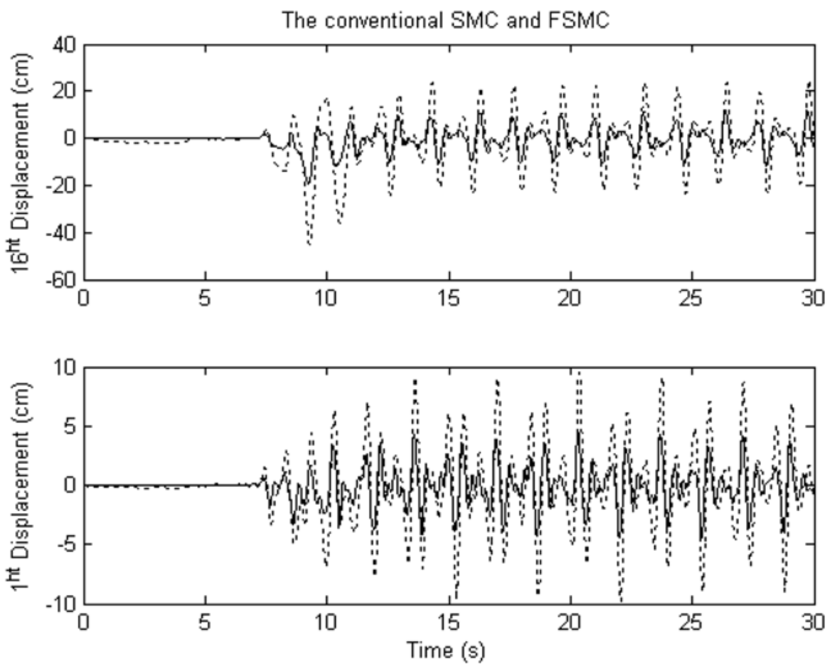

Fig. 18(b) The comparison of system response of the conventional SMC (…) and FSMC with moving sliding surface (—) (Hyogoken)

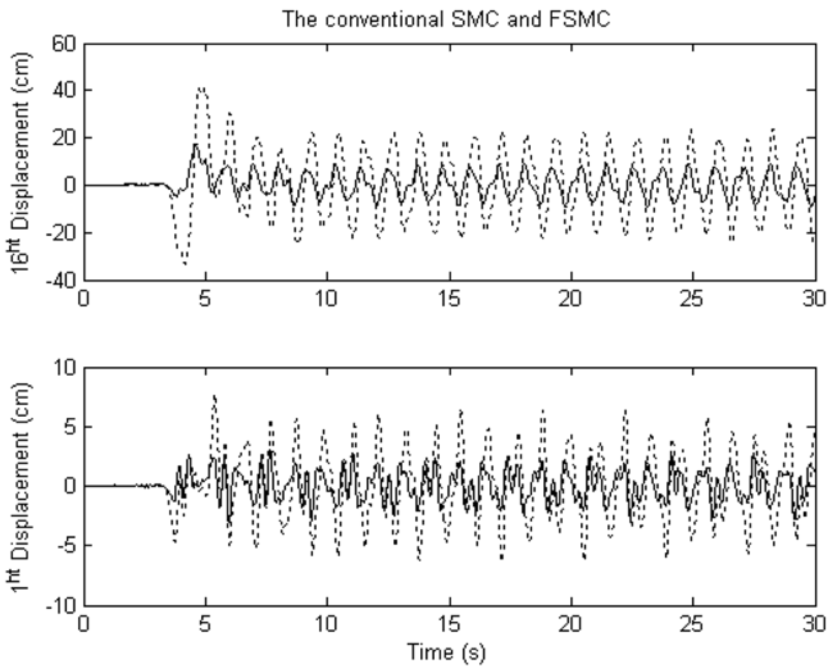

Fig. 18(c) The comparison of system response of the conventional SMC (···) and FSMC with moving sliding surface (—) (Northridge)

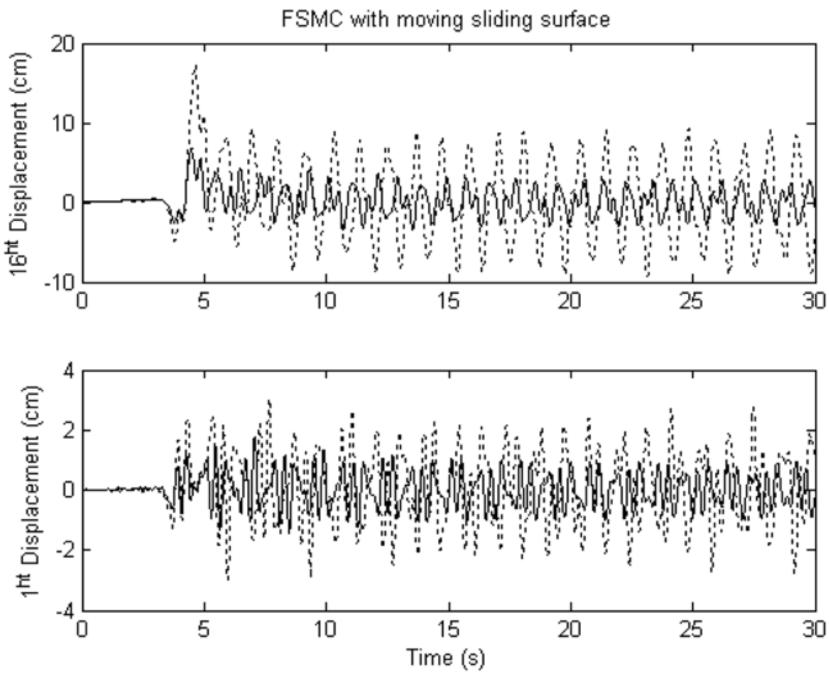

Fig. 19 The comparison of the responses of totally defined (—) and the system having −30% parametric uncertainties (···) Northridge (1994)

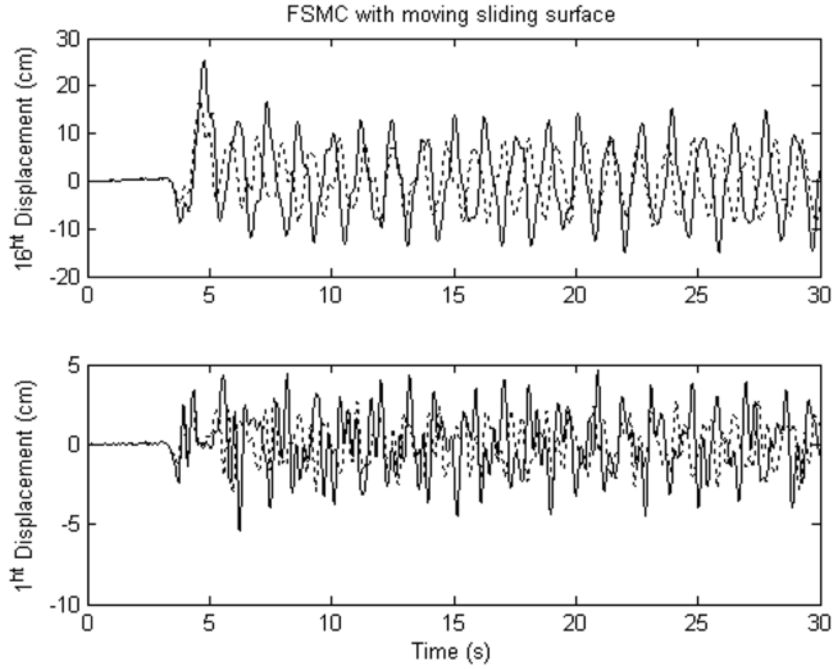

Fig. 20 The comparison of the responses of totally defined (—) and the system having +30% parametric uncertainties (···) Northridge (1994)

Table 5 The maximum displacements and accelerations of the considered building when totally defined and the system having 30% parametric uncertainties

Earthquakes	Stores	Max. Displacements (cm)			Max. Accelerations (m/s^2)		
		Uncontroled	SMC	Move with FSMC	Uncontroled	SMC	Move with FSMC
NORTHRİDGE (−%30)	16th Store	161.2222	30.7748	6.7762	24.9426	15.9071	10.2608
	1th Store	18.9075	5.1258	1.7714	12.7869	12.1293	9.6658
NORTHRİDGE (+%30)	16th Store	113.5032	49.5265	25.1671	19.0240	16.8718	12.2133
	1th Store	14.6644	9.1593	5.3532	13.9283	13.8681	11.1655

effect on the contrary of SMC. Moreover, Figs. 18(a)-(c) show that the amplitudes of earthquake-induced vibrations of the building applied FSMC with fuzzy moving sliding surfaces are damped remarkable if we compare with those of the SMC, for using different earthquake data. All maximum displacement and acceleration responses of the considered building with and without the controllers are shown in Table 4. This table shows that the FSMC with fuzzy moving sliding surfaces performs better response than the SMC. From these figures and Table 4, we get excellent responses for different earthquake events as well as chattering-free control forces. These results indicate that the proposed controller is an effective method for seismic isolation of structures.

To verify insensitiveness of FSMC with fuzzy moving sliding surfaces against the parametric or structured uncertainties, the values of the mass and stiffness have been deviated ±30%. As a result,

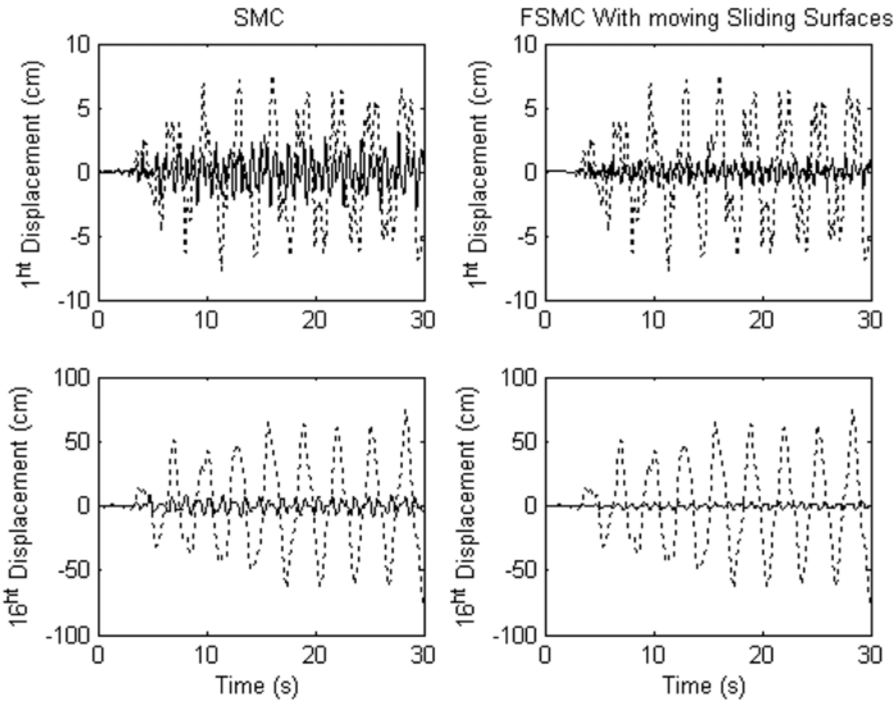

Fig. 21 The controlled and uncontrolled displacements for 20 ms time delay (Elcentro (1940))

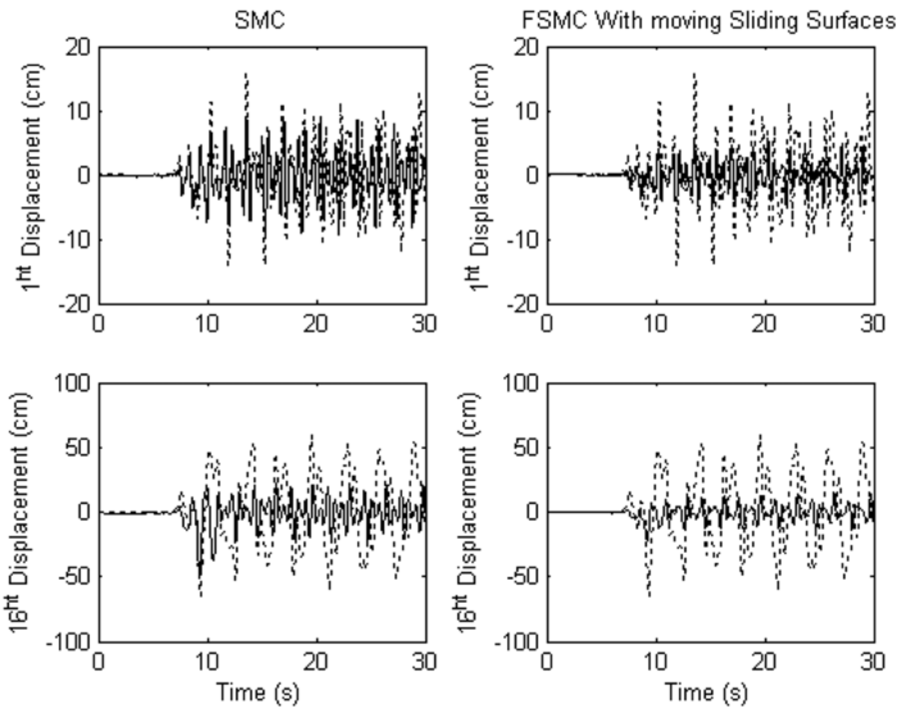

Fig. 22 The controlled and uncontrolled displacements for 20 ms time delay (Hyogoken (1995))

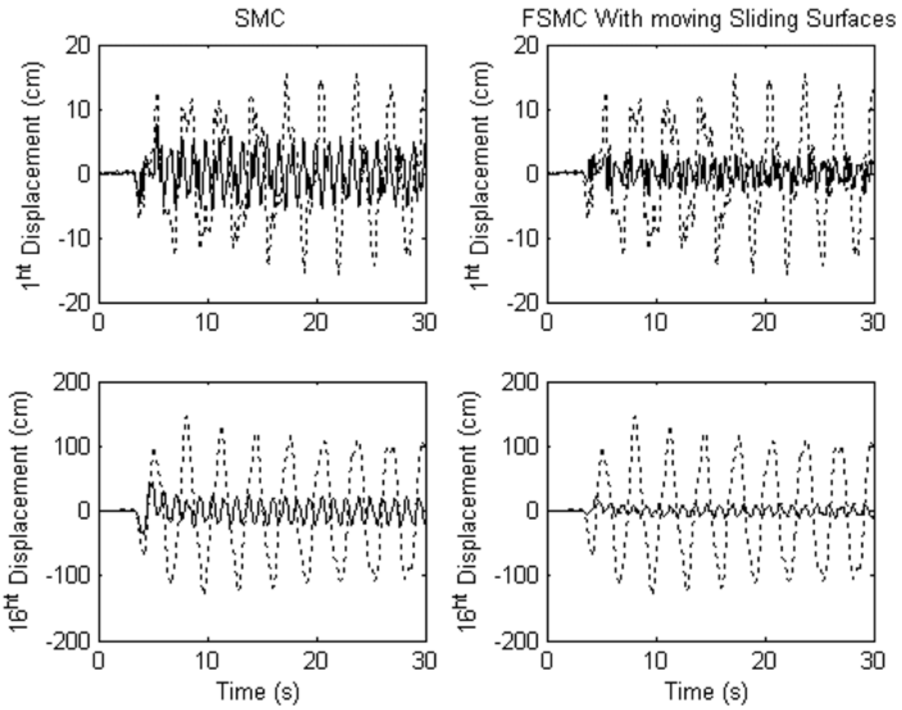

Fig. 23 The controlled and uncontrolled displacements for 20 ms time delay (Northridge (1994))

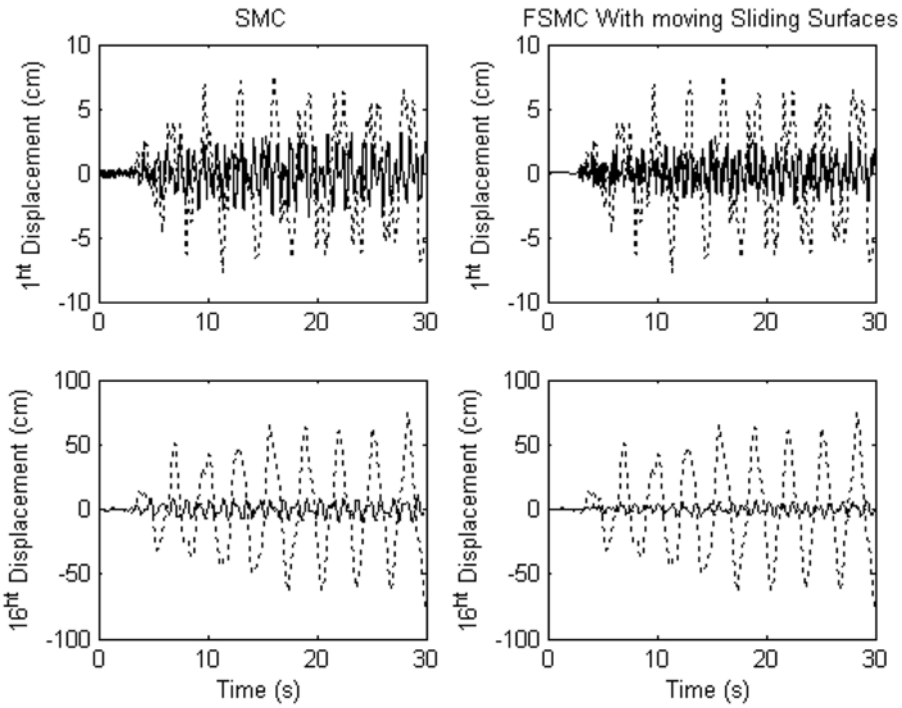

Fig. 24 The controlled and uncontrolled displacements for 40 ms time delay (Elcentro (1940))

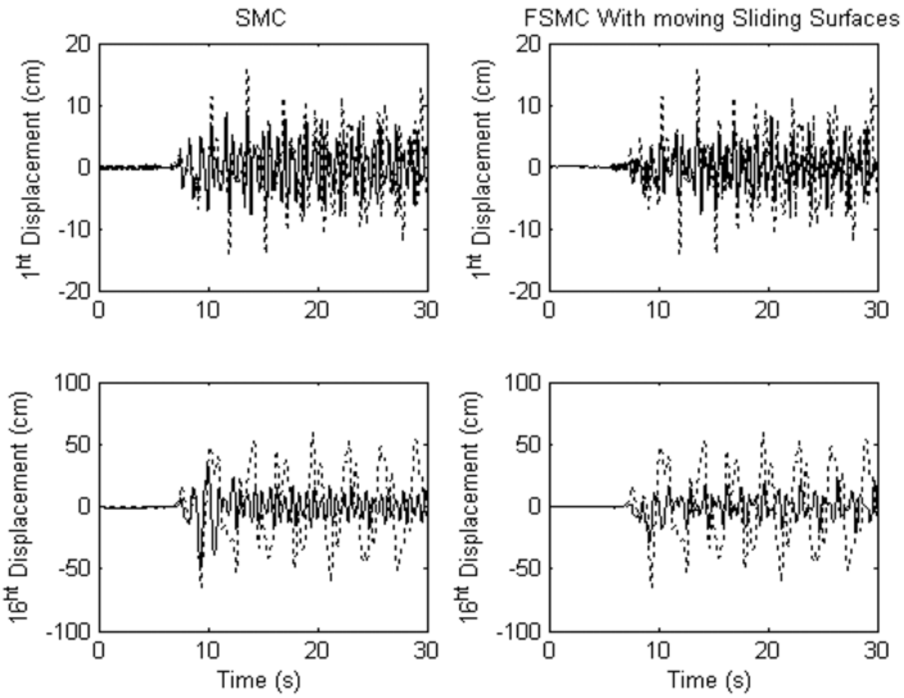

Fig. 25 The controlled and uncontrolled displacements for 40 ms time delay (Hyogoken (1995))

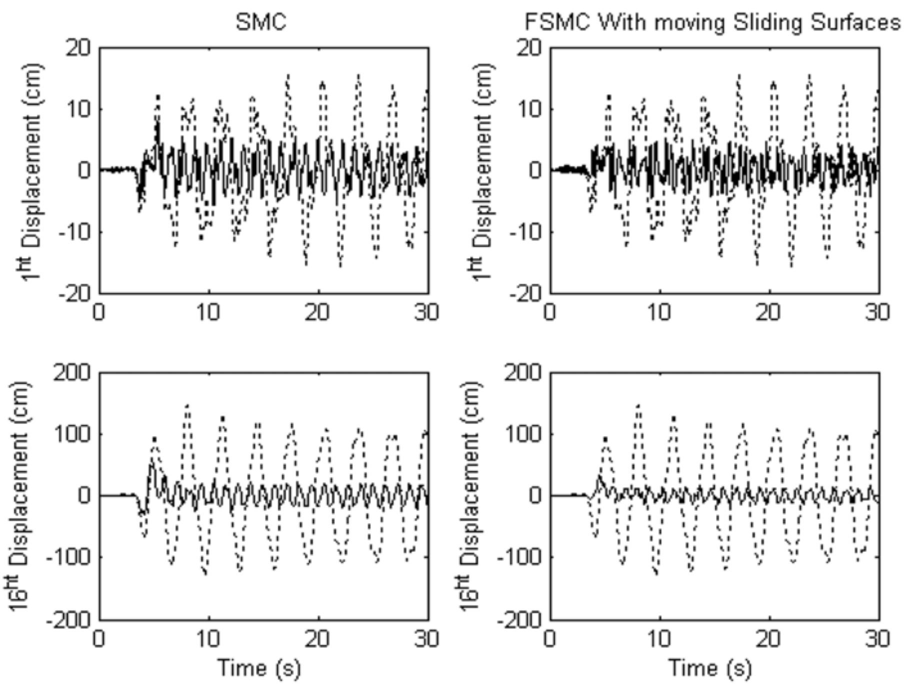

Fig. 26 The controlled and uncontrolled displacements for 40 ms time delay (Northridge (1994))

Table 6 The maximum displacement and acceleration responses of the considered building with and without the controllers for 20 ms time delay

Earthquakes	Stores	Max. Displacements (cm)			Max. Accelerations (m/s^2)		
		Uncontrolled	SMC	Move with FSMC	Uncontrolled	SMC	Move with FSMC
Elcentro 20 ms Delay	16th Store	76,7685	8.2405	3.6746	10,9045	8.7553	6.2902
	1th Store	7,7698	3.1286	1.2545	6,1656	6.4378	5.3921
Hyogo-ken 20 ms Delay	16th Store	64,2914	47.0259	21.3973	28,3552	23.2494	17.4287
	1th Store	15,5953	9.2953	5.4078	14,9466	13.9012	12.5945
Northridge 20 ms Delay	16th Store	145,8908	43.0852	23.0620	20,7386	18.6586	13.8697
	1th Store	15,7276	7.6095	3.5608	10,0144	11.6634	10.0043

Table 7 The maximum displacement and acceleration responses of the considered building with and without the controllers for 40 ms time delay

Earthquakes	Stores	Max. Displacements (cm)			Max. Accelerations (m/s^2)		
		Uncontrolled	SMC	Move with FSMC	Uncontrolled	SMC	Move with FSMC
Elcentro 40 ms Delay	16th Store	76,7685	10.4968	7.0516	10,9045	12.6189	13.1516
	1th Store	7,7698	3.4505	2.7803	6,1656	9.8753	13.0621
Hyogo-ken 40 ms Delay	16th Store	64,2914	47.3727	29.2898	28,3552	26.6163	29.5951
	1th Store	15,5953	8.7209	8.1621	14,9466	16.7588	21.2560
Northridge 40 ms Delay	16th Store	145,8908	51.3641	32.8029	20,7386	21.6167	18.7340
	1th Store	15,7276	8.0179	4.9192	10,0144	12.4229	16.9316

Figs. 19, 20 and Table 5 clearly show the robustness of the proposed controller.

Time delay is one of the important problems in real-time active control. The control action is applied to the system at a later moment after the control action is decided. The sources of time delay are data acquisitions, processing, transmissions, mechanical reactions of actuators and sensors. However, the time required for data acquisitions, processing and transmissions has shortened because of technology developments.

To verify the robustness of the proposed control algorithm with respect to small time delays, the numerical simulations have been evaluated. Figs. 21-26 and Tables 6, 7 show the displacement responses of the considered building with and without controllers for 20 and 40 ms time delays. It is seen that the system performances are still good as the length of time delay increases and instability has not yet been observed for this system.

For 40 ms time delay case, Table 7 indicates that the acceleration response only has minor degradation but instability has not yet been observed. The system remains stable for two cases. However, instability will occur as the length of the time delay exceeds a critical value. The critical time delay values for this algorithm will be evaluated for the next studies.

6. Conclusions

A new method employing fuzzy tuning approach to adjust sliding surface during earthquakes has been proposed for seismic isolation of structures. Extensive simulations based on different realistic seismological data indicate the advantages of the proposed control algorithm. The system response of FSMC with fuzzy move sliding surfaces has remarkably improved in terms of fast damping, robustness and less switches in the control bounds.

Then, the system responses and the chattering effect of the proposed controller have been compared with those of the conventional SMC. The proposed control method incredibly decreases the amplitudes of earthquake-induced vibrations for six different earthquake acceleration records and occurring less switches in the control bounds practically makes this control method more applicable among the others. That's why, real actuators can easily provide the control signals obtained by the proposed control algorithm.

As conventional SMC method, it is shown that FSMC with fuzzy moving sliding surfaces method is not sensitive against structural uncertainties.

The numerical simulations have been evaluated to verify the robustness of the proposed control algorithm with respect to small time delays since time delay is one of the important problems in real-time active control. The simulation results demonstrate that the system performances are still good as the length of time delay increases and instability has not yet been observed for this system. However, instability will occur as the length of the time delay exceeds a critical value. Further research is required to deal with the critical time delay values for this algorithm. This issue will be evaluated for the next studies.

Consequently, these results indicate that the proposed method is an effective method for seismic isolation of structures.

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Notation

$\mathbf{M}$: Mass matrices with $(N \times N)$ dimensions.
$\mathbf{C}$: Damping matrices with $(N \times N)$ dimensions.
$\mathbf{K}$: Stiffness matrices with $(N \times N)$ dimensions.
$\ddot{\mathbf{x}}$: The $(N \times 1)$ dimensional relative acceleration vector.
$\dot{\mathbf{x}}$: The $(N \times 1)$ dimensional relative velocity vector.
$\mathbf{x}$: The $(N \times 1)$ dimensional relative displacement vector.
$\mathbf{B}$: $(N \times 1)$ dimensional control location vector.
$\mathbf{H}$: $(N \times 1)$ dimensional the external force location vector.
$\boldsymbol{\delta}$: $(N \times 1)$ dimensional earthquake influence vector whose terms are all equal to one.
$\mathbf{A}$: $(2N \times 2N)$ dimensional system matrix.
$\mathbf{D_1}$: $(2N \times 1)$ dimensional controller location vector.
$\mathbf{D_2}$: $(2N \times 1)$ dimensional the excitation influence matrix.
$\mathbf{z}$: $(2N \times 1)$ dimensional state vector.
$\boldsymbol{\sigma}$: The sliding surface.
$\mathbf{S}$: $(1 \times 2N)$ dimensional sliding surface coefficient matrix.