SELF-TUNING FUZZY CONTROL OF THE 20-STORY NONLINEAR BENCHMARK BUILDING WITH PIEZOELECTRIC FRICTION DAMPERS

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ABSTRACT :

Semi-active control devices have been shown to be more energy efficient than active devices and more effective in reducing seismic structural vibration than passive devices. A new type of semi-active control device, the piezoelectric friction damper has been made in this paper. Piezoelectric actuators used in the dampers can quickly and accurately respond to a voltage signal. They are also effective over a wide frequency band with low power consumption, and are very reliable and compact in design. The damping capabilities of this device can be quickly varied by changing the voltage. Fuzzy control uses expert knowledge instead of differential equations, it does not require accurate information on structural and vibration characteristics of the system and is therefore an attractive alternative for complex and nonlinear systems. A self-tuning fuzzy control algorithm is proposed in this paper to control the response of a seismically excited 20-story nonlinear benchmark building with piezoelectric friction dampers. Interactive relationships between structural responses and input voltage of piezoelectric friction dampers are established by using a fuzzy controller. The results of the simulation indicate that the proposed fuzzy controller can effectively reduce the responses of the building under different earthquake excitations.

KEYWORDS: Piezoelectric Friction Damper, Self-tuning Fuzzy Control, Benchmark Buildings, Seismically Excited, Structural Control

1. INTRODUCTION

Buildings and civil infrastructures are subjected to natural hazards such as earthquake and wind loads. Structures under such multi-hazard environmental loads not only cause property loss, but also pose a real threat to life [1]. The magnitude 8.0 earthquake, centered in Wenchuan County in Sichuan Province, has killed 69,197 people, 374,176 people were injured and 18,222 missing as of 12 p.m. July 21, Beijing time.

To dissipate energy from earthquakes, reduce structural damage and prevent failure, control device have been developed and implemented in civil structures. These can be classified as passive, active, semi-active. Passive controllers do not require power to operate and are therefore very reliable. Active controllers require a large amount of energy for operation and have the ability to dissipate energy and/or apply a force to the structure. Semi-active controllers, on the other hand, require little power for operation, are more efficient than passive devices and guarantee stability since they do not add energy to the system. The piezoelectric friction damper is a particular type of semi-active control system, and it has been developed and applied to large civil engineering structures for seismic vibration control and has achieved successful results [2-4]. A new type of the piezoelectric friction damper has been made in this paper.

Most of the studies in the area of semi-active structural control have focused on the application of linear control theories because of the large body of proven linear control methods available and the tendency of keeping the structural response in the linear range. The mathematical model used for tall buildings is usually linear. However, such a model does not fully represent the behavior of the building when subjected to severe earthquake such as Wenchuan earthquake during which some yielding and nonlinear behavior is likely to occur.
Fuzzy control represents an alternative control approach to the classical control theory, the classical control

strategies are rarely implemented for nonlinear, time-variant and complex systems, here, fuzzy control may have its advantages. The fuzzy control has been investigated for the control of civil engineering structures [5, 6].

The main objective of this work is to apply the new piezoelectric friction damper and the self-tuning fuzzy control to the 20-story benchmark building [7] to handle the nonlinearity of the system.

2. PIEZOELECTRIC FRICTION DAMPER

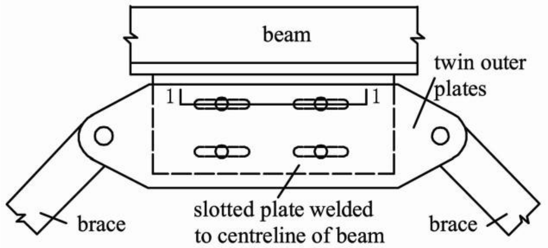
A new type of semi-active control device, the piezoelectric friction damper has been made as shown in Fig. 1. The piezoelectric friction damper is consisted of slotted bolted connection [8] and piezoelectric stacks, and it refers to a bolted connection where the slots in the main connecting plate, in which the bolts are seated, are parallel to the line of loading, brass insert plates as frictional materials. The piezoelectric stacks located between the outer plates are key to providing varying friction forces to the structure. The piezoelectric stacks can develop significant axial forces under voltage as long as it is restrained in the axial direction. Changing the supplied voltages can alter the contact force exerted by the piezoelectric stacks, which in turn alters the frictional forces. The holes in the brass insert plates and in the steel outer plates are of standard size. When the tensile or compressive force applied to the connection exceeds the frictional forces developed between the frictional surfaces, the main plate slips relative to the brass insert plates. This process is repeated with slip in the opposite direction upon reversal of the direction of force application. Energy is dissipated by means of friction between the sliding surfaces.

The piezoelectric stack actuators used in the piezoelectric friction damper were manufactured by China Electronic technology Group Corporation No.26 Research Institute. The piezoelectric strain coefficient d_{33} and the Young's Modulus of elasticity E_p are equal to 550×10^{-12} m/V and 6.0×10^{10} MPa. Each stack is 0.025 m in length and 0.025 m in width. It is composed of 100 individual piezoelectric layers stacked in series and wired in parallel, each 0.2 mm in thick.
N_p is the constrained force of the piezoelectric stacks under electric field, N_b is the clamping force of the bolt which restrain the strains of the piezoelectric stacks under electric field, then

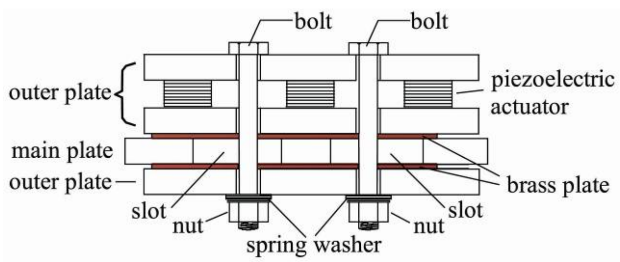
$$N_p = n\varepsilon_p E_p A_p \qquad N_b = 4\varepsilon_b E_b A_b \tag{2.1}$$

in which, $\varepsilon_p = (\Delta L_V - \Delta L)/L_p$, $\varepsilon_b = \Delta L / L_b$, $\Delta L_V = d_{33} V L_p / h$, ΔL_V is the elongation of the piezoelectric stacks under electric field, ΔL is the elongation of the bolts, E_p is the Young's Modulus of the piezoelectric stacks, d_{33} is the piezoelectric strain coefficient and V is the applied voltage on the piezoelectric stacks, A_p is the area of cross section of the stacks, L_p is the high of the stacks, h is the thickness of each layer, n is the number of the stacks; E_b is the Young's Modulus of the bolts, A_b is the area of cross section of the bolts, L_b is the length of the bolt, 4 is the number of the bolts.

$$N_p = N_b \tag{2.2}$$



(a) The planar graph



(b) 1-1 Section graph

Figure 1 Piezoelectric friction damper

From equation (1) and (2), N_p can be expressed as

$$N_p = K\frac{d_{33}}{h}V \qquad K = \frac{1}{\dfrac{1}{nE_pA_p} + \dfrac{L_b}{4L_pE_bA_b}} \tag{2.3}$$

The damping force model of the piezoelectric friction damper can be express as:

$$\boldsymbol{f}(t) = 2\mu N_p(t)\,\mathrm{sgn}[\dot{\boldsymbol{x}}(t)] \tag{2.4}$$

in which, $\dot{\boldsymbol{x}}(t)$ is the interstory velocity, μ is the coefficient of friction of the damper.

3. BENCHMARK BUILDING

The 20-story benchmark building used for this study was designed for the Los Angeles region as defined by Ohtori [7] in the problem definition. The benchmark building is 30.48 m by 36.58 m in width, and 80.77 m in height. Two far-field and two near-field historical ground motion records are selected: EI Centro 1940, Hachinohe 1968, Northridge 1994, and Kobe 1995 earthquakes. This benchmark study will consider various levels of each of the earthquake records including: 0.5, 1.0, and 1.5 times the magnitude of EI Centro and Hachinohe; 0.5 and 1.0 times the magnitude of Northridge and Kobe. This is a total of ten earthquake records to be considered in the evaluation of each control strategy. The evaluation criteria ($\boldsymbol{J}_1$—$\boldsymbol{J}_{17}$) are divided into four categories: Building responses, building damage, control damage, control devices, and control requirements.

4. SELF-TUNING FUZZY CONTROL

4.1. Basis Fuzzy Controller

The main idea of fuzzy control is to build a model of an expert operator who is capable of controlling the building without thinking in mathematical terms. The person controls the building by a set of linguistically expressed rules that result from the a priori know-how of the physics of the building.

The input variables to the fuzzy controller are chosen as the absolute value of the interstory drift (R_D) and its velocity (R_V) and the output as the applied voltage to the piezoelectric friction dampers. The membership functions for the inputs are defined on the normalized universe of discourse [-1, 1] and selected as five identical triangles (Figure. 2). Those for the output are defined on the universe of discourse [-1, 1] and selected as five identical triangles (Figure 3). The labels NB, NS, ZE, PS, PB refer to negative big, negative small, zero, positive small, positive big, respectively. Rules for computing the desired voltage are presented in Table 1. The fuzzifier factors used to convert the inputs into fuzzy variables are defined as *K_dis* and *K_vel*, for interstory drift and its velocity, respectively. The defuzzifier factor used to convert the fuzzy variables into voltage is defined as *K_volt*. To determine whether a relationship exists between the fuzzifer factors and the responses of buildings under earthquake, a preliminary parameter analysis has been performed. It consists in scaling the responses of buildings and performing simulations with each excitation for a range of values for *K_dis* and *K_vel*. According to these results, The values of *K_dis* and *K_vel* are shown as fellow:

$$K\_dis = 1/D_{max} \qquad K\_vel = 1/V_{max} \qquad K\_volt = -1000 \tag{4.1}$$

in which, D_{max} is the absolute value of the maximum uncontrolled displacement and V_{max} is the absolute value of the maximum uncontrolled velocity of the floors.

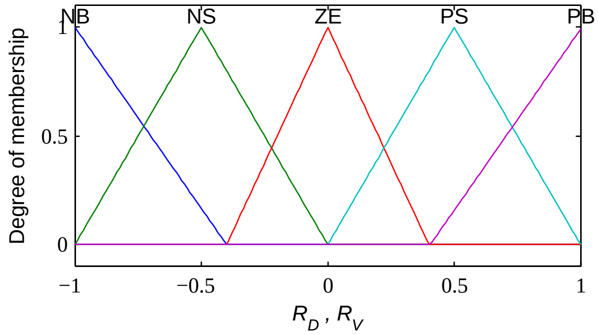


Figure 2 Membership functions for R_D, R_V

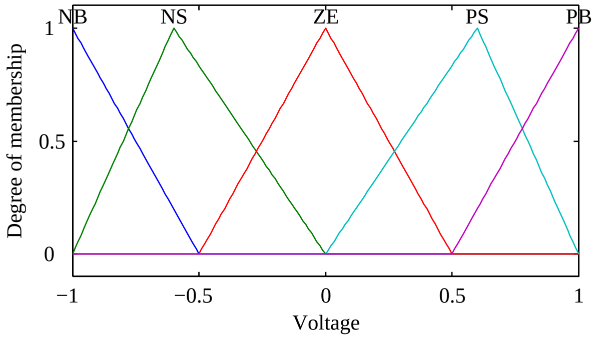


Figure 3 Membership functions for voltage

Table 1 Basis fuzzy control rules

		R_V				
		NB	NS	ZE	PS	PB
R_D	NB	PB	PB	PB	PS	PS
	NS	PS	PS	PS	ZE	ZE
	ZE	PS	PS	ZE	ZE	NS
	PS	ZE	ZE	NS	NS	NS
	PB	NS	NS	NB	NB	NB

Table 2 Self-tuning fuzzy control rules

		R_A		
		S	M	L
R_D	S	S	M	L
	M	M	M	L
	L	L	L	L

4.2. Self-tuning

A relationship has been found to exist between *K_vel* and the intensity of the seismic excitation. An equation is therefore derived to relate these two parameters and used to adjust the values for *K_vel* during the earthquake. Simulation results show that varying this scaling factor's values can improve the performance of the structure more than keeping it constant.

Figure 4 shows a diagram of the self-tuning mechanism developed. In this algorithm, ground acceleration (R_A) and interstory drift (R_D) are chosen as the inputs to the fuzzy controller 2 system that selects the desirable value for *K_vel* at each time step. The fuzzifier factor used to convert the inputs into fuzzy variables is defined as *K_a* and *K_d*, for acceleration and interstory drift, respectively. The defuzzifier factor used to convert the fuzzy variables into the parameter (R_{DA}) of the *K_vel* is defined as *K_da*. The membership functions for the inputs and outputs are defined on the universe of discourse [0, 1] and select as three identical triangles (Figure. 5 to 7). The labels S, M, and L refer to small, medium and large, respectively. Rules for computing the desired R_{DA} are shown in Table 2. When *K_a*=100, *K_d*=100 and *K_da*=2, the proposed fuzzy controller can effectively reduce the responses of the building under different earthquake excitations.

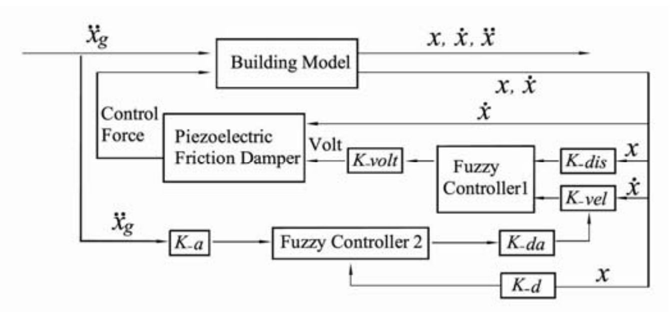


Figure 4 Diagram of self-tuning fuzzy control system

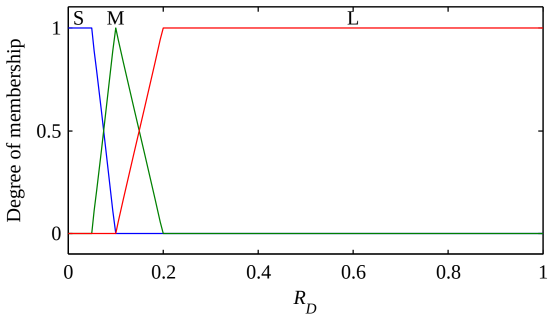


Figure 5 Membership functions for R_D

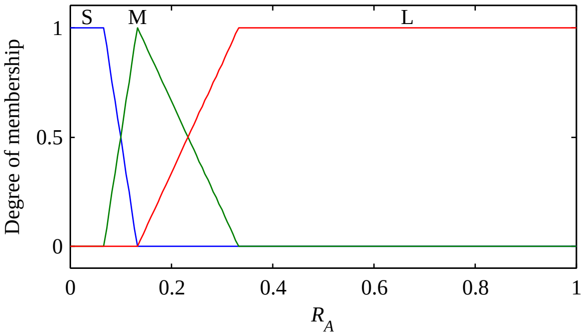


Figure 6 Membership functions for R_A

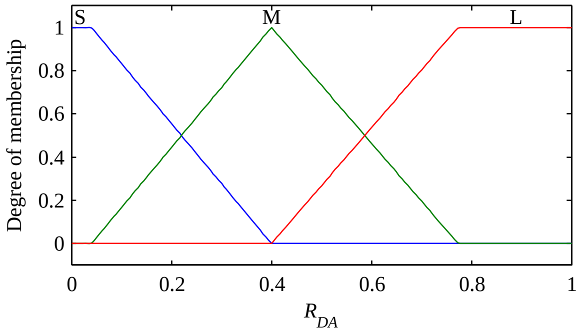
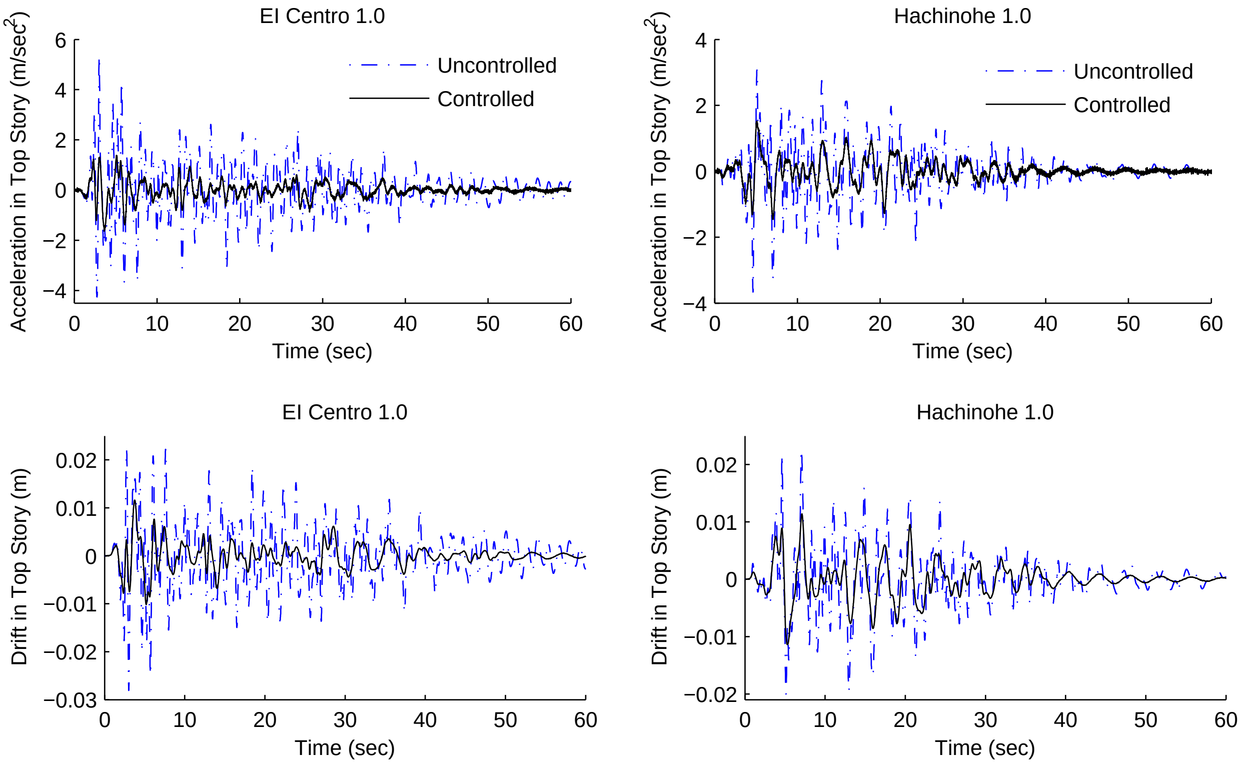


Figure 7 Membership functions for R_{DA}

5. CONTROL PERFORMANCE

The nonlinear 20-story benchmark model controlled with self-tuning fuzzy control strategy described is evaluated. The responses of the controlled structure are determined for each of the ten earthquake records using the MATLAB simulation discussed herein. The piezoelectric friction dampers are placed throughout the above ground stories of the 20-story benchmark building, connecting adjacent levels. To provide larger control forces at a particular location, multiple actuators can be employed, six piezoelectric friction dampers are located on the ground levels, and one piezoelectric friction damper is located on the first level, and two piezoelectric friction dampers are located on each of the second through nineteenth levels of the structures. Each piezoelectric friction damper is implemented in the structure using a chevron brace configuration, in which the piezoelectric friction damper is horizontal and rigidly attached between the two consecutive levels of the building. Thus, the piezoelectric friction damper placed on the first level will produce equal and opposite control forces on the first level and second level. In the analysis the compliance of the bracing is neglected.



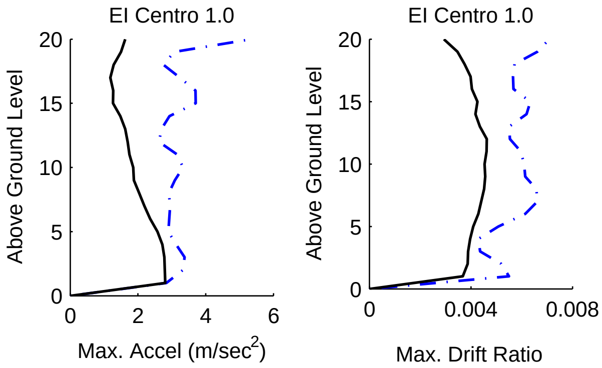


Figure 8 Responses under EI Centro earthquake

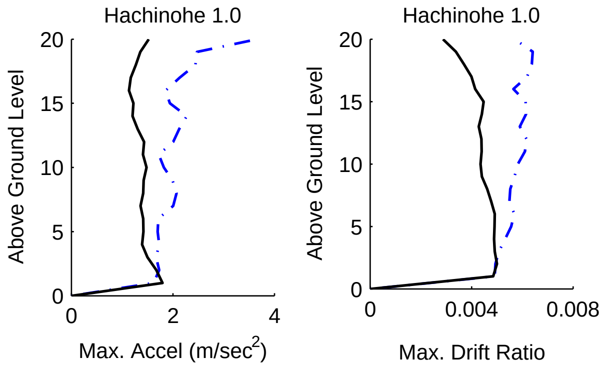


Figure 9 Responses under Hachinohe earthquake

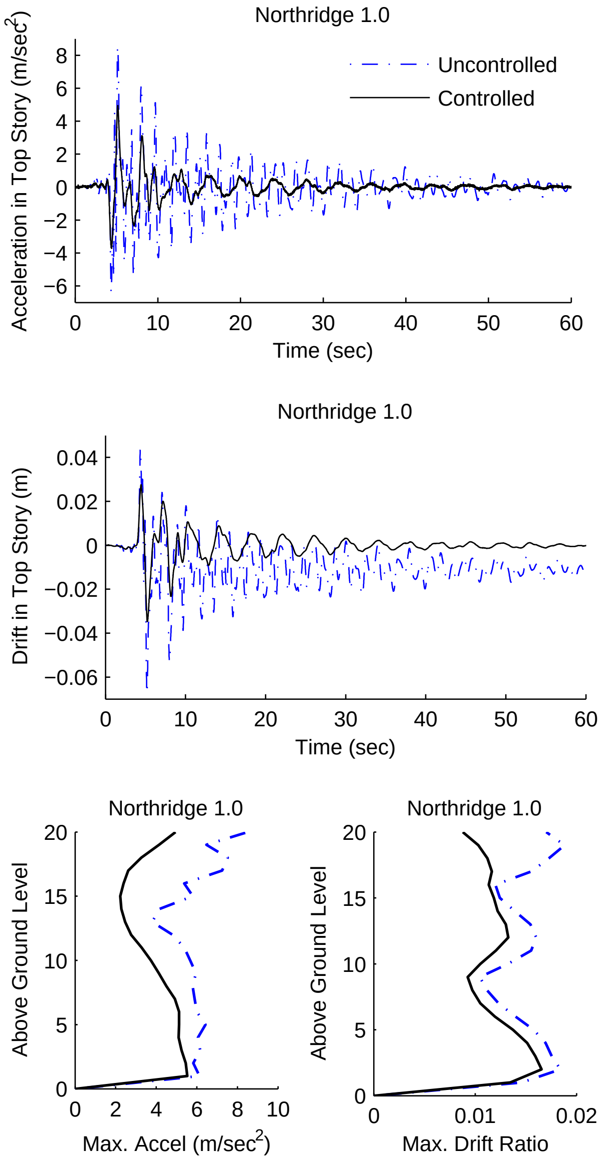


Figure 10 Responses under Northridge earthquake

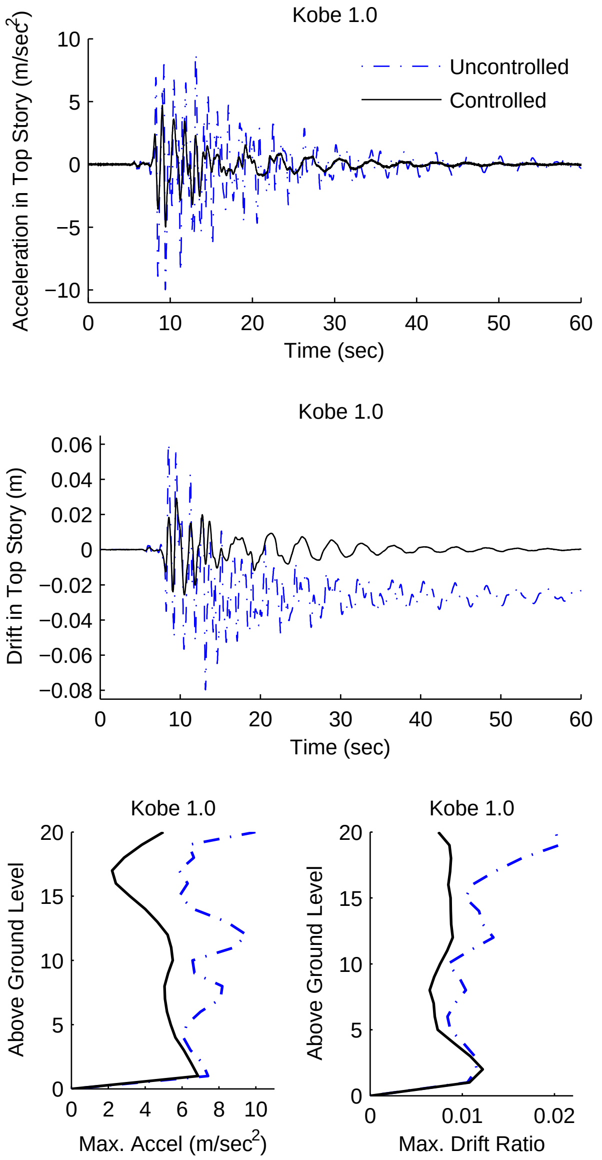


Figure 11 Responses under Kobe earthquake

Table 3 Earthquake evaluation criteria for the self-tuning fuzzy control strategy

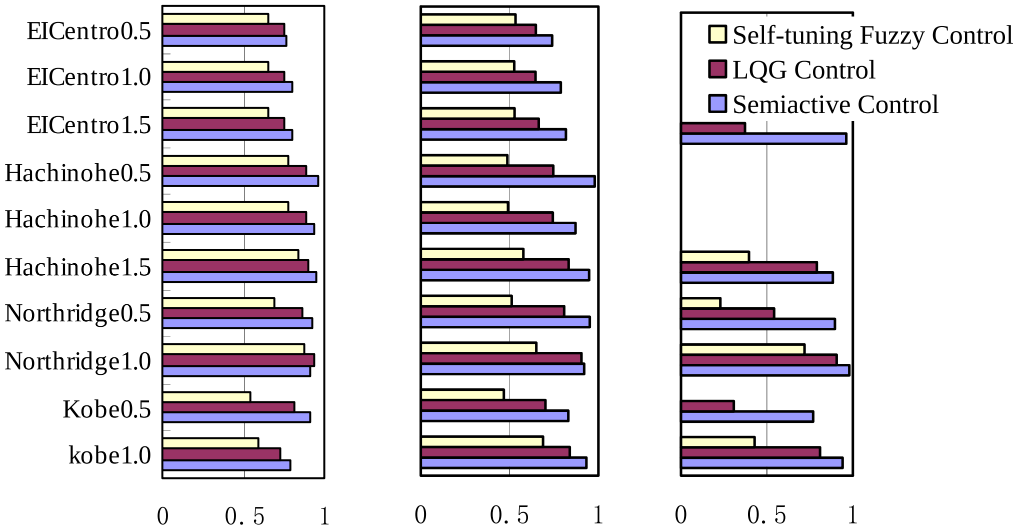
Earthquake intensity	EI Centro 0.5	EI Centro 1.0	EI Centro 1.5	Hachinohe 0.5	Hachinohe 1.0	Hachinohe 1.5	Northridge 0.5	Northridge 1.0	Kobe 0.5	Kobe 1.0	Max value
J_1(peak drift ratio)	0.650	0.653	0.655	0.778	0.780	0.838	0.691	0.880	0.537	0.596	0.880
J_2(peak level acceleration)	0.533	0.526	0.528	0.487	0.491	0.578	0.512	0.650	0.468	0.689	0.689
J_3(peak base shear)	0.683	0.684	0.795	1.026	1.027	1.053	0.893	1.038	0.802	1.157	1.157
J_4(norm drift ratio)	0.581	0.583	0.589	0.820	0.821	0.839	0.588	0.957	0.465	0.170	0.957
J_5(norm level acceleration)	0.331	0.326	0.338	0.494	0.478	0.488	0.395	0.484	0.317	0.440	0.494
J_6(norm base shear)	0.631	0.632	0.639	0.784	0.785	0.796	0.629	0.829	0.543	0.745	0.829
J_7(ductility)	0.671	0.674	0.628	0.958	0.910	0.936	0.686	0.890	0.511	0.700	0.958
J_8(dissipated energy)	—	—	0	—	—	0.427	0.040	0.384	0	0.107	0.427
J_9(plastic connections)	—	—	0	—	—	0.395	0.229	0.708	0	0.429	0.708
J_{10}(norm ductility)	0.641	0.643	0.576	0.794	0.795	0.868	0.501	0.978	0.473	0.231	0.978
J_{11}(control force) $\times 10^{-3}$	1.993	3.739	5.321	2.093	3.927	5.528	6.183	11.59	5.808	10.73	11.59
J_{12}(device stroke)	0.066	0.066	0.067	0.076	0.077	0.081	0.074	0.099	0.102	0.114	0.114
J_{13}(control power) $\times 10^{-3}$	1.778	3.494	5.493	1.917	3.793	5.654	6.013	14.46	7.677	15.57	15.57
J_{14}(norm control power) $\times 10^{-3}$	0.078	0.149	0.234	0.074	0.141	0.219	0.107	0.22	0.090	0.211	0.234
J_{15}(control devices)					43						
J_{16}(sensors)					20						
J_{17}(computer resources)					20						

Representative responses of the self-tuning fuzzy control systems to the full-scale EI Centro, Hachinohe, Northridge and Kobe earthquake are shown in Fig. 8, Fig. 9, Fig. 10 and Fig. 11. Time histories are provided for the absolute acceleration of the 20th floor of the building and interstory drift between the 19th and 20th floors. This response is selected because the maximum drift often occurs at the 20th floor. Maximum acceleration and maximum interstory drift ratio response profiles are provided for all floors of the building.

According to these times history results, the both peak acceleration and peak interstory drift are significantly reduced when the piezoelectric friction dampers are used to control the building. The response profiles show that peak story drifts are reduced at all floors. The maximum floor acceleration is always reduced in Fig. 8, Fig. 9, Fig. 10 and Fig. 11. In addition, it is obvious that in the case of severe earthquakes, such as the full-scale Northridge and Kobe earthquake significant permanent drifts remain for an uncontrolled building due to the development of plastic connections, which are suppressed with control using the piezoelectric friction damper.

The values of the evaluation criteria for the self-tuning fuzzy control system are provided in Table 3. In the fuzzy control strategy, The drift evaluation criteria, both peak drift ratio (J_1) and norm drift ratio (J_4), are reduced substantially from the uncontrolled cases, the floor accelerations, both peak level acceleration (J_2) and norm level acceleration (J_5), are also reduced substantially, though the peak base shear criteria (J_3) remain unaffected. The control force evaluation criteria (J_{11}) are reasonable. The building damage evaluation criteria show an overall improvement. The amount of energy dissipated through structural yielding (J_9) is reduced substantially. The control device criteria appear reasonable. The number of sensors (J_{16}) and control devices (J_{15}) are also reasonable, as well as the computational resources required to implement to a 20-state controller.

To compare the performance of the different controlled systems, the bar chart in Fig. 12 shows the values for maximum interstory drift ratio (J_1), maximum absolute acceleration (J_2), number of plastic connections (J_9), Note that in all cases, the self-tuning fuzzy control's results are smaller than the semi-active control [3] and LQG control [7].



(a) $\boldsymbol{J}_1$ (b) $\boldsymbol{J}_2$ (c) $\boldsymbol{J}_9$

Figure 12 Bar chart comparing the evaluation criteria for various controller

6. CONCLUSION

A new piezoelectric friction damper is designed and fabricated in this paper, the piezoelectric friction damper is regarded as the semi-control device, fuzzy control algorithm have been proposed for reducing nonlinear seismic response of 20-story benchmark buildings, interactive relationships between structural responses and fuzzifier factors, defuzzifier factors are established, considered the influence of the absolute value of the ground acceleration through fuzzy controller, the fuzzifier factors are gain-scheduled online. Numerical simulation is carried out for analyzing the nonlinear seismic responses of the controlled 20-story benchmark building, and the simulation results are compared to those of other control strategies. The results show that the self-tuning fuzzy control can reduce the nonlinear seismic response of 20-story benchmark building with piezoelectric friction dampers efficiently and minimize the damages in the building structures caused by strong earthquakes.

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