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Application of Variable Friction Damper to Transmission Tower Structure with Two Connection Ways

Meng Zhan $^{1)*}$***, Lizhen Zhang*** $^{2)}$***, Xiuyun Chen*** $^{1)}$ ***and Sheliang Wang*** $^{1)}$

$^{1)}$ College of Architecture Engineering, Huang Huai University, Zhumadian 463000, China.
$^{2)}$ College of Mechanical and Energy Engineering, Huang Huai University, Zhumadian 463000, China.
*Corresponding Author. E-Mail: zhanyi313@163.com

ABSTRACT

According to the operating characteristics of piezoelectric ceramic materials, the authors designed a kind of variable friction damper with reset function. Based on the transmission tower structure characteristics of force and deformation, the two damper installation ways put forward were bar connection and rope connection. The corresponding simulated earthquake shaking table test was carried out for model structure. Based on the characteristics of the two kinds of damper installation, fuzzy control strategy with strain response and speed response as input was established. Seismic response of transmission tower structure with non-control, passive control and semi-active control was tested under El Centro seismic wave. The experimental results showed that piezoelectric friction damper can effectively reduce the seismic peak responses of model structure under the two kinds of damper installation way. Fuzzy control algorithm with strain response and speed response as input whose system is simple is easy to the operation of the actual project. It can change in real time the friction according to the dynamic responses of the structure to realize the vibration control of structures.

KEYWORDS: Piezoelectric ceramic, Friction damper, Transmission tower, Shaking table test, Vibration control.

INTRODUCTION

Piezoelectric friction damper (Dai et al., 2011; Ozbulut et al., 2011; Unsal and Nieqreeki, 2003) is a kind of intelligent semi-active damping device, which has the characteristics of stable performance of friction energy dissipation and the characteristics of fast response speed of piezoelectric smart materials. It also possesses the advantages of small input energy of semi-active control. At present, many scholars have proposed many types of piezoelectric friction damper for vibration control and have conducted some research on related analysis and application in civil engineering (Lu et al., 2010; Lu et al., 2011; Dong et al., 2011; Dong et al., 2016). Chen verified the effectiveness of designed piezoelectric friction dampers for structural seismic response control by numerical analysis and experimental research (Garrett et al., 2000; Chen et al., 2003; Chen and Chen, 2004). Ng investigated semi-active coupling control of a building complex, which consisted of a main building and a podium structure, using variable friction dampers for mitigating seismic responses (Ng and Xu, 2007). Etedali carried out seismic control of a benchmark isolated building equipped with piezoelectric friction dampers using PD/PID controllers (Etedali et al., 2013). Although the piezoelectric friction dampers showed good inhibitory effect on the structural vibration response, they studied mainly the theoretical calculation and simulation analysis;

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therefore, it is necessary to strengthen the study with shaking table of the piezoelectric friction damper.

Fuzzy control is the combination of fuzzy mathematics and the control theory. Compared with the traditional semi-active control algorithm, fuzzy control does not need to establish an accurate mathematical structure model. It can put nonlinear, high-order and non-stationary complex objects under effective control. At present, fuzzy control has been widely applied to structural vibration control (Yan et al., 2000; Aldawod et al., 2001; Zhao and Li, 2011). But, if the number of dampers increases in practical engineering, the fuzzy control system will need more sensors, which will increase the complexity of the control system and engineering economic investment. Therefore, establishing suitable practical engineering fuzzy controllers is of great significance.

In this paper, a kind of resetting piezoelectric friction damper was designed. According to the transmission tower model's characteristics of structure force and deformation, two ways of installing damper were put forward; bar connection and rope connection and thus a fuzzy controller which used strain response and speed response as input was established. Then, transmission tower structure of earthquake simulation shaking table test was made. The vibration reduction effects in the cases of uncontrolled, passive friction damping control and fuzzy control at El Centro wave were compared and analyzed. The reset-type piezoelectric friction damper and fuzzy control which used strain response (speed response) as input verified their effectiveness of controlling the structure's vibration.

Reset-Type Piezoelectric Friction Damper

Damper Design

The piezoelectric friction damper (see Fig. 1) is composed of damper body, piezoelectric ceramic actuator, sleeve, spring, roof, lid of piston, lid of damper, push-pull rod and balance beam. The energy consumption of piston is slightly higher than that of shell in clear height, which consists of the balance beam, roof, base, gasket and sleeve. The diameter of the reset spring is slightly larger than the diameter of a pull rod; it is slightly longer than the range; they are set on the balance beam and a lever, respectively. The piston's reset function is to ensure that the dampers can dissipate energy during the slide in rope connection. In the damper design, we considered that piezoelectric ceramic actuator is not resistant to the curved scissors and a reasonable structure ensures that the piezoelectric actuators only stand axial compression. Piezoelectric ceramics are brittle materials; in the sleeve, we made a gasket up and down to receive strength evenly to stay away from brittle failure. Piezoelectric friction damper was installed to the structure of the bar; when the structure suffered external disturbance, the push-pull rod made reciprocating movement and drove the piston motion, which produced sliding friction energy dissipation and then by applying a voltage to piezoelectric ceramic, the friction force of the damper was adjusted in real time and the semi-active control was realized.

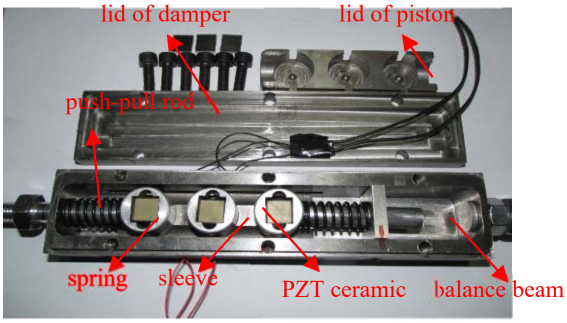


Figure (1): Piezoelectric friction damper

Control Force of Damper

Piezoelectric friction damper control test device is shown in Fig. 2. The test used the displacement control and load amplitude is set to 3mm. In the experiment, there are two piezoelectric ceramic actuators. Initial friction force was 100N and the range of drive voltage was 0-150V in steps of 30V. The loading speed was 90mm/min. The damper was put under different voltage control loads, respectively, where each load was from the beginning of the damper's equilibrium position, then back to the equilibrium position. Damper hysteresis curve is plotted in Fig. 3. From the figure, the piezoelectric friction damper is stable in energy dissipation; with the increase of voltage, output force of the damper increases gradually and the adjustable voltage maximum friction force is 250N. When the load is steady, the control force of piezoelectric friction damper corresponding to different voltage values is expressed as:

$$F = -\mu(N_0 + 1.6U)\, sgn(\dot{x}) \qquad U \geq 0 \qquad (1)$$

where F is the piezoelectric friction damper control force, μ=0.48 is the coefficient of friction, N_0 is the initial preloading of piezoelectric friction damper. U is the input voltage, which can be given by the fuzzy control algorithm.

Figure (2): Test device

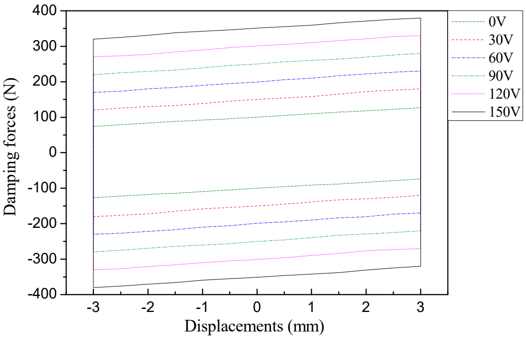


Figure (3): Damper hysteretic curves

Shaking Table Test

Model Structure Test

North China power grid of 110 kV high-voltage transmission tower was used as the research object. By the proportion of 1:10 scale, the model of simplified damper transmission tower is shown in Fig. 4. Tower leg part had 1 layer, tower part had 3 layers, tower head part had 2 layers; a total of 6 layers. Model structure's total height was 2.96m; 1.8m. Tower head's width was 0.56m; root's width was 0.9m. All bars adopted had dimensions of 30mm×30mm×3mm of equal angle steel and were made of Q235 steel. Elastic modulus was 206GPa and Poisson ratio was 0.3; the density was 7800 kg/m^3. The welding was used between the top horizontal bar of cross-arm and the four main vertical rods; bolt connection was used between the low horizontal bar of cross-arm and the main vertical rod to ensure the stability of the structure and the convergence of calculation results. In order to verify the damper control of reset type piezoelectric friction, all the diagonal models of transmission tower structure were got rid of and 5kg quality pieces at the third and sixth layers on the cross-arm ends were placed to simulate the counter weight.

(a) bar connection **(b) rope connection**

Figure (4): Transmission tower model structure with damper

Installation of Damper

The damping effect, implementation of structure and economy as well as other factors were mainly considered in the installation of piezoelectric friction damper. The control effect of piezoelectric friction damper was mainly related to the relative displacement at the ends of the damper. Therefore, dampers can be installed in the smaller stiffness of structure, in which layer displacement was big. In bar connection, the study (Chen et al., 2009) showed that the tower had a big deformation and the cross-arm section bar was dense, with small activity space. It was difficult to install control devices; so, a semi-active piezoelectric bar was set in the second and third layers along the diagonal structure. In rope connection, in order to increase the damper sliding displacement as much as possible and to consider the ease of rope connection, a piezoelectric friction damper was connected to both sides of the model structure, respectively. The damper's one end was fixed on the vibration table, while the other end was connected with the fifth layer cross-arm through a pulley. The rope was in a state of tension, but had no pretension before the test. The installation of dampers is shown in Figs. 5(a) and 5(b).

(a) bar connection **(b) rope connection**

Figure (5): Installation of piezoelectric friction damper

Apparatus and Equipment in the Test

The vibration control experiment was carried out at 4m×4m of simulated earthquake vibration table in the structural engineering seismic lab in Xi'an University of Architecture and Technology. As illustrated in Fig. 6, the main test equipment included: LMS, dynamic resistance strain collection system, multi-channel piezoelectric pile driver power supply, small dynamic strain recorder, type 891 eight-line amplifier and control system. Among them, the A/D converter, the controller in which applied voltage was determined by control algorithm and D/A converters are all completed by real-time simulation system DSPACE.

Figure (6): Test equipment

Installation of Sensors and Strain Gauges

Speed sensors were set along the X and Y directions in the fifth layer of transmission tower model structure and were used for data collection and feedback control in rope connection. The size of the control input took X direction and Y direction resultant velocity. Strain gauges were arranged on the semi-active piezoelectric bars at the second and third floors, respectively, for feedback control in bar connection. Acceleration sensors were decorated in each layer according to the X and Y directions in countertop and transmission tower structure and were only used to collect data. Displacement response can be acquired by the acceleration's second integral.

Fuzzy Control Strategy

Due to that the internal force of the semi-active piezoelectric bar directly reflected the force of the damper control required, the strain response of the semi-active bar was used as the input of the fuzzy controller in bar connection. Due to that the speed of response reflected the characteristics of the ground motion (He et al., 2003), Lasso's installation height layer's velocity response was used as input variable for the fuzzy controller in rope connection. According to the actual situation, single-input and single-output fuzzy controller was chosen. The domain boundaries of input variable were taken as the strain response or the absolute peak value of velocity response in the uncontrolled state. The control voltage was taken for output variable; the universe of discourse was from 0 to 150V. There were seven language values of input/output variables, which were [NB, NM, NS, O, PS, PM, PB]. Fuzzy comprehensive domain was from -3 to 3. Gauss function was chosen as membership function. Mamdani fuzzy model was used for fuzzy reasoning; the operation adopted was minimum operation; a single fuzzy point was adopted. Fuzzy control rule is shown in Table 1. Center of gravity method was used for solving ambiguity (Sun et al., 2011).

Table 1. Fuzzy control rule

ε(V)	NB	NM	NS	0	PS	PM	PB
U	NB	NM	NS	0	PS	PM	PB

Two piezoelectric friction dampers were controlled respectively and worked at the same time in bar connection; two dampers, controlled at the same time, worked alternately in rope connection. Earthquake excitation was generated by the vibration table. The strain collection device and speed sensors measured the strain response or speed response of the model structure directly; the voltage values were calculated online through fuzzy control algorithm and applied to piezoelectric ceramic through stabilized voltage supply. Then, the control force was applied to model the structure according to Eq. (1) and semi-active control was realized.

Analysis of Test Results

To validate the effectiveness of the proposed piezoelectric friction damper and the fuzzy control algorithm in structural vibration control, El Centro wave was chosen to verify the damping effect of damper in the shaking table test; load directions were X and XY directions; load duration was 30s. Acceleration peak value was adjusted to 0.2g and 0.4g, respectively. There were three kinds of control strategies; they were passive friction damper control, uncontrolled and under no applied voltage; strain response (speed response) was used as the input of fuzzy control. Limited to length, given here is only the seismic response of model structure in X direction under seismic wave peak of 0.2g.

Tables 2 and 3 show the acceleration response peak values and the corresponding control effects under two-damper installation of different control strategies. As seen from the tables, under the two kinds of installation, the piezoelectric friction damper can effectively reduce the seismic peak response of the model structure. Compared with the passive control, fuzzy control can adjust the control force of damper in real time according to the dynamic response, getting a better control effect. In bar connection, the best control effect was at the top of the structure; the vibration reduction rate was 37.31%; it is mainly because the corresponding stiffness values of second and third layers were increased after the installation of dampers. And in rope connection, second and third layers, which had less stiffness in the structure, showed optimal control effect; maximum damping rate was 41.42%. Overall, the rope connection control effect is relatively better than that of bar connection. This is mainly because in rope connection, relative sliding displacement is larger at the ends of the damper, where there is more friction energy dissipation.

Table 2. Acceleration response peak values for bar connection

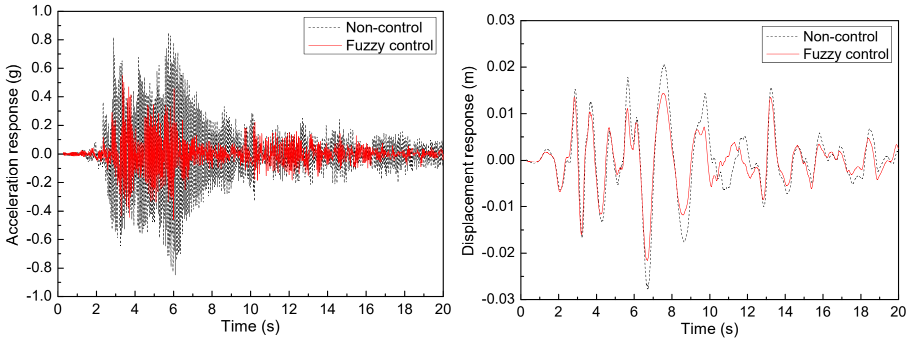
Control strategy	Peak acceleration response (g)					
	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6
No control	0.393	0.623	0.650	0.507	0.725	0.884
Passive control	0.384	0.605	0.557	0.444	0.577	0.686
α (%)	2.31	2.84	14.32	12.29	20.40	22.35
Fuzzy control	0.369	0.592	0.494	0.404	0.461	0.554
β (%)	6.07	5.08	24.00	20.27	36.32	37.31

Table 3. Acceleration response peak values for rope connection

Control strategy	Peak acceleration response (g)					
	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6
No control	0.393	0.623	0.650	0.507	0.725	0.884
Passive control	0.344	0.459	0.468	0.429	0.588	0.662
α (%)	12.28	26.42	28.00	15.42	18.91	25.11
Fuzzy control	0.303	0.356	0.368	0.378	0.517	0.533
β (%)	20.11	40.92	41.42	22.97	26.28	37.59

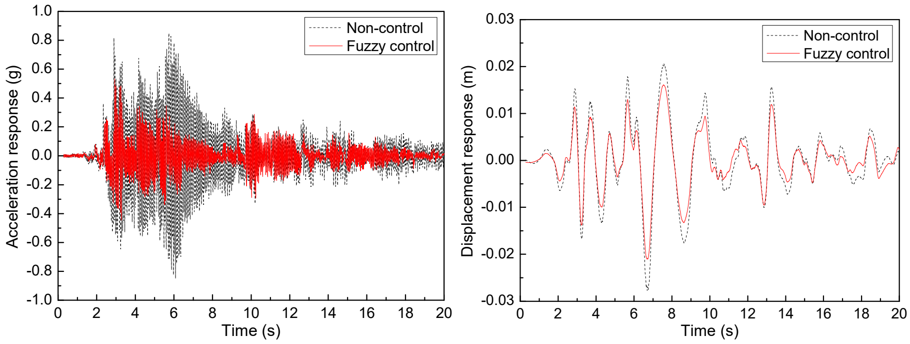
* α (β) = (Response without control –Response with control) / Response without control.

Figs. 7 and 8 display the acceleration and displacement response time-history curves of the top structure under non-control and fuzzy control. As seen from the figures, the designed piezoelectric friction damper and the fuzzy control strategy using strain response (speed response) as input can effectively restrain the structural dynamic response.



(a) Acceleration response **(b) Displacement response**

Figure (7): Dynamic response time history curves for bar connection



(a) Acceleration response **(b) Displacement response**

Figure (8): Dynamic response time history curves for rope connection

CONCLUSIONS

According to the characteristics of the transmission tower structure model, this paper puts forward two ways of installing damper; bar connection and rope connection. Based on strain response and speed response as input of fuzzy control strategy, respectively, the structure is simulated by earthquake shaking table test. The following conclusions are drawn:

- The designed reset-type piezoelectric friction damper is light, easy to install and remove. It takes less space and can be used in both bar connection and rope connection. It can effectively reduce the seismic response of model structure.
- Using strain response (speed response) as the input of fuzzy control is a kind of simple and intelligent control algorithm, which can adjust the structure's damper control force in time based on the dynamic response and inhibit the vibration response of the model structure as well.
- Single input fuzzy control algorithm adopted in the test needs less actuators for feedback control. Also, the control system is simple and convenient for practical engineering applications.

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