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Fuzzy Control of Seismic Structure with an Active Mass Damper

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ABSTRACT

Fuzzy theory is highly promising for active structural control. The advantage of fuzzy controllers over classical controllers is the limited number of measured structural responses used to implement the control rules and its intrinsic robustness. In this paper, Fuzzy rules were generated firstly by learning from sample data obtained from the performance of the system under optimal control algorithm. Secondly, the numerical simulation was carried out to verify the effectiveness of the designed fuzzy controllers. Lastly, Shaking table tests of a 1:8 scaled twelve-story steel frame structure using an active mass damper driven by fuzzy controller were conducted. The simulation and test results showed that the fuzzy controllers were very effective in reducing the response of model structure under seismic excitation and reductions of 40%~60% in displacements could be achieved, Moreover, modified fuzzy control system considering the influence of multiple inputs had a better structural vibration control effect.

KEYWORDS: *Structural Vibration Control, Fuzzy rules, Simulation, Shaking table test, Active Mass Damper*

1. INTRODUCTION

Research and development in active control of civil engineering structures has an approximately 40-yr history, starting in the 1970s [1]. In recent years, remarkable progress has been made [2, 3]. Active mass damper (AMD) system has been widely adopted into the vibration control of many tall buildings across the world due to its advantages such as excellent vibration control, wide adaptability and flexibility. In 1989 Japan accomplished the first building with AMD system – Kyobashi Center – and the control over structural wind vibration and seismic response; in1995, the AMD system was adopted to accomplish the wind vibration control over the bridge during the construction stage of Nakajima bridge; in 2001 in the joint study by China and US, the AMD system was accomplished in wind vibration control of Nanjing TV tower.

Different classical and robust control algorithms have been proposed for reducing building responses. The most common ones are LQR, LQG, clipped control, bang–bang control, H_∞ control, sliding mode control, pole assignment, independent model space control, and so on. But, recently, the fuzzy controller has been used for optimization of the active control of civil engineering structures [4, 5]. The fuzzy set theory was introduced by Zadeh in 1965. In 1974 Mamdani successfully used the ‘IF-THEN’ rule on the automatic operating control of steam generator. It has revealed the feasibility of applying fuzzy theory on engineering control, and has since attracted discussions and researches. As an alternative to classical control theory, it allows the resolution of imprecise or uncertain information. Moreover, fuzzy control can be adaptive by modifying its rules or membership functions and employing learning techniques [6, 7].

Although many studies have been made on numerical simulation of fuzzy control of building vibrations[8], in a few investigations, experimental research on fuzzy control are conducted and the control objects are small scale models. Therefore, researchers are still faced with challenges when investigating the Fuzzy control system in reduction of the structural vibrations.

This paper researches the active fuzzy control of large scale structure model by using the AMD system for simulation and experimental tests. First, the fuzzy rules are extracted from the numeric data using a fuzzy neural network method; second, the two fuzzy controllers are designed, simulation analysis is conducted. Finally, to verify the validity of the fuzzy control algorithms over the AMD system, experimental research is performed on 1:8 scaled twelve-story structure with the AMD system under seismic excitation.

2. GENERATE FUZZY RULES FROM DATA PAIRS

Numeric data based fuzzy modeling is considered as an efficient approach to generate the fuzzy rules. There are two challenging problems in fuzzy modeling. The first one is to extract significant input variables among all possible input candidates; the second one is to determine the needed rules. The control object is based on twelve storey steel frame structure model, which is modeled as a shear frame. The structure is considered as a linear system. Without loss of generality, we use a two-input one-output model as a generic representation of fuzzy system. In design of the fuzzy control system, the building's top story displacement and velocity responses are considered as the feedback variables, and control force is selected as output variable. To deal with the second problem, a fuzzy neural network method is employed to generate the fuzzy rules. First, simulation of active control of a preliminary model based on the linear quadratic optimal algorithm is carried out. The sample data of the top floor relative displacement, the top floor relative velocity, and the control force are obtained. Then, the self-organizing Kohonen network is used to produce the sub-clusters. The purpose of this stage is to classify the given training data into a small number clusters using competitive learning.

When unsupervised learning is completed, a collection of p fuzzy clusters is produced for each input and output data. Then, a fuzzy neural network model is built (as shown in Fig. 2.1). It is a five-layer structure, the first layer is input layer; the second layer is a fuzzification layer of input variables; the third layer is antecedent; the forth layer is both consequent and fuzzification layer of output variables; the fifth layer is output layer, including input and defuzzification. Input/output data enter the network from two-direction to generate fuzzy rule. By using competitive learning algorithm to get the connection weight vectors between the third layer and the fourth layer, the model structure is obtained and the fuzzy rules are found.

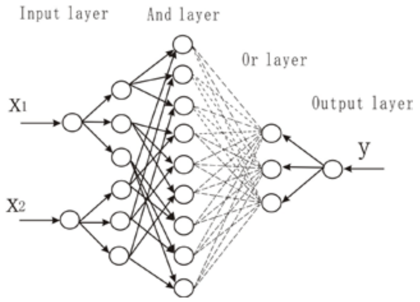
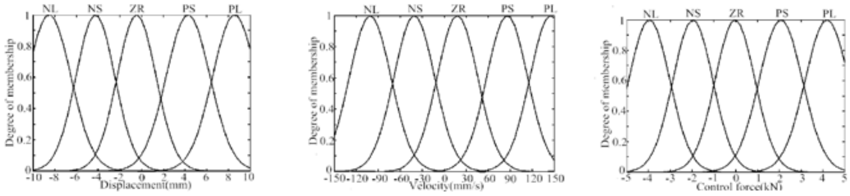


Figure 2.1 Fuzzy neural network model

In this paper, the controller was designed using five membership functions for each input variable and output signal. The rules of fuzzy control are summarized in Table 2.1. The input/output subsets are: NL=negative large values, NS=negative small values; ZR=zero value; PS=positive small values; and PL=positive large values. The membership functions chosen for the input and output variables are Gaussian shaped as illustrated in Fig.2.2. Figure 2.3 shows the output surface of fuzzy controller. Based on the simulation result of control and uncontrolled case of the model, the displacement domain is [-10mm, 10mm], the velocity domain is [-150mm/s, 150 mm/s] and the control force domain is [-5kN, 5kN].



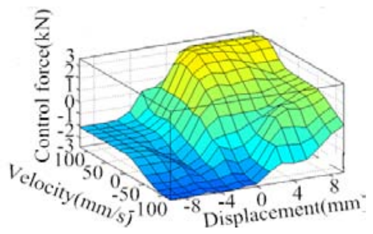


Figure 2.2 Membership functions of input variables and output variable

Figure 2.3 Output surface of fuzzy controller

Table 2.1 Fuzzy rules for the controller design

Velocity \ Displacement	NL	NS	ZR	PS	PL
NL	PL	PL	PL	NS	NS
NS	PS	PL	PL	NS	NS
ZR	PS	ZR	ZR	NL	NS
PS	PS	PS	NL	NL	NL
PL	ZR	NL	NL	NL	NL

3. NUMERICAL SIMULATION OF FUZZY CONTROL

Numerical simulation of fuzzy control is conducted through a 1:8 scaled twelve-story model structure with an active mass damper (AMD) system. The properties of the model structure are as shown in Table 3.1. The North-West (NW) component of the Taft earthquake and North-South (NS) component of the EL Centro earthquake with a peak ground acceleration of 0.11g are used for the input excitation, where the time axis has been scaled down by 1/2.5.

Table 3.1 Properties of model structure

Floor number	Height/m	Mass/kg	StiffnessN/m
1	0.45	790	3.24×10^{7}
2-11	0.45	790	4.2×10^{6}
12	0.45	600	2.4×10^{6}

Note: the 12th story mass includes mass of AMD.

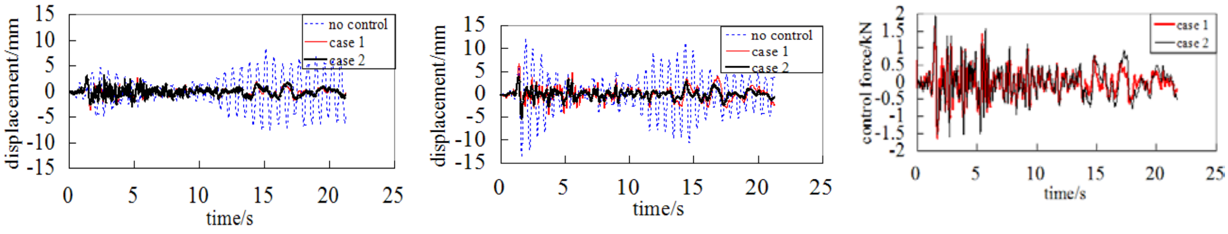
The controller is designed based on two input variables (displacement and velocity of the building’s top story). For high-rise buildings, control effect may be not so good for only two-input variables. However, questions remain as to the design and implementation of fuzzy logic controls for the multi-input one-output system. Instead of designing such a multi-input fuzzy logic control, we will propose a modified two-input one-output system by considering the effect of multi-input variables. First, we need to determine the variables of multi-input. In order to ensure the structural safety, which basically depends on the building displacement response, numerical simulation is conducted to choose different input variables based on getting the maximum reduction in displacement response of the building’s top story. When the displacement and velocity of middle floor are combined with the displacement and velocity of top story as the variables of multi-input, the control effect is much better than the other cases. Therefore, the following operating cases are defined: (1) uncontrolled case: the cart is locked on the top floor. (2) Case 1: two input fuzzy control, which include displacement and velocity of the structure’s top story. (3) Case 2: modified two input fuzzy control, considering the influence of multi-inputs, which include displacement and velocity of the structure’s top floor, as well as displacement and velocity of sixth floor.

The fuzzy rules are encoded in the fuzzy toolbox in MATLAB. The fuzzy controller is implemented into the SIMULINK code. Before the inputs enter the fuzzy logic controller, the velocity of 6th story is combined with the velocity of 12th story, the displacement of 6th story is combined with the displacement of 12th story. Therefore, the effect of multi-input is considered. Table 3.2 shows the results of the simulation under different operating cases in terms of each story peak displacement for the Taft earthquake. The simulated 6th-story displacement histories, 12th-story displacement histories and control force histories of the model under different operating cases for the Taft earthquake are shown in Fig.3.1.

Table 3.2 Comparison of the effectiveness of the different algorithm used in this study (for the Taft earthquake)

Cases	control force /kN	peak displacement/mm											
	U_{max}	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}
Uncontrolled	—	0.24	2.12	3.96	5.69	7.23	8.49	9.49	10.34	11.32	12.13	12.74	13.28
Case 1	1.63	0.11 (54%)	0.93 (56%)	1.75 (56%)	2.36 (59%)	3.19 (56%)	3.58 (58%)	4.25 (55%)	4.98 (52%)	5.35 (53%)	5.92 (52%)	6.29 (51%)	6.72 (50%)
Case 2	1.95	0.10 (58%)	0.85 (60%)	1.51 (62%)	1.93 (66%)	2.45 (66%)	3.09 (64%)	3.63 (62%)	4.05 (61%)	4.42 (61%)	4.83 (60%)	5.11 (60%)	5.47 (58%)

Note: The percent of the brackets indicates that the vibration control effect of each story displacement.



a) Displacement of 6th story b) Displacement of top story c) Control force

Figure 3.1 displacement histories and control force histories of model under Taft earthquake input

As can be seen from the table and figures, that the maximum structural displacement response is decreased from 13.28mm to 5.47 mm under Case 2 while the maximum response is reduced to 6.72mm under Case 1 for the Taft earthquake, the vibration control effect for maximum displacement of the sixth story of the 12-story structure model is about 58%, and 64% for the Case 1 and Case 2 algorithm, respectively, while the vibration control effect for maximum displacement of the sixth story of the 12-story structure model is about 50%, and 58% for the Case 1 and Case 2 algorithm, respectively. Therefore, it is seen that the designed Case2 system is more effective than Case1 system in view of reducing the displacement response of the example building. Furthermore, from Fig. 3.1, it can be seen that the active control force needed for obtaining the above reductions in Case 2 system is more than that of Case1 system; however, it is still in the controller action range. Obviously, it illustrates that the modified two-input fuzzy control algorithm is effective in mitigating the system's response in the case of increasing the limited sensors and control force.

4. SHAKING TABLE TEST

4.1. Test setup

The fuzzy control experimental tests of twelve story model structure were performed at the Mechanics and Structure Laboratory of Harbin Institute of Technology, China. Earthquake simulation shaking table size is 3m×4m, the maximum force of shaking table is 250kN, the maximum displacement is ±250mm, and frequency range is 0～25Hz，the maximum load bearing is 15 t. Actuator stroke for AMD system is ±150mm, maximum output force is 20kN, and the actuator is equipped with a displacement sensor and a load sensor. Instrumentation was used to measure displacements and accelerations at critical locations. Some acceleration was converted to the velocity through multi-function voltage filter.

The control system was designed based on MATLAB/Simulink for the shaking table test; discretization of continuous control system was carried out. Then, the input and output variables were defined using dSPACE, model codes were generated automatically. Using ControlDesk for data acquisition, data real-time got into the pre written algorithm, and control force was obtained through a series of operations. ControlDesk took this control force as the control to MTS. The MTS achieved the active controlling command and put the command to drive the actuator of the system, and then the actuator pushed the mass movement of the AMD system through which the structural vibration response was reduced.

4.2. Experimental Results

Fig. 4.1 shows the twelve story structure model and the AMD system. The mass of the structure is 9290kg, the height of the model structure is 5.4m, length is 2.25m, and width is 1.125 m, respectively. An active mass damper was installed on the top floor; the mass of cart is 175kg, which is about 2% of the building's total mass. The sensors were installed on the shake table and the floor of fourth, sixth, eighth, eleventh and twelfth story. The measured data from shake table, sixth and twelfth floor were taken as input signal for the controller; the other data were used for analysis.

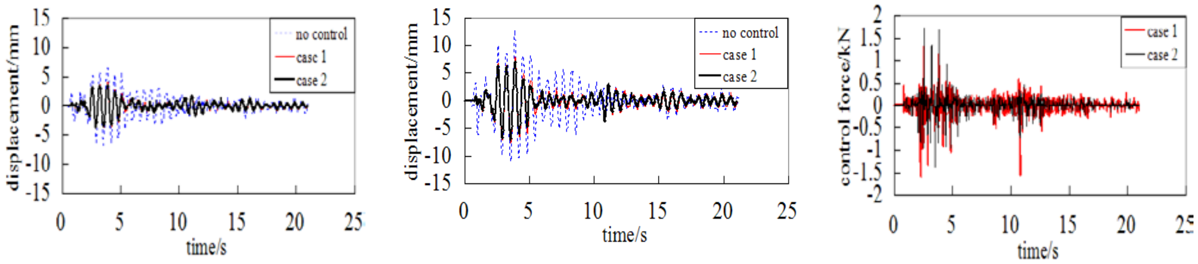
The North-West (NW) component of the Taft earthquake and North-South (NS) component of the EL Centro earthquake with a peak ground acceleration of 0.11g were used for the input excitation, where the time axis has been scaled down by 1/2.5. In the experiment, the model structure with the AMD system under uncontrolled case was studied. The first two frequencies of the structure model are 3.30Hz and 9.98Hz, respectively.

Figure 4.1 12-story model structure with AMD system

Table 4.1 shows the results of the experiment under different operating cases in terms of peak displacement of some stories for the EL Centro earthquake. Fig.4.2 shows the measured 6th-story displacement histories, 12th-story displacement histories and control force histories of the model under different operating cases for the EL Centro earthquake. The test results show that the fuzzy controllers are very effective in reducing the responses of model structure under seismic excitation and the reductions of about 40% in relative displacements can be achieved. Moreover, it is found that the modified two-input algorithm has better control effect than Case 1.

Table 4.1 Measured displacement values of model structure under EL Centro earthquake input

Cases	control force /kN	peak displacement/mm				
	U_{max}	x_4	x_6	x_8	x_{11}	x_{12}
Uncontrolled	—	3.39	6.58	8.52	11.19	12.27
Case 1	1.59	2.18 (36%)	3.95 (40%)	5.02 (41%)	6.77 (39%)	7.86 (36%)
Case 2	1.72	1.91 (44%)	3.57 (46%)	4.72 (45%)	6.08 (46%)	7.00 (43%)



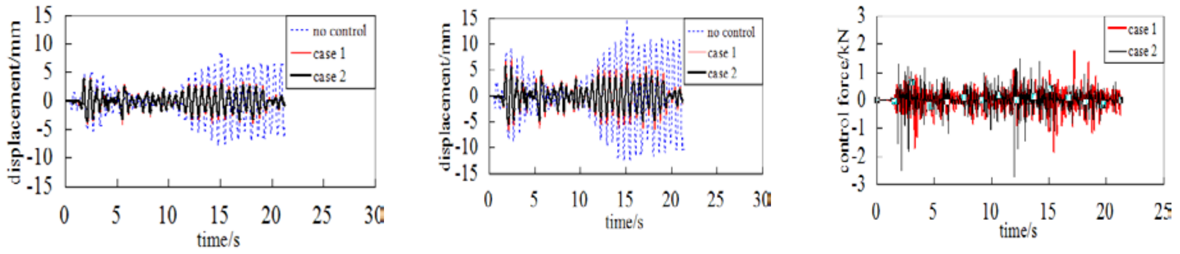
a) Displacement of 6th story b) Displacement of top story c) Control force

Figure 4.2 Measured time histories of displacement and control force under EL Centro earthquake input

For the Taft earthquake wave, Table 4.2 shows the measured results under different operating cases in terms of peak displacement of some stories. Fig.4.3 shows the measured 6th-story displacement histories, 12th-story displacement histories and control force histories of the model under different operating cases. The test results show that the fuzzy controllers are very effective in reducing the responses of model structure under seismic excitation and the reductions of more than 50% in relative displacements can be achieved. Moreover, the results also indicate that the performance of the modified two-input fuzzy controller is very remarkable, although the control force is more than that of ordinary two-input system.

Table 4.2 Measured displacement values of model structure under Taft earthquake input

Cases	control force /kN	peak displacement /mm				
	U_{max}	x_4	x_6	x_8	x_{11}	x_{12}
Uncontrolled	—	4.09	8.49	10.66	13.15	14.19
Case 1	1.84	1.97 (52%)	4.21 (50%)	5.15 (52%)	6.39 (51%)	6.92 (51%)
Case 2	2.71	1.72 (58%)	3.73 (56%)	4.52 (58%)	5.64 (57%)	5.66 (60%)



a) Displacement of 6th story b) Displacement of top story c) Control force

Figure 4.3 Measured time histories of displacement and control force under Taft earthquake input

5. CONCLUSIONS

The paper shows how the use of a fuzzy control approach can represent a possible way to control the response of a model structure controlled by an active mass driver. A 1:8 twelve-story model structure is used as an example and its controller is designed. Fuzzy rules are extracted using fuzzy neural network method from the numerical data. The properties of model for generating fuzzy rules can be preliminary. The simulation and experimental shaking table tests are conducted on the model structure using an active mass damper, and the results show that the proposed fuzzy algorithms are effective in suppressing the building response subject to earthquakes. In addition, it is found that the modified two-input algorithm has better control effect than that of ordinary two-input system. The results of the experimental tests also confirm the potential of using the adopted fuzzy controller for the real implementation because of its intrinsic robustness and the limited number of measured structural responses. This work shows that the adopted fuzzy controller has great potential in active structural control.

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