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ACTIVE CONTROL OF ASYMMETRIC STRUCTURES USING FUZZY CONTROLLED ATMD

F. Amini[1], R. Baghaei[2] and S. Forouzan[3]

ABSTRACT

In this paper, the performance of active tuned mass damper systems in reducing earthquake induced responses of structures is investigated. A tuned mass damper is a device consisting of a mass, a spring and a damper that is attached to a structure in order to reduce the dynamic responses of the structure. The frequency of the damper is tuned to a particular structural frequency so that when that frequency is exceeded, the damper will resonate out of phase with the structural motion. Energy is dissipated by the damper inertia force acting on the structure. The effectiveness of a tuned mass damper can be increased by attaching an actuator to the tuned mass. The effect of adding an actuator is to produce additional force that complements the force generated by the tuned mass and therefore increases the equivalent damping of the TMD.

In this paper, the attention is focused on control of earthquake induced responses of an eight-story asymmetric structure with the aid of a fuzzy controlled bidirectional active tuned mass damper system. Intelligence, high speed performance and stability are all main advantages of fuzzy controllers. Like other fuzzy systems, fuzzy rule bases are the most important parts of fuzzy controllers. In this research the performance of three fuzzy rule bases with different specifications is compared. Fuzzy rule bases are designed to generate the control signal such that rotational and transitional displacements of the structure are reduced simultaneously. The performance of fuzzy controllers also depends on the definition of fuzzy sets for each variable. The effect of change in type of membership functions used to define fuzzy sets is also investigated and finally trapezoidal membership functions are identified to have the best performance.

Introduction

A critical aspect of the design of buildings and other civil engineering structures is the reduction of motions, deflections and forces induced by environmental dynamic loadings such as winds and earthquakes. Recent technological advances can now allow engineers to design intelligent structures capable of counteracting such undesirable vibrations by incorporating active control systems in the design of modern structures. Passive, semi-active and active control schemes are becoming an integral part of the structural systems for the last two decades. Active tuned mass damper (ATMD) systems have been a popular area of research for some time and significant progress have been made in this area.

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[1] Dept. of Civil and Environmental Engineering, Iran University of Science and Technology, Narmak, Tehran, Iran
[2] SAZEH consulting engineers, 26 Javad Sarafraz St., Dr. Beheshti Ave, Tehran 15876, Iran.
[3] Dept. of Computer Engineering, Tehran University, Tehran, Iran

The main objective of this study is to apply different fuzzy controllers to an eight-storey structure. The main advantages of fuzzy controller are: (1) it is one of the few mathematical model free approaches to system identification and control which makes the system easier to design than developing an accurate model of structural system needed for control system design. This can be done by using human experience and expertise to implement the fuzzy controller, (2) it tolerates the uncertainties of the input data from wind or earthquake excitations and structural vibration sensors and as a consequence, the resulting fuzzy controller possesses an inherent robustness, (3) the fuzzy controller has the ability to handle the non-linear behavior of the structure caused by large displacements or material non-linearity and damage, (4) fuzzy controller can be adaptive by modifying its rules or membership functions and employing learning techniques. Fuzzy controller has been investigated for the active control of civil engineering structures and the current study builds on previous work in this area.

The building under consideration is an eight-storey structure with about 20% eccentricity in each storey. An ATMD system controlled by different fuzzy controllers with different specifications is used in order to achieve control goal. Two earthquake records (Elcentro and Kobe 1995) are used to excite the model.

Structural model

An eight-storey building is considered as the structural model in this study. The structure has a footprint of 15 m × 15 m and a total mass of 3×10^6 kg. The model is designed to have identical floor heights of 3.0 m. taking advantage of the fact that masses are effectively lumped at the floor levels, simplifies the analyses and hence the frame is represented by an eight lumped mass dynamic system. The distance between the center of mass and center of rigidity of each story is assumed to be 3.0 m in each direction. Three degrees of freedom are considered for each storey: two translational in orthogonal directions and one rotational about Z-axis of the structure. The natural frequencies of the structure in first translational and rotational modes of vibration are 0.586 Hz and 0.593 Hz respectively, and the corresponding damping ratios are assumed to be 3% of critical damping. An ATMD is installed on the top floor with an eccentricity with respect to center of mass of the floor in order to enable the controlling system to reduce rotational responses of the structure. The ATMD system is a hybrid combination of passive and active systems. It consists of a tuned mass damper (TMD) with a control force actuator, which means it can supply control passively as well as actively. The TMD system consists of an inertial mass of 1% of the total mass of the eight-storey model, a stiffness element which is determined by tuning the natural frequency of the TMD system to the frequency of the first translational mode of vibration of the structure. The damping element of the TMD system is determined by setting the damping ratio at 5% of critical value. The active control part (the controllable part) is a hydraulic actuator used to provide the required control force to counteract the forces induced by earthquake excitation.

The equations of motion of eight-storey model in state space are:

$$\dot{x} = Ax + Bu + EW$$
$$z = C_z x + D_z u + F_z W$$
$$y = C_y x + D_y u + F_y W + v$$

Where z is the controlled output vector of dimension 78 and includes the translational and rotational displacement, velocity and acceleration of floors 1-8 and translational responses of damper moving mass. The y vector is the measured output vector of dimension 52 and includes the displacements and accelerations defined in the vector z. the v vector is the measured noise, x is the state vector, u is the control force, and W is the earthquake excitation. A is the system matrix, B is a control location vector and C_y, D_y, F_y, C_z, D_z and F_z are matrices of appropriate dimensions.

Performance criteria

To evaluate the control system performance, the following indexes are considered. These indexes are mostly non-dimensional. The first three evaluation criteria for the controllers pertain to their ability to reduce maximum floor RMS translational and rotational acceleration:

$$J_1 = \max(\ddot{x}_1, \cdots, \ddot{x}_8) / \max(\ddot{x}_{1O}, \cdots, \ddot{x}_{8O})$$
$$J_2 = \max(\ddot{x}_1, \cdots, \ddot{y}_8) / \max(\ddot{y}_{1O}, \cdots, \ddot{y}_{8O})$$
$$J_3 = \max(\ddot{\theta}_1, \cdots, \ddot{\theta}_8) / \max(\ddot{\theta}_{1O}, \cdots, \ddot{\theta}_{8O})$$

Where $\ddot{x}_i, \ddot{y}_i, \ddot{\theta}_i$ and $\ddot{x}_{iO}, \ddot{y}_{iO}, \ddot{\theta}_{iO}$ are translational and rotational accelerations of the floors in controlled and not controlled cases respectively.
Next three performance indexes relate to ability of controllers to reduce maximum RMS base reaction during an earthquake:

$$J_4 = \max(R_{x_1}, \cdots, R_{x_8}) / \max(R_{x_{1O}}, \cdots, R_{x_{8O}})$$
$$J_5 = \max(R_{y_1}, \cdots, R_{y_8}) / \max(R_{y_{1O}}, \cdots, R_{y_{8O}})$$
$$J_6 = \max(R_{\theta_1}, \cdots, R_{\theta_8}) / \max(R_{\theta_{1O}}, \cdots, R_{\theta_{8O}})$$

Performance indexes J_7 through J_9 are defined to be the ratio between maximum interstorey drifts in controlled and not controlled cases:

$$J_7 = \max(D_{x_1}, \cdots, D_{x_8}) / \max(D_{x_{1O}}, \cdots, D_{x_{8O}})$$
$$J_8 = \max(D_{y_1}, \cdots, D_{y_8}) / \max(D_{y_{1O}}, \cdots, D_{y_{8O}})$$
$$J_9 = \max(D_{\theta_1}, \cdots, D_{\theta_8}) / \max(D_{\theta_{1O}}, \cdots, D_{\theta_{8O}})$$

Performance indexes J_{10}, J_{11} and J_{12} are ratios between maximum roof displacements in controlled and not controlled cases:

$$J_{10} = x_{P8} / x_{P8o}$$
$$J_{11} = y_{P8} / y_{P8o}$$
$$J_{12} = \theta_{P8} / \theta_{P8o}$$

The last performance index is the total impulse produced during an earthquake by controllers:

$$J_{13} = \int_{t=0}^{T} F_x dt + \int_{t=0}^{T} F_y dt$$

From performance criteria defined above, it is obvious that the better the performance and efficiency of the controller, the smaller the values of performance indexes J_1 through J_{13}.

Fuzzy logic controller

Fuzzy logic introduced by Zadeh, enables the use of linguistic directions as a basis for control. Generally very robust and capable of handling non-linear systems, fuzzy logic controllers (FLC) usually require expert knowledge in their construction. Fuzzy sets are defined in a universe of discourse. For a given universe of discourse U, a fuzzy set is determined by a membership function that maps members of U on to a membership range in the interval (0,1). There are two ways to define the membership for a fuzzy set: numerical or functional. A numerical definition expresses the degree of membership function of a fuzzy set as a vector of numbers whose dimension depends on the level of discretization in the universe of discourse. A functional definition denotes the membership function of a fuzzy set in a functional form such as triangular function, trapezoidal function or a Gaussian function. The basic structure of a typical FLC is illustrated in figure1.

Fuzzification: This is the process of mapping from observed inputs to fuzzy set in the various input universes of discourse. In process control, the observed data are usually crisp, and fuzzification is required to map the observed range of crisp inputs to corresponding fuzzy values for the system input variables. the mapped data are further converted into suitable linguistic terms as labels of fuzzy sets defined for system input variables.

Knowledge base: this is a collection of the expert control rules needed to achieve the control goal. A fuzzy rule base consists of a set of fuzzy IF-THEN rules. It is the heart of fuzzy system in the sense that all other components are used to implement these rules in a reasonable and efficient manner. Because the fuzzy rule base consists of a set of rules, the relationship among these rules (properties of set of rules) is very important. These properties are: (i) completeness which means that at any point in the input space there is at least one rule that fires, i.e. the membership value of the IF part of the rule at this point is non-zero, (ii) consistency: a set of fuzzy IF-THEN rules is consistent if there are no rules with the same IF parts but different THEN parts, (iii) continuity: a set of fuzzy IF-THEN rules is continuous if there do not exist such neighboring rules whose then parts of fuzzy sets have empty intersection.

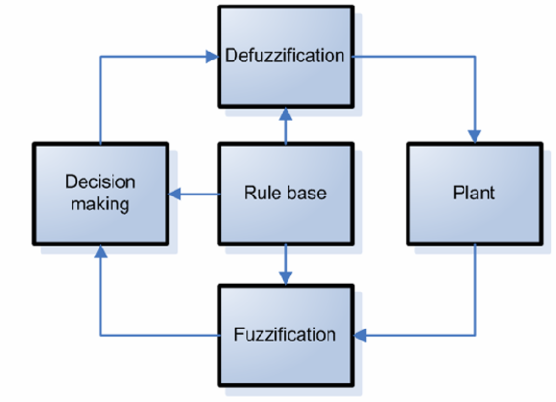


Figure 1.   Basic structure of a FLC.

Decision making: In a fuzzy inference engine, fuzzy logic principles are used to combine the fuzzy IF-THEN rules in the fuzzy rule base into a mapping form a fuzzy input set to an output set. There are various ways in which the observed input values can be used to identify which rules should be used and to infer an appropriate fuzzy control action. Among the various fuzzy inference methods, the most commonly used fuzzy inference methods in the FLC are:

- The point-valued MAX-MIN fuzzy inference method.
- The point-valued MAX-PRODUCT fuzzy inference method.
- The point-valued SUM-|PRODUCT fuzzy inference method.

Defuzzification: This is the process of mapping from a space of inferred fuzzy control actions to a space of non-fuzzy control actions. A defuzzification strategy is aimed at producing a non-fuzzy control action that best represents the probability distribution of the inferred fuzzy control action. In real-time implementation of FLC, the commonly used defuzzification strategies are the mean of maximum (MOM) and the center of area (COA).

In this paper, the combination of membership values is set to be done by MAX-MIN method and the COA method is used as the defuzzification scheme to obtain the output crisp value.

Fuzzy controller design

There are two principal approaches to fuzzy controller design. The heuristic approach exploits expert knowledge and analysis of the behavior of a controlled process to generate fuzzy control rules, while the deterministic approach determines the structure and parameters of control rules by means of fuzzy modeling so that the objective is satisfied. The heuristic approach to fuzzy controller design can be roughly summarized in following three steps:

- Analyze the real system and choose state and control variables
- Derive fuzzy IF-THEN rules that relate the state variables to control variables
- Combine these derived fuzzy IF-THEN rules into a fuzzy system and test the closed loop system with the fuzzy system as a controller

The design of the fuzzy controller uses crisp data directly from a number of sensors; these data are then converted into linguistic or fuzzy membership functions through the fuzzification process. The number of sensors used in the system is dependent on the number of input variables used in the controller.

In this study three types of fuzzy controllers are designed and implemented in order to generate the control signal such that earthquake induced responses of the structure be reduced. As mentioned before, the selection of input variables of the fuzzy controller is the first step in design of fuzzy controller. In design of first fuzzy controller translational and rotational displacements of the top storey of the structure are considered as input variables and five fuzzy sets are defined for each variable.

Following abbreviations are used in definition of fuzzy sets:

Table 1. Fuzzy variables.

PL	Positive Large
P	Positive
Z	Zero
N	Negative
NL	Negative Large

Fuzzy rule base of first fuzzy controller is shown in table 2. Completeness condition of the rule base is satisfied by generating 125 fuzzy rules to handle all probable conditions that may happen.

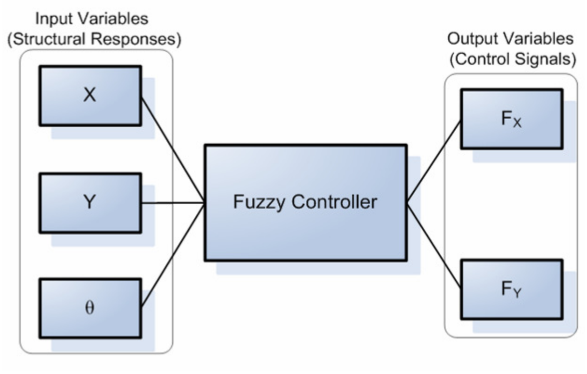


Figure 2. Basic structure of the first fuzzy controller.

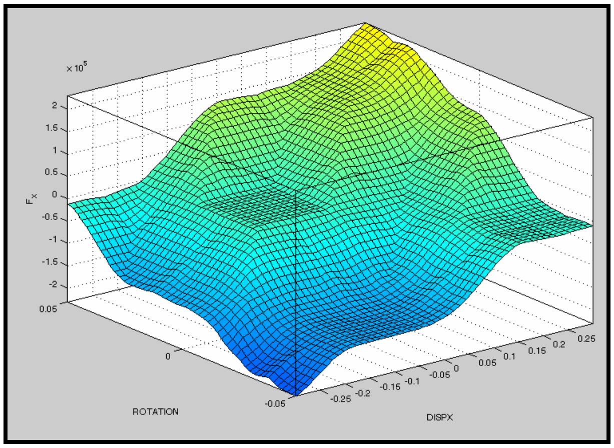


Figure 3. Control surface of the first fuzzy controller.

Table 2. Fuzzy rulebase of the first fuzzy controller.

θ	Δ_X	Δ_Y	F_X	F_Y
NL	NL	NL	NL	Z
NL	NL	N	NL	Z
NL	NL	Z	NL	Z
NL	NL	P	NL	P
NL	NL	PL	NL	PL
NL	N	NL	NL	Z
NL	N	N	NL	Z
NL	N	Z	N	P
NL	N	P	N	P
NL	N	PL	N	PL
NL	Z	NL	N	Z
NL	Z	N	N	Z
NL	Z	Z	N	P
NL	Z	P	N	PL
NL	Z	PL	Z	PL
NL	P	NL	N	Z
NL	P	N	N	Z
NL	P	Z	Z	P
NL	P	P	Z	PL
NL	P	PL	Z	PL
NL	PL	NL	Z	Z
NL	PL	N	Z	P
NL	PL	Z	Z	P
NL	PL	P	Z	PL
NL	PL	PL	Z	PL
N	NL	NL	NL	Z
N	NL	N	NL	Z
N	NL	Z	NL	Z
N	NL	P	NL	P
N	NL	PL	NL	PL
N	N	NL	N	Z
N	N	N	N	Z
N	N	Z	N	Z
N	N	P	N	PL
N	N	PL	N	PL
N	Z	NL	N	Z
N	Z	N	N	Z
N	Z	Z	N	Z
N	Z	P	Z	P
N	Z	PL	Z	PL
P	N	Z	Z	Z
P	N	P	Z	Z
N	P	NL	Z	N
N	P	N	Z	Z
N	P	Z	Z	P
N	P	P	Z	P
N	P	PL	Z	PL
N	PL	NL	Z	Z
N	PL	N	Z	Z
N	PL	Z	Z	P
N	PL	P	Z	P
N	PL	PL	Z	PL
Z	NL	NL	NL	NL
Z	NL	N	NL	N
Z	NL	Z	N	Z
Z	NL	P	N	Z
Z	NL	PL	Z	Z
Z	N	NL	N	N
Z	N	N	N	N
Z	N	Z	Z	Z
Z	N	P	Z	Z
Z	N	PL	Z	P
Z	Z	NL	Z	N
Z	Z	N	Z	N
Z	Z	Z	Z	Z
Z	Z	P	Z	P
Z	Z	PL	Z	P
Z	P	NL	Z	N
Z	P	N	Z	Z
Z	P	Z	Z	Z
Z	P	P	P	P
Z	P	PL	P	P
Z	PL	NL	PL	PL
Z	PL	N	P	Z
Z	PL	Z	P	Z
Z	PL	P	P	P
Z	PL	PL	PL	PL
P	NL	NL	Z	NL
P	NL	N	Z	NL
P	NL	Z	N	N
P	NL	P	Z	Z
P	NL	PL	Z	Z
P	N	NL	Z	NL
P	N	N	Z	N
P	N	PL	Z	Z
P	Z	NL	Z	NL
P	Z	N	Z	N
P	Z	Z	Z	N
P	Z	P	P	Z
P	Z	PL	P	Z
P	P	NL	P	N
P	P	N	P	N
P	P	Z	P	Z
P	P	P	P	Z
P	P	PL	P	Z
P	PL	NL	PL	NL
P	PL	N	PL	N
P	PL	Z	PL	Z
P	PL	P	PL	Z
P	PL	PL	PL	Z
PL	NL	NL	Z	NL
PL	NL	N	Z	N
PL	NL	Z	Z	N
PL	NL	P	Z	Z
PL	NL	PL	Z	Z
PL	N	NL	Z	NL
PL	N	N	Z	N
PL	N	Z	Z	N
PL	N	P	Z	Z
PL	N	PL	Z	Z
PL	Z	NL	Z	NL
PL	Z	N	P	N
PL	Z	Z	P	N
PL	Z	P	P	Z
PL	Z	PL	P	Z
PL	P	NL	P	NL
PL	P	N	P	N
PL	P	Z	P	Z
PL	P	P	P	Z
PL	P	PL	P	Z
PL	PL	NL	PL	NL
PL	PL	N	PL	N
PL	PL	Z	PL	Z
PL	PL	P	PL	Z
PL	PL	PL	PL	Z

In the second and third fuzzy controllers structural velocities in each direction are also assumed as input variables. An increase in the number of input variables causes the required number of fuzzy rules to satisfy the completeness condition of the fuzzy rule base to rise rapidly. Increased number of fuzzy rules raises the complexity of the fuzzy controller which may affect the speed of control system and reduce its effectiveness. In order to reduced the number of required rules for fuzzy controllers two sub-controllers are designed to generate the control forces which may be exerted to the mass damper in each direction separately. Each sub-controller uses rotational displacement and velocity and translational displacement and velocity in one of the major directions and produces the control force in the same direction.

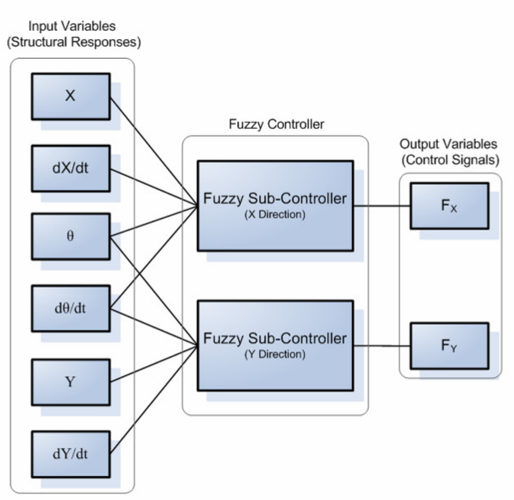


Figure 4. Basic structure of the second and third fuzzy controllers.

The difference between second and third fuzzy controllers is the number of fuzzy sets defined for each input variable. In the second fuzzy controller three fuzzy sets are specified for input variables: Negative, Zero and Positive. Definition of fuzzy sets in the range of input variables of third fuzzy controller and output variables of second and third fuzzy controllers is the same as the first controller.

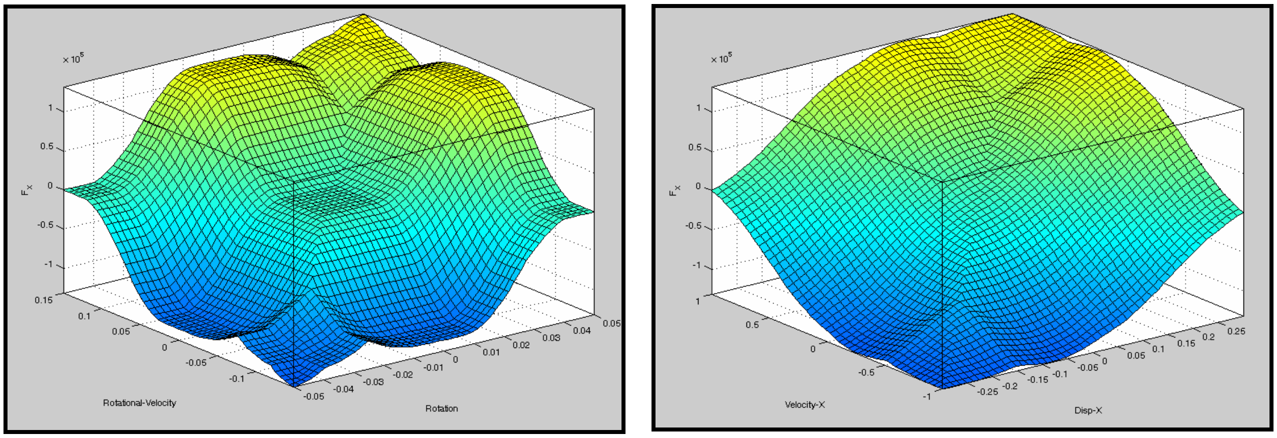


Figure 5. Control surfaces of the second fuzzy controllers (X-direction sub-controller).

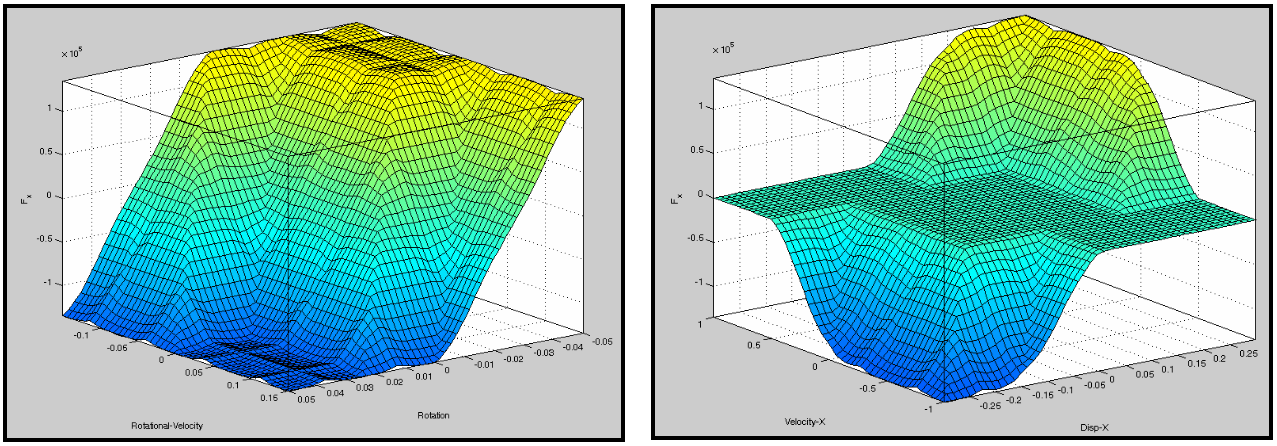


Figure 6. Control surfaces of the third fuzzy controllers (X-direction sub-controller).

In this study, functional definition is used to define fuzzy sets in the universe of discourse of each variable. In this type of definition of fuzzy sets, degree of membership of every member of universe of discourse to a fuzzy set is assigned by membership function of the set. As mentioned before, different functions may be used as membership function. In this paper the effect of change in the type of function used as the membership function is also investigated. Three of most commonly used membership functions are used to define fuzzy sets in the range of input and output variables. Performance of fuzzy controllers with Gaussian, Trapezoidal and Triangular membership functions is evaluated.

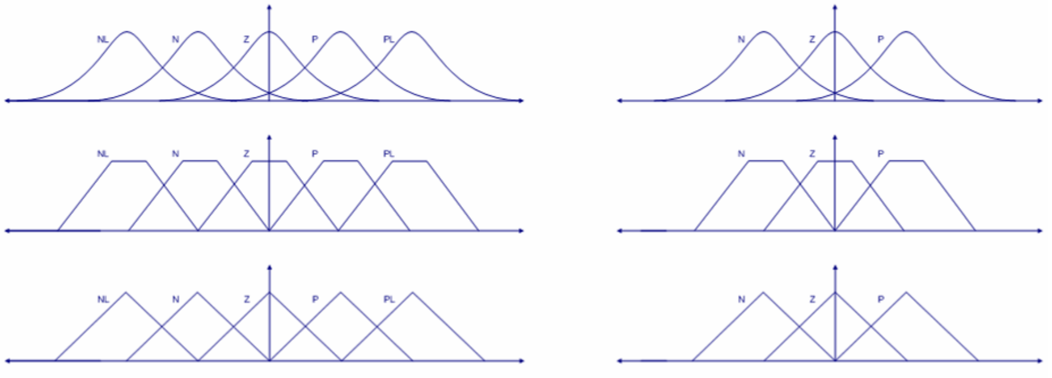


Figure 7. Membership functions of fuzzy sets.

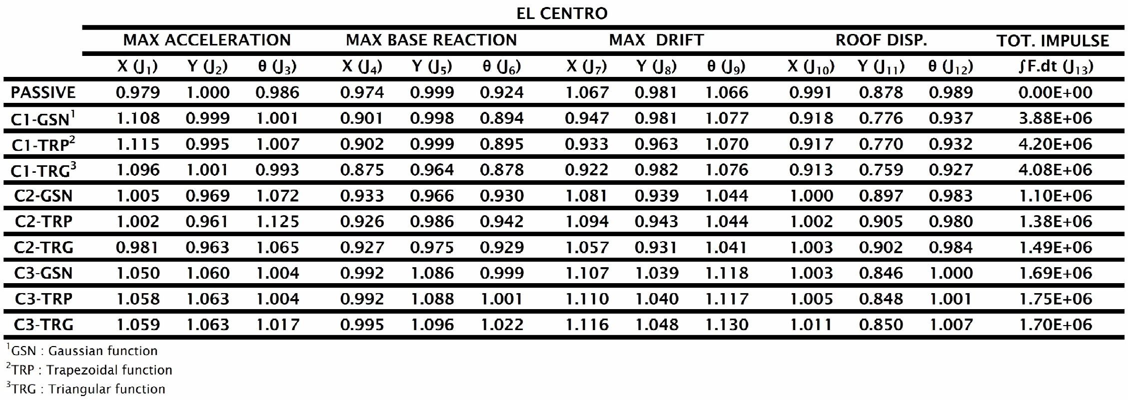
Control Performance

The international association for structural control (IASC) was formed early 90s with the aim of encouraging and facilitating international research collaborations and benchmark studies. The IASC has identified four earthquake records to be used to check the performance of any control system for seismic applications. These earthquake records are two far-field (El Centro 1940 and Hachinohe 1968) and two near-field (Northridge 1994 and kobe 1995). The absolute peak accelerations of these earthquake records 0.3417, 0.2250, 0.8267 and 0.8178 g, respectively. As mentioned before, records of El Centro 1940 and Kobe 1995 are scaled in intensity and used as the ground motion accelerations.

The simulation analysis of the eight-storey structure without control, with TMD system and with ATMD system using fuzzy controllers are implemented into the SIMULINK program. Fuzzy controllers are implemented into SIMULINK program using an integration time step of 0.001 s and the control signal is computed every 0.01 s. The maximum control force is limited to 300kN.

The simulation analysis of the eight-storey model with and without TMD system is conducted using the two earthquake records. Table 3 shows the simulation results of the TMD and ATMD controlled model.

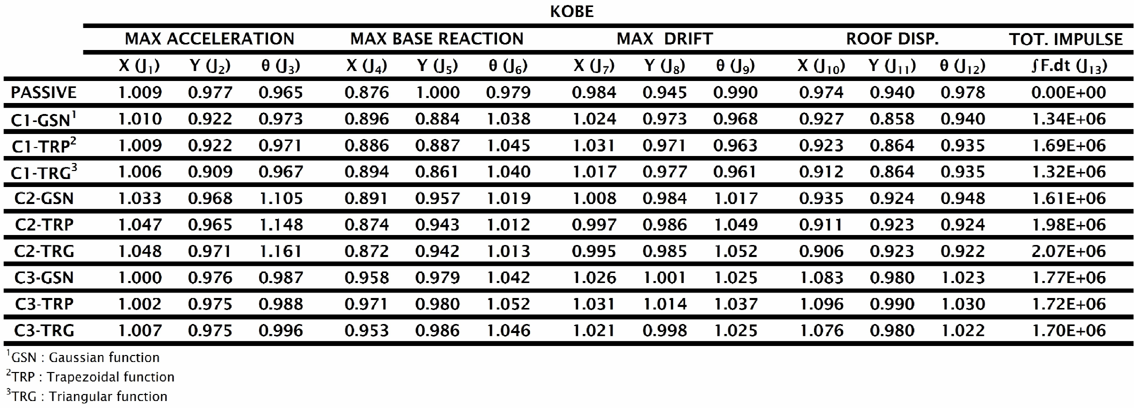
Table 3. Evaluation criteria comparison for the eight-storey model in different control strategies under two earthquakes.



EL CENTRO

	MAX ACCELERATION			MAX BASE REACTION			MAX DRIFT			ROOF DISP.			TOT. IMPULSE
	X (J_1)	Y (J_2)	θ (J_3)	X (J_4)	Y (J_5)	θ (J_6)	X (J_7)	Y (J_8)	θ (J_9)	X (J_{10})	Y (J_{11})	θ (J_{12})	∫F.dt (J_{13})
PASSIVE	0.979	1.000	0.986	0.974	0.999	0.924	1.067	0.981	1.066	0.991	0.878	0.989	0.00E+00
C1-GSN[1]	1.108	0.999	1.001	0.901	0.998	0.894	0.947	0.981	1.077	0.918	0.776	0.937	3.88E+06
C1-TRP[2]	1.115	0.995	1.007	0.902	0.999	0.895	0.933	0.963	1.070	0.917	0.770	0.932	4.20E+06
C1-TRG[3]	1.096	1.001	0.993	0.875	0.964	0.878	0.922	0.982	1.076	0.913	0.759	0.927	4.08E+06
C2-GSN	1.005	0.969	1.072	0.933	0.966	0.930	1.081	0.939	1.044	1.000	0.897	0.983	1.10E+06
C2-TRP	1.002	0.961	1.125	0.926	0.986	0.942	1.094	0.943	1.044	1.002	0.905	0.980	1.38E+06
C2-TRG	0.981	0.963	1.065	0.927	0.975	0.929	1.057	0.931	1.041	1.003	0.902	0.984	1.49E+06
C3-GSN	1.050	1.060	1.004	0.992	1.086	0.999	1.107	1.039	1.118	1.003	0.846	1.000	1.69E+06
C3-TRP	1.058	1.063	1.004	0.992	1.088	1.001	1.110	1.040	1.117	1.005	0.848	1.001	1.75E+06
C3-TRG	1.059	1.063	1.017	0.995	1.096	1.022	1.116	1.048	1.130	1.011	0.850	1.007	1.70E+06

[1] GSN : Gaussian function
[2] TRP : Trapezoidal function
[3] TRG : Triangular function



KOBE

	MAX ACCELERATION			MAX BASE REACTION			MAX DRIFT			ROOF DISP.			TOT. IMPULSE
	X (J_1)	Y (J_2)	θ (J_3)	X (J_4)	Y (J_5)	θ (J_6)	X (J_7)	Y (J_8)	θ (J_9)	X (J_{10})	Y (J_{11})	θ (J_{12})	∫F.dt (J_{13})
PASSIVE	1.009	0.977	0.965	0.876	1.000	0.979	0.984	0.945	0.990	0.974	0.940	0.978	0.00E+00
C1-GSN[1]	1.010	0.922	0.973	0.896	0.884	1.038	1.024	0.973	0.968	0.927	0.858	0.940	1.34E+06
C1-TRP[2]	1.009	0.922	0.971	0.886	0.887	1.045	1.031	0.971	0.963	0.923	0.864	0.935	1.69E+06
C1-TRG[3]	1.006	0.909	0.967	0.894	0.861	1.040	1.017	0.977	0.961	0.912	0.864	0.935	1.32E+06
C2-GSN	1.033	0.968	1.105	0.891	0.957	1.019	1.008	0.984	1.017	0.935	0.924	0.948	1.61E+06
C2-TRP	1.047	0.965	1.148	0.874	0.943	1.012	0.997	0.986	1.049	0.911	0.923	0.924	1.98E+06
C2-TRG	1.048	0.971	1.161	0.872	0.942	1.013	0.995	0.985	1.052	0.906	0.923	0.922	2.07E+06
C3-GSN	1.000	0.976	0.987	0.958	0.979	1.042	1.026	1.001	1.025	1.083	0.980	1.023	1.77E+06
C3-TRP	1.002	0.975	0.988	0.971	0.980	1.052	1.031	1.014	1.037	1.096	0.990	1.030	1.72E+06
C3-TRG	1.007	0.975	0.996	0.953	0.986	1.046	1.021	0.998	1.025	1.076	0.980	1.022	1.70E+06

[1] GSN : Gaussian function
[2] TRP : Trapezoidal function
[3] TRG : Triangular function

Average value of performance indexes resulted from applying different membership functions (Gaussian, Trapezoidal and Triangular) are used to compare the performance of each fuzzy controller in reducing responses of the structure affected by far-field and near field earthquakes. Fig 8 shows the average of performance indexes of each fuzzy controller for far-field and near field earthquakes.

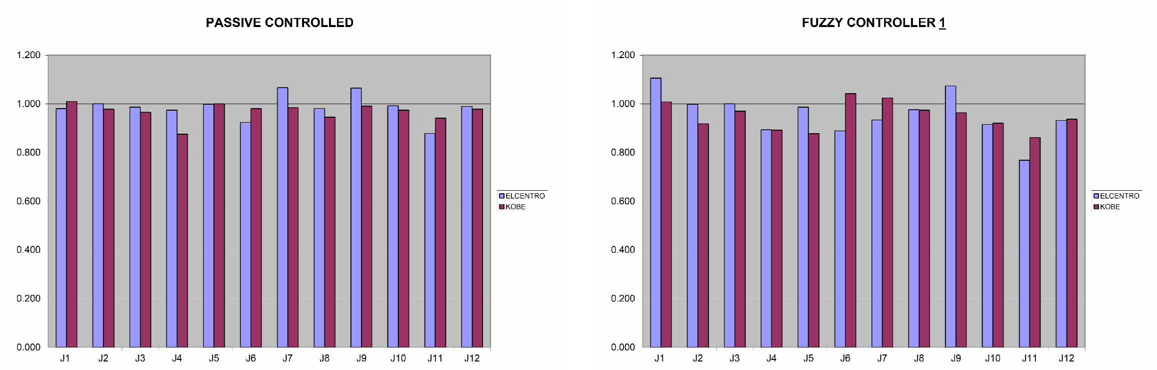


Figure 8. Average of performance indexes in each control strategy.

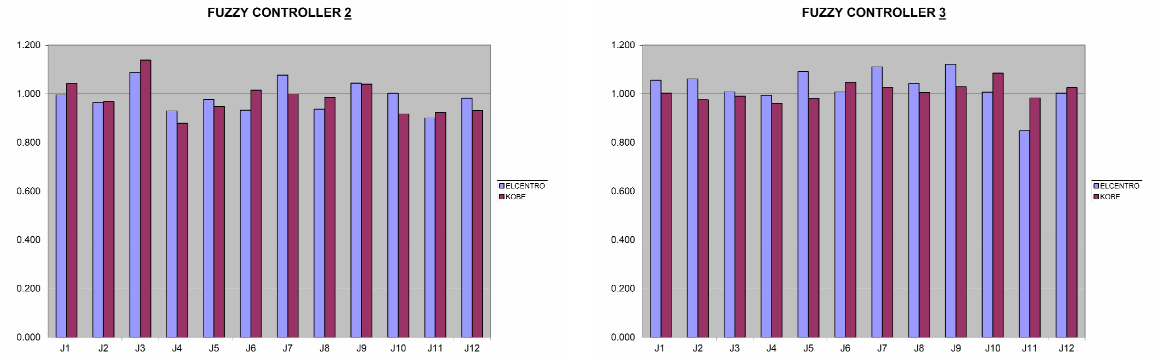


Figure 8. (continued) Average of performance indexes in each control strategy.

Conclusions

Results of analyses show that the overall performance of ATMD controlled buildings with various fuzzy controllers is better than the performance of passively controlled and uncontrolled buildings in both near and far field earthquakes. From comparison between criteria indexes of different ATMD controlled buildings, it may be concluded that the first fuzzy controller with 125 rules has the best performance of all. It seems that increase in the number of fuzzy rules without changing the maximum intensity of actuator force causes second and third controllers to generate control signals with lower level of control force and consequently lower control performance. The main outcome of this comparison is that increase in the number of fuzzy rules although increases the precision of the controller, will not necessarily improve the overall performance of the fuzzy controller and the designer should deal with such trade off problems carefully.

Another result of the comparison between performances of ATMD controlled buildings is that fuzzy controllers with trapezoidal membership functions have generally lowest criteria indexes and therefore best control performance among others.

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