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VIBRATION CONTROL OF BUILDINGS USING ATMD AGAINST EARTHQUAKE EXCITATIONS THROUGH INTERVAL TYPE-2 FUZZY LOGIC CONTROLLER

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ABSTRACT

This study focuses on the application of interval type-2 FLC (IT2FLC) in active tuned mass damper (ATMD) for the control of a building modeled as a single degree of freedom (SDOF) system. Since taking the first mode of a structure gives a good approximation of the building response, a SDOF system which demonstrates the characteristics of the first structural mode is used. One of the main shortcomings of the type-1 fuzzy systems is their inability to consider uncertainty in fuzzy rules. IT2FLS has the ability to handle this problem. It also takes into account uncertainty in loading and structural behavior. To evaluate the efficiency of the proposed control method, an 11-storey realistic shear building is used. The IT2FLC is designed for the first mode characteristics of the mentioned structure for getting the maximum response reduction under different types of earthquake excitations. The results obtained by proposed control scheme were compared with those of uncontrolled structure, structure with TMD and structure with ATMD through type-1 FLC. Numerical results indicate that IT2FLC is very effective in reducing the structural responses compared with that of the type-1 FLC. It is also found that designing the proposed controller for the first structural mode can significantly reduce the structural response of realistic building.

Keywords: Active tuned mass damper; IT2FLC, type-1 FLC; SDOF system, earthquake excitation; response reduction.

1. INTRODUCTION

The response reduction of structures to dynamic loadings like earthquake and wind loads has been a subject of study for many decades. Therefor there is a need to use structural control

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method for decreasing response and damage in structures. Structural control methods are divided into several categories including passive, active, semi-active and hybrid control systems [1].

Passive systems have been extensively used because of easy application, high reliability and low cost. However, passive systems have some deficiencies like limited control capacity. Tuned mass damper (TMD) is one of the oldest passive control devises which was first used by Frahm [2]. Following him, many studies were done for determining optimum parameters of TMD for decreasing the structural response [3-13]. Active control systems were proposed due to limitations of passive systems. In these systems, control force is generated by external energy source and is applied to the structure through actuator according to a specified control algorithm.

One of the advantages of active control systems is their strong capacity for mitigating the structural response. If the flexibility and height of the structure increase, the significance of the active control systems has increased. However, active control systems have some limitations like high costs of equipment and dependency on a continuous power supply. Concept of active structural control was firstly introduced by Yao [14]. Among the active control devices which are reported in the literatures [15], active tuned mass damper (ATMD) has been a popular area of research in the last three decades [16-32]. Performance of an ATMD depends on the mass damper and controller characteristics. Active control force in an ATMD can be generated by different control algorithms. Some of these algorithms are based on mathematical calculations like optimal control [16], pole assignment [17], H_2 and H [20], bang-bang [27] and genetic algorithm [32] methods. However, in the last few years, application of smart control algorithms like fuzzy has been increased. Because of its ability to handle uncertainties and nonlinearities, independency on mathematical model and its inherent robustness, structural control with ATMD through FLC has attracted the extensive attention of researchers during the recent years [18-19, 21-26, 28-31]. One of the first applications of FLC in an ATMD was performed by Battaini et al [18]. They used a 3-storey benchmark building with an ATMD on the top floor. This structure was analyzed for different earthquake records. They [19] also used a 76-storey benchmark building and the structure was subjected to wind loads. They showed how FLSs can be exploited in structural control. Aldawod et al [21-25] use two benchmark problems of 5 and 76 stories with an ATMD on the roof level. These structures were analyzed under different types of loadings including earthquake and wind loads. They showed that FLC is very effective in reducing the structural response in comparison with those of obtained by LQR and LQG methods. Ahlawat et al [26] used GA for optimization of mass damper and FLC parameters of ATMD which is placed on the top floor of the 76-storey benchmark building. Another application of GA for optimizing ATMD characteristics was provided by Pourzeynali et al [28]. They used an 11-storey realistic shear building and the structure is analyzed under different types of earthquakes including both far-field and near-field ground accelerations. They indicated that FLC with optimized parameters has a better performance in comparison with optimal control in reducing structural response. Wang et al [29] used fuzzy sliding mode controller in an ATMD. The results showed the efficiency of proposed controller in reducing the structural response. Guclu et al [30] applied FLC for a 15-storey shear building using an ATMD and Results indicated the high effectiveness of FLC to PD controller when subjected to the Kocaeli earthquake ground motion.

All the applied fuzzy logic systems in the previous studies are denoted as type-1 fuzzy logic systems. It is obvious that the available information which is used for creating fuzzy rules has uncertainty. This uncertainty is not considered in type-1 fuzzy logic systems. To deal with this problem, type-2 fuzzy logic systems were first proposed by Zadeh in 1975 [33]. These systems are developed forms of type-1 fuzzy sets and have the ability of considering uncertainty in the available information needed for constructing fuzzy rules. Basic concepts related to type-2 fuzzy sets were gradually improved by Mendel et al [34-39]. Liang and Mendel [37] offered an impressive method for calculation of input and antecedent operations for interval type-2 fuzzy logic systems (IT2FLSs) using the meaning of upper and lower membership functions. Karnik and Mendel [35] expanded the centroid of an interval type-2 fuzzy logic set. Mendel [40] also described important advancements for type-2 fuzzy sets and systems.

Although type-2 Fuzzy logic systems have been successfully applied in many engineering problems [41-45], its application in active structural control using ATMD is considered as a new concept.

This study presents the application of IT2FLSs for generating active control force between structure and ATMD through an actuator. To examine the effectiveness of the proposed control method, an 11-storey realistic shear building with an ATMD on the top floor is considered. Firstly, IT2FLC is designed for a SDOF system for getting the maximum response reduction under different types of earthquake records including both far-field and near-field ground accelerations. The mass, stiffness and damping constants of the proposed system are chosen as the first mode characteristics of the realistic 11-storey building [28]. Then, the designed IT2FLC for the SDOF system is used as the ATMD controller of the 11-storey building. The obtained results by the proposed control method were compared with those of uncontrolled structure, structure with TMD and structure with ATMD through type-1 fuzzy logic controller. The results show that IT2FLS is an effective control method among the other control algorithms for reducing the structural response and also the response of SDOF system driven by the designed IT2FLC has a good agreement with the response of realistic building when the same controller is used.

2. STRUCTURAL MODEL

A SDOF system with an ATMD on the roof level can be considered as two degree of freedom system (Figure 1) and the equation of motion for the proposed system under seismic excitation can be written as follow:

$$M.\ddot{U}(t) + C.\dot{U}(t) + K.U(t) = -M.E.a_g + E_f.F \tag{1}$$

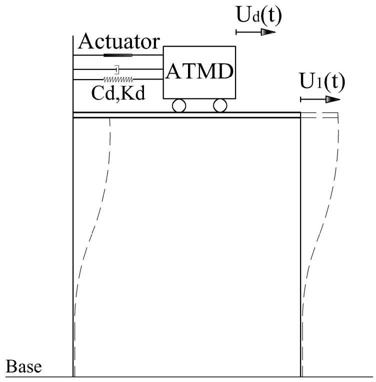


Figure 1. SDOF system with ATMD

Where, M, K and C, are the mass, stiffness and damping matrices of the SDOF structure with an ATMD, respectively. U(t) is the horizontal displacement vector with respect to the ground. E is the influence vector which represents column of ones. E_f is a vector indicates the location of control force. M, K and C matrices and U(t), E and Ef vectors are given by the following equations:

$$U(t) = \{u_1(t), u_d(t)\}^T \tag{2}$$

$$M = \mathrm{diag}[m_1, m_d] \tag{3}$$

$$K = \begin{bmatrix} k_1 + k_d & -k_d \\ -k_d & k_d \end{bmatrix} \tag{4}$$

$$C = \begin{bmatrix} c_1 + c_d & -c_d \\ -c_d & c_d \end{bmatrix} \tag{5}$$

$$E = \{1,1\}^T \tag{6}$$

$$E_f = \{0, -1, +1\}^T \tag{7}$$

Equation 1 can be written in the standard state-space form as follow:

$$\dot{X} = A.X + B_f.F + B_g.a_g \tag{8}$$

Where X is a vector of size 2*2. A, B_f and Bg are defined by the following equations:

$$X = \begin{Bmatrix} \{u\}_{2*1} \\ \{\dot{u}\}_{2*1} \end{Bmatrix} \tag{9}$$

$$A = \begin{bmatrix} [0]_{2*2} & [I]_{2*2} \\ [-M^{-1}.K]_{2*2} & [-M^{-1}.C]_{2*2} \end{bmatrix} \tag{10}$$

$$B_f = \begin{Bmatrix} \{0\}_{2*1} \\ \{M^{-1}.E_f\}_{2*1} \end{Bmatrix} \tag{11}$$

$$B_g = \begin{Bmatrix} \{0\}_{2*1} \\ \{-E\}_{2*1} \end{Bmatrix} \tag{12}$$

In which, [0] and [I] are zero and identity square matrices of size 2, respectively. The responses of different degree of freedom system can be determined by solving equation 8.

3. INTERVAL TYPE-2 FUZZY LOGIC SYSTEMS

A type-2 fuzzy set in a universal set of X is defined as $\tilde{A}$ and can be determined by:

$$\tilde{A} = \int_{x\in X} \left(\mu_{\tilde{A}}(x)/x\right) \tag{13}$$

$\mu_{\tilde{A}}(x)$, indicates the secondary membership function and is defined by:

$$\mu_{\tilde{A}}(x) = \int_{u\in J_x} \left(f_x(u)/u\right),\ J_x \in [0,1] \tag{14}$$

Where $f_x(u)$, J_x and u, are secondary grade, domain of secondary membership function and a fuzzy set in [0,1], respectively. When $f_x(u)=1$ for $\forall\ u \in J_x$, then secondary membership functions are as interval sets and the obtained fuzzy set can be called an interval type-2 fuzzy set (IT2FS). It can be shown as below:

$$\tilde{A} = \int_{x\in X} \left(\mu_{\tilde{A}}(x)/x\right) = \int_{x\in X} \left(\left(\int_{u\in J_x} (1/U)\right)/x\right),\ J_x \in [0,1] \tag{15}$$

Equation 15 implies that IT2FS illustrates a uniform uncertainty in the primary membership. An IT2FS is defined based on its upper and lower membership functions. In an interval type-2 fuzzy logic system (IT2FLS), footprint of uncertainty (FOU) is defined based on the upper and lower membership functions as:

$$\mathrm{FOU}(\tilde{\mathrm{A}}) = \bigcup_{\mathrm{x}\in \mathrm{X}} \left(\overline{\mu}_{\tilde{\mathrm{A}}}(\mathrm{x}), \underline{\mu}_{\tilde{\mathrm{A}}}(\mathrm{x})\right) \tag{16}$$

Figure 2 shows an interval type-2 fuzzy membership function with footprint of uncertainty (FOU), upper and lower bounds, and its standard deviation. The general structure of an IT2FLC is illustrated in Figure 3 in which the components are denoted as follows:

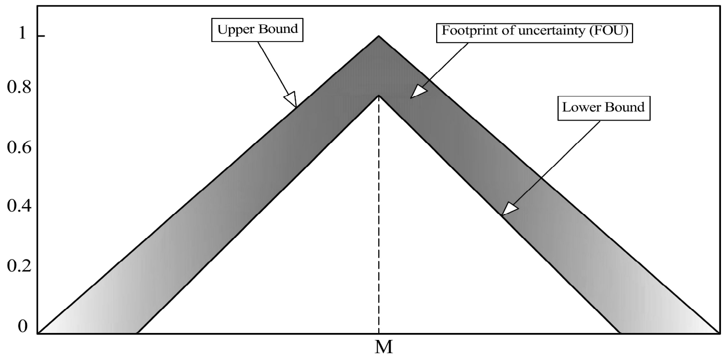


Figure 2. Interval type-2 fuzzy MF

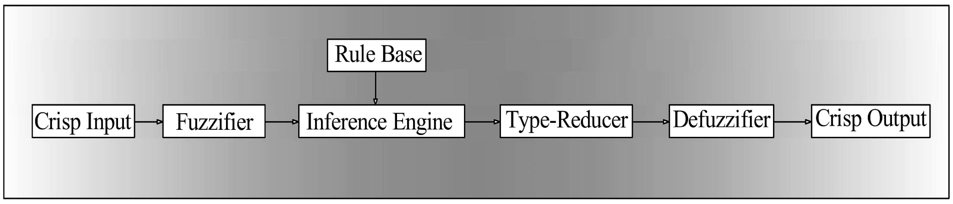


Figure 3. IT2FLS structure

3.1 Fuzzifier

Fuzzifier maps the measured inputs into fuzzy linguistic values with the help of fuzzy reasoning mechanism. In the present study, singleton fuzzifier was used which its output is a single point of a unity membership grade.

3.2 Rule base

In this part which is a set of IF-THEN rules, the knowledge of experts will be placed. J^{th} rule in IT2FLS can be written as:

$$Rj : If\ x_1\ is\ \tilde{F}_1^{\,j}\ and\ x_2\ is\ \tilde{F}_2^{\,j}\ and\ ...x_n\ is\ \tilde{F}_n^{\,j}\ then\ y\ is\ \tilde{G}^{\,j} \tag{17}$$

Where x_i(i=1,2,…,n) and y are IT2FLS input and output, respectively and also show the type-1 or type-2 antecedent and consequent sets, respectively.

3.3 Inference engine

In IT2FLS, the inference engine combines rules and represents a mapping from input to output IT2FLS. Using input and antecedent operations, the firing set is obtained as:

$$F^{\,j}(X) = \prod_{i=1}^{n} \mu_{\tilde{F}i^{\,j}}(x_j) \tag{18}$$

Where, t-norm is assumed to be product. Since the present study discusses IT2FLS, the firing input sets are defined based on the upper and lower membership functions as:

$$F^{j}(X)=\left(\underline{f}^{j}(X),\overline{f}^{j}(X)\right) \tag{19}$$

Where * shows the t-norm and $\underline{f}^{j}(X)$ and $\overline{f}^{j}(X)$ are the j[th] upper and lower membership functions, respectively and can be determined by:

$$\underline{f}^{j}(X)=\underline{\mu}_{\tilde{F}1^{j}}*\underline{\mu}_{\tilde{F}2^{j}}*\ldots*\underline{\mu}_{\tilde{F}n^{j}} \tag{20}$$

$$\overline{f}^{j}(X)=\overline{\mu}_{\tilde{F}1^{j}}*\overline{\mu}_{\tilde{F}2^{j}}*\ldots*\overline{\mu}_{\tilde{F}n^{j}} \tag{21}$$

3.4. Type reducer and defuzzifier

Since the output of the inference engine is an IT2FS, a type reducer is needed before defuzzification to convert IT2FS into type-1 fuzzy set. Type reducer was first proposed by Karnik & Mendel [36,39]. In [39], five different methods of type reduction have been suggested. Among these methods, center of sets (COS) has been extensively used due to easy calculation with the help of Karnik & Mendel's iterative algorithm [36]. The COS type reducer is an interval set which is determined by left-end point (y_l) and right-end point (y_r) and can be written as:

$$\mathrm{Y}_{\mathrm{COS}}[\mathrm{y}_{l},\mathrm{y}_{r}]=\int_{\theta^{1}}\ldots\int_{\theta^{M}}\int_{f^{1}}\ldots\int_{f^{M}}\left(1/\left(\left(\sum_{j=1}^{M}\mathrm{f}^{j}.\theta^{j}\right)/\left(\sum_{j=1}^{M}f^{j}\right)\right)\right) \tag{22}$$

Where $f_{j}\in F_{j}=\left(\underline{f}_{j}(X),\overline{f}^{j}(X)\right)$ and θ^{j} is the centroid of j[th] consequent set. In general, there is no closed-form formula for calculating y_l and y_r. However, Karnik and Mendel [34] have proposed two algorithms for calculating end-points which are known as KM iterative algorithms. In case of using singleton fuzzifier, product inference engine and COS type reducer, y_l and yr can be written as:

$$y_{l}=\left(\left(\sum_{j=1}^{M}f_{l}^{\,j}.\theta_{l}^{\,j}\right)/\left(\sum_{j=1}^{M}f_{l}^{\,j}\right)\right) \tag{23}$$

$$y_{r}=\left(\left(\sum_{j=1}^{M}f_{r}^{\,j}.\theta_{r}^{\,j}\right)/\left(\sum_{j=1}^{M}f_{r}^{\,j}\right)\right) \tag{24}$$

Where $\theta_{l}^{\,j}$ and $\theta_{r}^{\,j}$ are related to left-end point and right-end point of j[th] consequent set, respectively. Finally, the obtained set from type reducer can be defuzzified by using the average of y_r and y_l [37], as below:

$$y=\left[(y_{l}+y_{r})/2\right] \tag{25}$$

4. INTERVAL TYPE-2 FUZZY LOGIC CONTROLLER DESIGN

Fuzzy logic controller is designed based on the crisp data directly received through the structure. This data is mapped on to fuzzy sets through the fuzzification process. In the present study, IT2FLC has been designed using two input variables each one having three upper and three lower membership functions (MFs), and one output variable with seven upper and seven lower MFs. The upper and lower MFs chosen for the input and output variables are triangular shaped and have been defined on the common interval [-1,1]. These MFs are shown in Figures 4 and 5, respectively. The fuzzy variables used to describe the fuzzy space are defined in table 1. According to figures 4 and 5, H_i and Li (i=z,n,p) = lower MF parameters of input variables; H_m and m = lower MF parameters of output variables.

Table 1: Fuzzy variables

Membership function	Variable	Definition
Input	P	Positive
	Z	Zero
	N	Negative
Output	PB	Positive Big
	PM	Positive Medium
	PS	Positive Small
	Z	Zero
	NS	Negative Small
	NM	Negative Medium
	NB	Negative Big

In this study, displacement and velocity of the roof level of the SDOF system are chosen as input variables of controller for the IT2FLC design. In real applications, some sensors must be installed on the floors to measure the acceleration responses of building and an integrator is used to convert the acceleration measurements to the displacement and velocity responses. The main purpose of using two input variables for the IT2FLC is to show the efficiency of the fuzzy approach in the control problem. These input variables help in generating the inference rule base. If displacement is zero and velocity is not zero, control action with small intensity should be applied to maintain the structure close to its neutral position. If displacement and velocity are of the same sign, the structure is moving toward its extreme position and a control force with high intensity should be applied. If velocity is zero and displacement is not zero, or displacement and velocity are of the opposite sign, the structure is returning to its neutral position and a relatively small control force is applied. In this study, the inference rules have been developed by expert’s knowledge and are shown in Table 2. Specifications of the IT2FLC used in this study have been given in Table 3.

Table 2: Inference rules for the IT2FLC

	Velocity		
Displacement	N	Z	P
N	PB	PM	PS
Z	PS	Z	NS
P	NS	NM	NB

Table 3: Specifications of IT2FLC

Aggregation = Maximum
Fuzzy Inference = Mamdani Type
Type reducer = COS
Defuzzification = Center Average

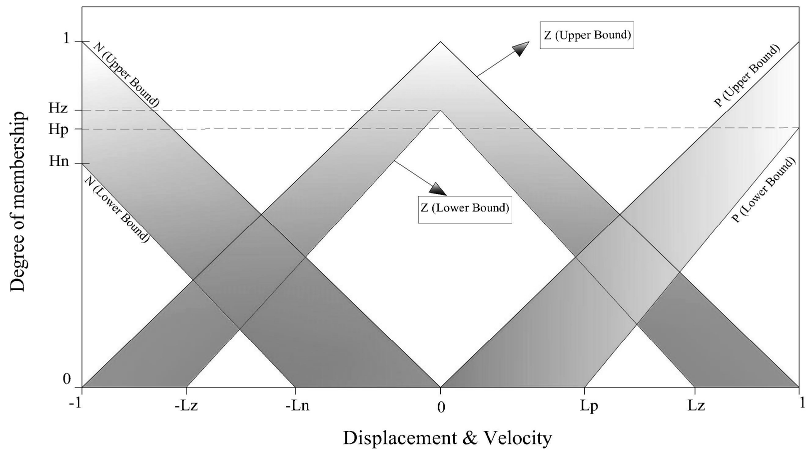


Figure 4. MFs of input variables (displacement and velocity)

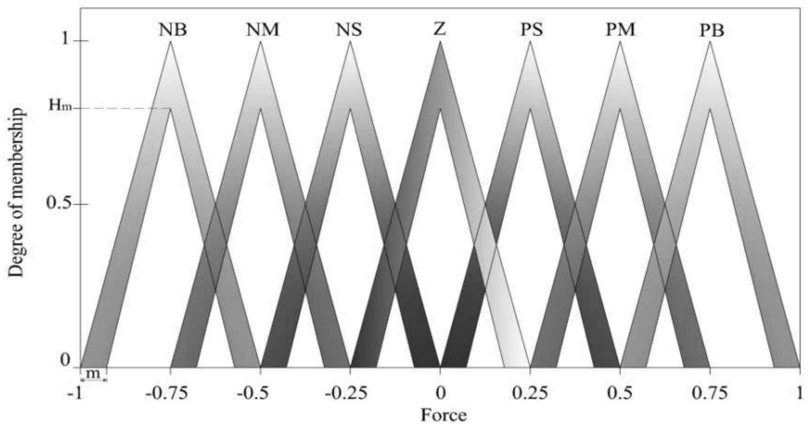


Figure 5. MFs of output variable (active control force)

5. NUMERICAL STUDY

To evaluate the efficiency of the proposed control method in reducing the structural response, an 11-storey realistic shear building with an ATMD on the top floor is chosen [28] and the structure is assumed to be subjected to earthquake excitations.

The International Association for Structural Control (IASC) has identified four earthquake records to be applied for investigating the efficiency of any control system in seismic applications. These ground accelerations are El Centro and Hachinohe as far-field and Northridge and Kobe as near-field earthquakes. The peak absolute accelerations of these earthquake records are 0.3417g, 0.2250g, 0.8267g and 0.8178 g, respectively. To examine the effectiveness of the proposed control method, the four aforementioned earthquake records, but scaled in intensity, are used in this study. The earthquake records used are El Centro and Hachinohe with original intensity, Northridge with 30% of its original intensity and Kobe with 40% of its original intensity [24]. In this paper, only the simulation results of two earthquakes (Hachinohe as far-field and Kobe as near-field) are considered. This is due to the similarity of the results of the other two ground accelerations.

At first, IT2FLC in ATMD is designed for a SDOF system which its properties are chosen as the first mode characteristics of the 11-storey building. The properties of SDOF system and mass damper are provided in table 4 [28]. The important reasons for selecting a SDOF system are: its good approximation to the first structural mode, modeling simplicity and low computational time.

Table 4. Properties of SDOF system and mass damper

	Mass (Kg)	Stiffness (N/m)	Damping ratio (%)
SDOF system	1.057e6	5.148e7	5
Mass damper	62190	3029140	7

The peak displacement response and RMS displacement of the SDOF system were compared in different cases including: uncontrolled, controlled with TMD and controlled with ATMD through type-1 FLC and IT2FLC in Figure 6. These results along with peak response reductions (Response reduction $=\left\{\frac{\text{(Uncontrolled response - Controlled response)}}{\text{Uncontrolled response}}*100\right\}$) are also presented in Tables 5 and 6, for different control systems and different earthquake records, respectively.

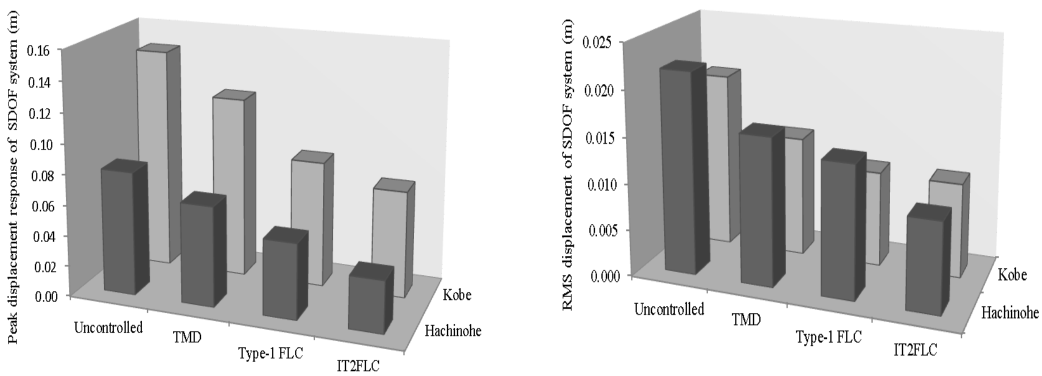


Figure 6. Controlled and uncontrolled peak displacement response and RMS displacement of SDOF system under the Kobe and Hachinohe earthquake records

Figure 6. Controlled and uncontrolled peak displacement response and RMS displacement of SDOF system under the Kobe and Hachinohe earthquake records

Table 5: Peak displacement response and peak response reduction using different control systems

Earthquake	Peak displacement response of SDOF system (m)				Peak response reduction (%)		
	Uncontrolled	TMD	Type-1 FLC	IT2FLC	TMD	Type-1 FLC	IT2FLC
Hachinohe	0.081	0.066	0.049	0.034	19.1	39.1	58.2
Kobe	0.146	0.119	0.083	0.070	18.6	43.5	52.2

Table 6: RMS displacement using different control systems

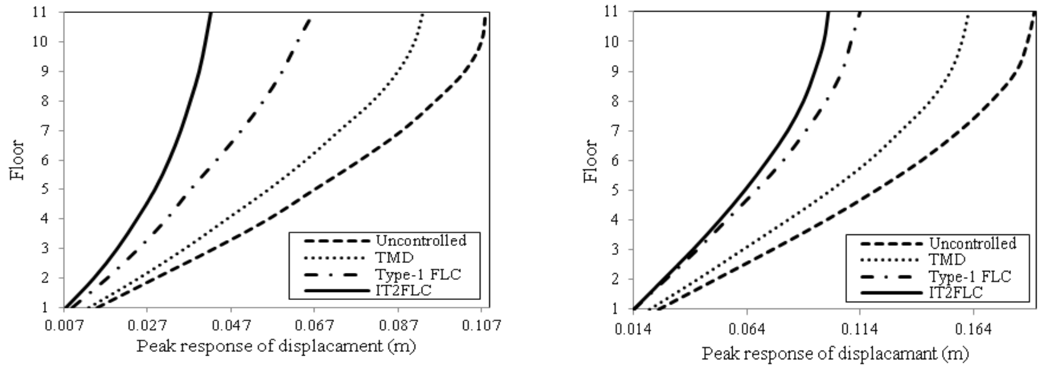
Earthquake	RMS Displacement of SDOF system			
	Uncontrolled	TMD	Type-1 FLC	IT2FLC
Hachinohe	0.0219	0.0160	0.0143	0.0097
Kobe	0.0191	0.0130	0.0103	0.0102

The results show that IT2FLC decreases the peak displacement response and RMS displacement of SDOF structure more than the other controller systems (see Table 5 and 6). The important reason that IT2FLC reduces the structural response more than type-1 FLC is the ability to handle uncertainties in fuzzy rules. The available information used to construct the fuzzy rules, can itself be uncertain. Such uncertainties can only be considered by IT2FLC. Uncertainty in fuzzy rules can be caused by different sources. For example, if we ask about choosing membership function parameters of input (Displacement and velocity) and output (Control force) variables from different experts, we will get different answers from each expert. This is the proof to show uncertainties in antecedent and consequent fuzzy sets. In addition, different experts give different answers to the same question. It means that there are various consequents for the same antecedent. For example, experts have different viewpoints about MFs of control force for the same MFs of displacement and velocity. Uncertainty can also be caused by other sources like earthquake excitation. The measured structural response for activating the FLC can itself be noisy under the effect of ground acceleration. These types of uncertainties can only be handled by IT2FLC. Now, the designed IT2FLC for SDOF system is used as the ATMD controller of the 11-storey realistic building. The properties of the 11-storey building are provided in Table 7 [28].

Table 7: Parameters of the 11-storey realistic building

Floor	**Mass (kg)**	**Stiffness (N/m)**
1	215370	4.68E+08
2	201750	4.76E+08
3	201750	4.68E+08
4	200930	4.50E+08
5	200930	4.50E+08
6	200930	4.50E+08
7	203180	4.50E+08
8	202910	4.37E+08
9	202910	4.37E+08
10	176100	4.37E+08
11	66230	3.12E+08

The peak displacements of the building stories are compared in different cases including: uncontrolled, controlled with TMD and controlled with ATMD through type-1 FLC and IT2FLC in Figure 7. These results along with peak response reductions are also presented in Table 8, for different control systems and different earthquake records.



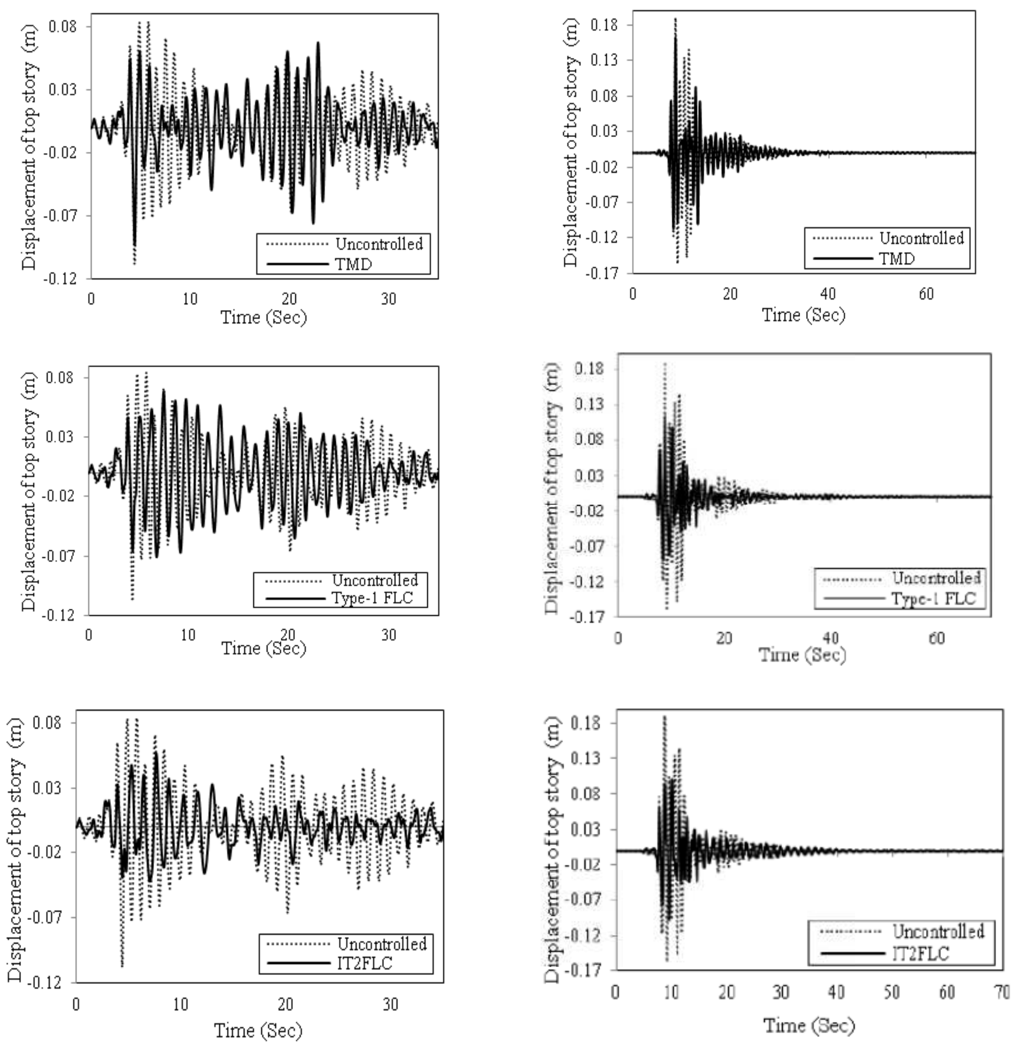
(a) Hachinohe (b) Kobe

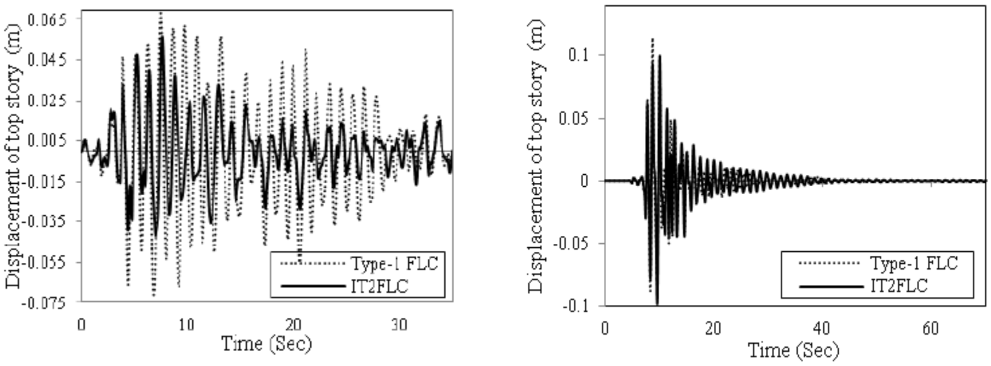
Figure 7. Controlled and uncontrolled peak displacement responses of floors

Table 8: Peak response and peak response reduction using different control systems

Floor	Peak response of displacement				Response reduction percentage (%)		
	Uncontrolled	TMD	Type-1 FLC	IT2FLC	TMD	Type-1 FLC	IT2FLC
Hachinohe							
1	0.015	0.013	0.009	0.008	13.3	40.0	50.0
2	0.029	0.025	0.017	0.014	13.8	40.0	51.0
3	0.043	0.036	0.025	0.020	16.3	42.1	54.0
4	0.056	0.046	0.032	0.025	17.9	43.6	56.3
5	0.067	0.056	0.037	0.028	16.4	44.3	58.5
6	0.078	0.065	0.044	0.031	16.7	44.1	60.0
7	0.088	0.073	0.050	0.035	17.0	43.8	60.8
8	0.096	0.081	0.055	0.037	15.6	42.9	61.1
9	0.103	0.087	0.059	0.039	15.5	42.4	61.7
10	0.107	0.091	0.063	0.041	15.0	41.2	61.8
11	0.108	0.093	0.067	0.042	13.9	38.1	60.9
Kobe							
1	0.025	0.021	0.014	0.014	16.0	44.0	44.0
2	0.050	0.042	0.028	0.027	16.0	44.0	46.0
3	0.075	0.062	0.042	0.040	17.3	44.0	46.7
4	0.099	0.082	0.055	0.052	17.2	44.4	47.5
5	0.121	0.101	0.068	0.063	16.5	43.8	47.9
6	0.141	0.118	0.080	0.073	16.3	43.3	48.2
7	0.158	0.132	0.090	0.082	16.5	43.0	48.1
8	0.172	0.145	0.099	0.089	15.7	42.4	48.3
9	0.183	0.154	0.106	0.094	15.8	42.1	48.6
10	0.188	0.159	0.110	0.097	15.4	41.5	47.9
11	0.191	0.162	0.114	0.100	15.2	40.3	47.6

It is seen from the Table 8 that IT2FLC reduces the uncontrolled peak displacement response of the top floor about 23% (for the Hachinohe earthquake) and 8% (for the Kobe earthquake) more than that of the responses obtained by type-1 FLC. This feature of IT2FLC is revealed in the time history responses. Comparison of displacement time history responses of the top floor for different control systems compared to uncontrolled response when subjected to Hachinohe (as far-field) and Kobe (as near-field) earthquakes are presented in Figure 8. As can be seen from the Figure 8, although TMD, ATMD with type-1 FLC and ATMD with IT2FLC, decrease the time responses, ATMD with IT2FLC shows its priority over TMD and ATMD with type-1 FLC in reducing the structural response. As shown in Figure 8, the controlled time response of displacement can be significantly decrease compared to the history responses obtained by type-1 FLC.

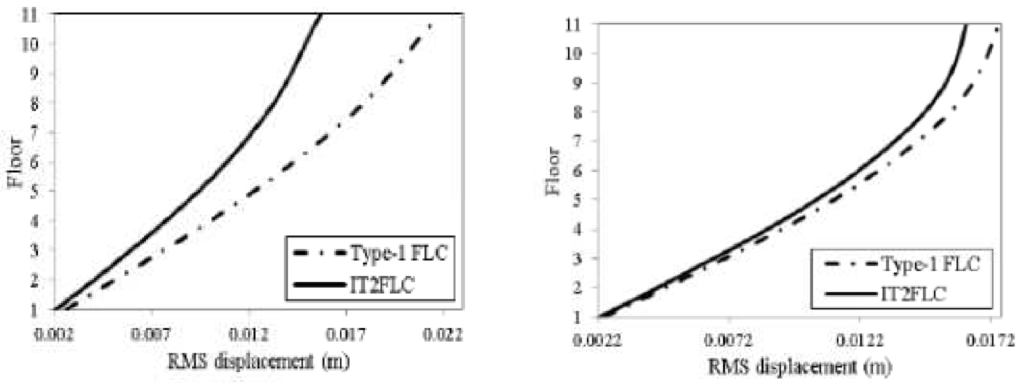




(a) Hachinohe (b) kobe

Figure 8. Comparison of displacement time history responses of the top story for different control systems under the Kobe and Hachinohe earthquake records

Another criterion for comparison of type-1 FLC and IT2FLC is RMS displacement of stories. This parameter is obtained for the realistic building in case of using type-1 FLC and IT2FLC under Hachinohe and Kobe ground accelerations as shown in Figure 9. As expected, IT2FLC decreased the RMS displacement responses of floors more than that of obtained by type-1 FLC and it can be understood that a superior improvement in terms of RMS reductions observed when using IT2FLC in an ATMD.

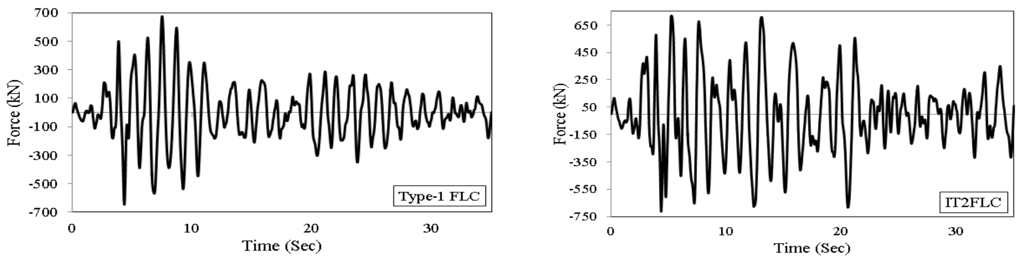


(a) Hachinohe (b) kobe

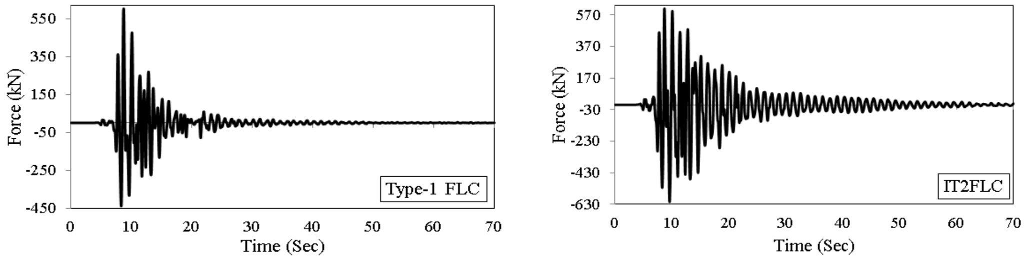
Figure 9. Comparison of RMS displacement of stories in case of using type-1 FLC and IT2FLC

From Figures 8 and 9 it can be understood that the proposed control method decrease the structural responses (Peak displacement response of floors, Time history response of top floor and RMS displacement of floors) for both near-field and far-field earthquakes. However, the response reduction is more for far-field ground accelerations.

The corresponding active control forces are shown in Figure 10. Figure 10 shows that the peak value of active control force in IT2FLC is a little more than that of the type-1 FLC. It is notable that the differences in maximum control force needed for type-1 FLC and IT2FLC is insignificant. The maximum control force required to reduce the structural response in IT2FLC is about 10% more than that of type-1 FLC. Although relatively large control force needs additional expenses, the structural member size, reduces considerably and causes economical advantages by decreasing the peak displacement response of floors.



(a) Hachinohe



(b) Kobe

Figure 10. Comparison between the active control forces needed in type-1 FLC and IT2FLC for the Hachinohe and Kobe earthquakes

The Stability of the FLC system can be checked through the ability of controller to return the structure to the rest position from initial conditions. The stability test is performed considering the structural system with extreme initial conditions and checking the ability of FLC to reach to rest condition [18]. Figure 11 demonstrates the stability of the IT2FLC in terms of control force. The results show that the IT2FLC is stable and drive the structure to the equilibrium position.

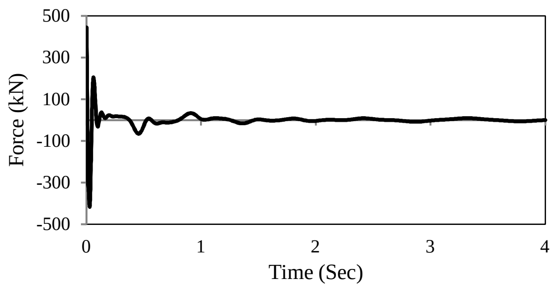


Figure 11. Fuzzy control stability test in terms of control force

4. CONCLUSION

This is the first study on the application of interval type-2 fuzzy logic systems for evaluating the active control force in an ATMD controller based on getting the maximum response reduction of the building top floor. In design of interval type-2 fuzzy logic controller (IT2FLC), displacement and velocity of a SDOF system are considered as the controller feedback gains. To investigate the efficiency of proposed control method, the designed IT2F LC for the SDOF system is used as the ATMD controller of the 11-storey realistic shear building. Numerical results revealed that:

1. IT2FLC is quite effective in reducing the structural responses compared with that of obtained with type-1 FLC.
2. IT2FLC reduces the peak displacement response of the top floor about 23% and 8% more than that of the displacement responses obtained by type-1 FLC, for the Hachinohe and Kobe earthquakes, respectively.
3. Comparison between RMS displacement response of stories in case of using type-1 FLC and IT2FLC, show that IT2FLC reduces the RMS responses of floors, more than that of the type-1 FLC. Thus, IT2FLC decreases the time history responses of floors more than those obtained by type-1 FLC.
4. The designed IT2FLC for a SDOF system with the first mode characteristics of the 11-storey building can be effectively estimated response of the realistic building.
5. The maximum active control force in the IT2FLC system for reducing the structural response is a little more than that of the type-1 FLC and is about 10%.

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