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SEMI-ACTIVE CONTROL OF THE WIND-EXCITED BENCHMARK TALL BUILDING USING A FUZZY CONTROLLER*

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Abstract– Semi-active control systems having the adaptability aspects of active control methods along with the reliability and stability of passive controllers have been recently used to control structures against natural hazards. In this paper, a fuzzy logic based controller is designed to attenuate vibrations of a tall building under cross wind excitations. The building considered is the benchmark 76-story reinforced concrete office tower proposed for the city of Melbourne, Australia. A collection of semi-active dampers is used at the first story to apply control forces to the structure where the damping is found through the fuzzy logic controller. Higher levels of performance are achieved in mitigating structural responses, especially the average RMS displacement response through the application of the fuzzy controller. Also investigated in the present study is the robustness of the whole structure-controller system to uncertainties in the stiffness matrix in the form of multiplicative perturbations. Simulation results verify the superior performance of the semi-active fuzzy controller over the passive controller in response mitigation of the perturbed structure.

Keywords– Semi-active control, fuzzy logic controller, wind excitation, passive damper

1. INTRODUCTION

Reducing structural responses and consequently the damaging effects of natural hazards such as earthquakes and winds are nowadays one of the most important fields of study on which many researchers are working. Many devices have been proposed and used in real world to reduce structural responses known as structural control systems. These systems can be generally classified as passive, active, and semi-active methods in most typical projects. Passive structural control systems are easy to install and require no external power for operation. Hence, the control system properties cannot be modified after installation. Active control methods refer to systems that require a power source to apply control forces whose magnitudes are determined through the feedback of measured responses of the structure and/or excitations applied to the structure. Semi-active control systems lie between the two aforementioned controllers having the adaptability aspects of active control systems along with the reliability and stability of passive controllers. Semi-active control systems often require low power to operate a small electronic device to adjust the mechanical properties of the device. Among all of the control devices that have been used in semi-active control systems, variable dampers are the most popular. A comprehensive illustration of these systems has been described by Spencer and Sain and Symans and Constantinou [1, 2].

Different methods have been proposed to determine the magnitude of control forces or characteristics of semi-active devices [3]. One of these approaches is the fuzzy control method. Because of its great

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features, the fuzzy control method has been used in many fields of engineering and more recently in some civil engineering applications [4]. A few researchers have investigated the control of civil engineering structures through the fuzzy logic control approach and the studies conducted have shown the satisfactory performance of fuzzy controllers [5-13].

In this study, the Fuzzy Logic control is used to operate a group of semi-active dampers in the first floor to mitigate the structural response of the 76-story benchmark building introduced by Yang et al. [14]. The controller acquires information on the response of the structure from only two sensors. Furthermore, the robustness of the structure-controller system to uncertainties in the stiffness matrix is evaluated. The results are compared to the responses of the system without control and the system with passive control.

2. STRUCTURAL MODEL AND BENCHMARK PROBLEM

The governing differential equations of motion for an n-degree of freedom structure in the linear state are

$$M\ddot{x}(t)+C\dot{x}(t)+Kx(t)=Ew(t) \tag{1}$$

where M, C, and K are mass, damping, and stiffness matrices respectively. Vectors x(t) and w(t) are n×1 which represent story displacements, all with respect to the ground and wind forces applied to the building. E is the influence matrix relating wind excitation to each degree of freedom. Using the state space representation, Eq. (1) takes the following form.

$$\dot{Z}(t)=AZ(t)+Hw(t) \tag{2a}$$

$$y(t)=FZ(t)+v(t) \tag{2b}$$

where Z(t) is the 2n-dimensional state vector

$$Z(t)=\begin{Bmatrix} x(t) \\ \dot{x}(t) \end{Bmatrix} \tag{3}$$

and A is the 2n×2n system matrix.

$$A=\begin{bmatrix} o & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix} \tag{4}$$

H is the 2n×n location matrix which specifies the location of the wind excitation.

$$H=\begin{bmatrix} I \\ M^{-1}E \end{bmatrix} \tag{5}$$

y(t) and v(t) are the output measured and measured noise vectors respectively. In the above equations, 0 and I represent zero and identity matrices respectively with appropriate dimensions.

Control forces are applied to the structure through variable dampers whose damping can be adjusted between an upper and a lower limit. Consequently, a component is introduced to the system's equations of motion as follows.

$$\dot{Z}(t)=AZ(t)+Bc(t)Z(t)+Hw(t) \tag{6}$$

in which c(t) is the damping of the variable damper device. Matrix B is defined as follows

$$B=\begin{bmatrix} o_{n\times n} & o_{n\times n} \\ o_{n\times n} & -M^{-1}b \end{bmatrix} \tag{7}$$

and b indicates the location of dampers throughout the structure.

The first two components in the right hand side of Eq. (6) are combined to have the new system matrix $\widetilde{A}(t)$.

$$\dot{Z}(t) = \widetilde{A}(t)Z(t) + Hw(t) \tag{8}$$

where

$$\widetilde{A}(t) = A + Bc(t) \tag{9}$$

The structure considered in this paper is the 76-story reinforced concrete building proposed previously by Yang et al. [14] for an office tower for the city of Melbourne, Australia. The building consists of a concrete core, designed to withstand almost the entire wind loads and a concrete frame designed to carry the vertical loads of the building and part of the wind loads. The plan view of the building is shown in Fig. 1. The total mass of the building, including heavy machinery in the plant rooms is 153000 tons. The building is slender and wind sensitive with a height to width ratio of 306.1/42=7.3. The building model is a vertical cantilever beam with 76 translational and 76 rotational degrees of freedom. The rotational degrees of freedom are removed by static condensation; thereby, 76 degrees of freedom representing lateral story displacements are kept. The first five natural frequencies of the simplified model of the structure are 0.16, 0.765, 1.992, 3.790, and 6.395 Hz. The first three mode shapes are shown in Fig. 2.

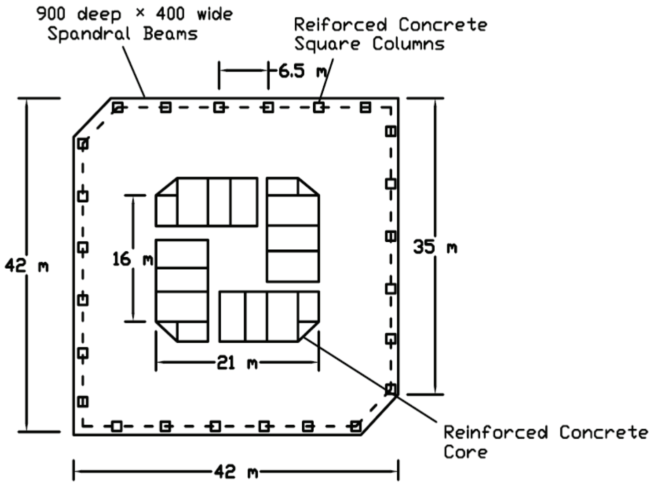

Fig. 1. Plan view of the building [14]

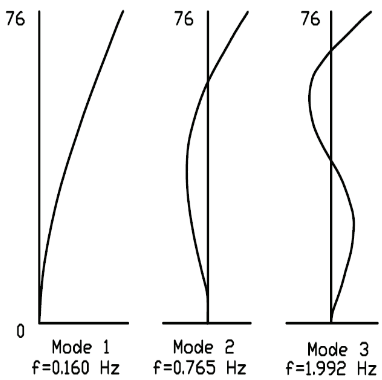

Fig. 2. First three Mode shapes [14]

The damping matrix for the building was calculated based on 1% damping ratio for the first five modes.

Semi-active dampers are applied to the first story of the building. These dampers are assumed ideal and the controller-structure interactions are ignored; therefore, the required damping found from the control algorithm is achievable by dampers. Since story diaphragms are nearly rigid, a large number of dampers can be utilized in the first story which totally results in one lateral control force. For simplicity, control forces from all of the variable dampers are condensed into one single force which allows modeling the effect of all dampers through only one damper. Consequently, the semi-active location matrix b in equation 7 is

$$b = \begin{bmatrix} 1 & 0 & \dots & 0 \\ 0 & 0 & & \\ \vdots & & \ddots & \vdots \\ 0 & & \cdots & 0 \end{bmatrix}_{n\times n} \tag{10}$$

A schematic view of the building together with the semi-active damper is shown in Fig. 3.

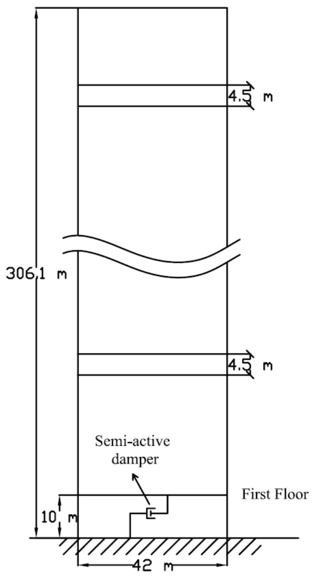

Fig. 3. Schematic view of the benchmark building

3. FUZZY LOGIC CONTROLLER

Fuzzy logic has come a long way since it was first introduced by Zadeh [15] to deal with the imprecision and uncertainty that is often present in real applications. In the theory of fuzzy logic, significance is more important than precision, and as a result, fuzzy set theory allows for human reasoning using linguistic directions as a basis rather than mathematical equations [16]. In fuzzy set theory objects have a degree of membership within a set, while in traditional mathematics they have either 0 or 100 percent membership within a set. The fuzzy set environment is described by a membership function which is defined over a specified range. There are many shapes for membership functions but the most common is the triangular shape. Linguistic variables such as Small, Medium, and Large are used to represent the domain knowledge. Many membership functions can be defined for a fuzzy logic system which can overlap. This causes a non-fuzzy number to belong, at the same time, to different fuzzy sets with different degrees of membership. After definition of membership functions, fuzzy rules are defined. Fuzzy rules convert values of fuzzy input variables into fuzzy sets of output variables. These rules are in the form of IF {Rule Premise} THEN {Rule Consequence}. These statements are based on practical human reasoning. The basic operators of fuzzy logic are fuzzy intersection (AND), fuzzy union or disjunction (OR), and fuzzy complement (NOT); their operands are fuzzy sets. The result of the AND (OR) operation is the minimum (maximum) of the membership function of its fuzzy set operand. The {Rule Consequence} provides a linguistic value for each output variable; its true value is the numeric result of the {Rule Premise}. The next stage is the fuzzification process where the fuzzifier converts each input variable value into the relevant fuzzy variable using its own set of linguistic variables (fuzzy sets) and their pertinent membership functions. Using the fuzzy rule base developed earlier, the fuzzy implication process is implemented to map input variables to output membership functions. If there is more than one input corresponding to an output, a fuzzy operation is performed in which the degree of membership of inputs is combined in preparation for fuzzy implication. The fuzzy aggregation process follows in which the output sets are combined into a single universe of discourse. The final stage of the fuzzy logic process is defuzzification, which is responsible for the translation of the fuzzy reasoning engine resulting in a crisp set of output values. The flowchart of a typical fuzzy logic analyzer is illustrated in Fig. 4.

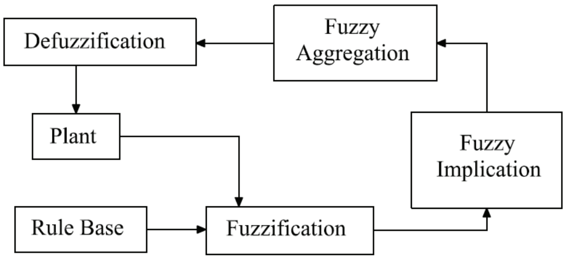

Fig. 4. Flowchart of fuzzy logic analysis

A variety of methods are used to perform defuzzification, the most common are:

1. The Mamdani method [17] that returns the centroid of the output fuzzy region as the crisp output of the fuzzy interface system.
2. The TVFI (Truth Value Flow Inference) method that returns a weighted average as the crisp output of the fuzzy interface system [18].

Many applications have been found for fuzzy logic theory in different fields of science but one of the most prevalent uses of this theory is in structural engineering applications, called fuzzy control. Fuzzy control has a number of great features which make it ideal toward other control approaches. Some of these advantages are:

1. Fuzzy logic control, unlike most control methods is not sensitive to simulation and prediction of the response [19, 20]. In civil engineering applications, the model of the subjected structures can be estimated and simulated, but they are not completely true. These uncertainties are treated easier by fuzzy logic control than by other methods. As a consequence, in the presence of uncertainties in the system model e.g. mass, damping, and stiffness matrices and noise in measured responses, the performance of fuzzy controllers is still satisfactory.
2. Implementing control methods in real is a problem, but the fuzzy controller can be easily implemented to real time control.

The fuzzy logic controller designed for this study has two input and one output variable. Since the top story response of a building represents the amplitude of the first mode of the structure which has the largest contribution to the response, the displacement of the 76th floor and its velocity are used as input variables. The fuzzy output is the damping of the semi-active device. Each fuzzy input has ten membership functions while the fuzzy output has six membership functions. These functions are shown in Figs. 5 and 6 respectively. Definitions of fuzzy input and output membership functions abbreviations are presented in Table 1.

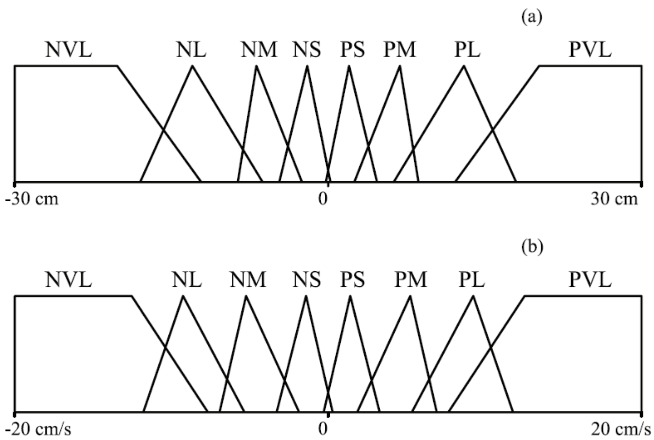

Fig. 5. Input membership functions, (a) displacement and (b) velocity

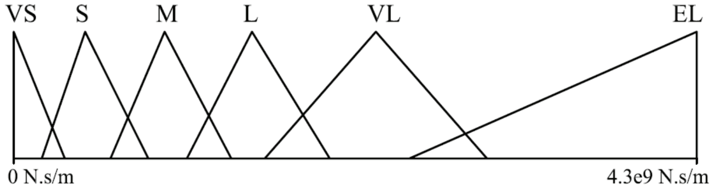

Fig. 6. Output membership functions

Table 1. Fuzzy Variables

Input Variable		Definition	Output variable		Definition
PVL		Positive and very large	VS		Very small
PL		Positive and large	S		Small
PM		Positive and medium	M		Medium
PS		Positive and small	L		Large
NS		Negative and small	VL		Very large
NM		Negative and medium	EL		Extremely large
NL		Negative and large			
NVL		Negative and very large			

A fuzzy rule base with 100 rules, developed to relate input-output membership functions, is presented in Table 2 and the resultant control surface is shown in Fig. 7. The concept behind the proposed rule base is similar to a bang-bang controller when the structure moves away from the center position. In this case, the story displacement and velocity have the same sign and therefore having a large damping ratio applies large resisting forces to slow down the increase in the displacement response. In the other case when the displacement and velocity have different signs, the structure returns to the origin and the state of the system is desirable. However, if the displacement or velocity in this part is very large, the structure will have large responses when it passes the origin and moves away. To prevent large deformations at the next stage, large damping forces are imposed when displacement and velocity are large and have opposite signs. This part of the controller acts as a predictor to attenuate the future response of the structure.

Table 2. Fuzzy rules for the rule base

Displacement of 76th floor	Velocity of 76th floor							
	NVL	NL	NM	NS	PS	PM	PL	PVL
NVL	EL	EL	EL	VL	S	S	VL	EL
NL	EL	EL	EL	L	M	S	L	VL
NM	VL	L	M	S	S	S	S	L
NS	L	M	S	VS	VS	S	M	L
PS	L	M	S	VS	VS	S	M	L
PM	L	S	S	S	S	M	L	VL
PL	VL	L	S	M	L	EL	EL	EL
PVL	EL	VL	S	S	VL	EL	EL	EL

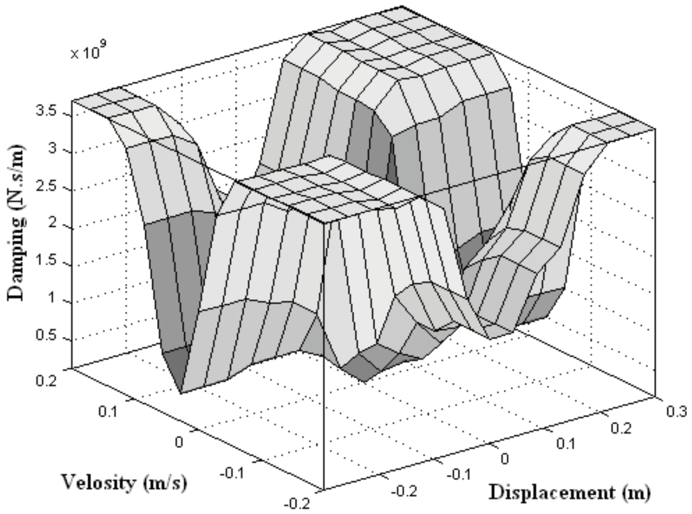

Fig. 7. Fuzzy control surface

4. PERFORMANCE CRITERIA

A number of performance criteria introduced by Yang et al. [14] are used here to evaluate the controller performance. The first criterion is based on the ability of the controller to reduce the maximum floor root mean square (RMS) acceleration.

$$J_1 = \max\left(\sigma_{\ddot{x}_1}, \sigma_{\ddot{x}_{30}}, \sigma_{\ddot{x}_{50}}, \sigma_{\ddot{x}_{55}}, \sigma_{\ddot{x}_{60}}, \sigma_{\ddot{x}_{65}}, \sigma_{\ddot{x}_{70}}, \sigma_{\ddot{x}_{75}}\right) / \sigma_{\ddot{x}_{75o}} \tag{11}$$

where $\sigma_{\ddot{x}_i}$ is the RMS acceleration of the ith floor, and $\sigma_{\ddot{x}_{75o}}$ is the RMS acceleration of the 75th floor for the uncontrolled case. The second criterion is the average reduction of displacement for selected floors above the 49th floor, i.e.

$$J_2 = \frac{1}{6}\sum_i \left(\sigma_{\ddot{x}_i} / \sigma_{\ddot{x}_{io}}\right) \qquad \text{for i = 50, 55, 60, 65, 70 and 75} \tag{12}$$

where $\sigma_{\ddot{x}_{i0}}$ is the RMS acceleration of the ith floor without control. The third and fourth performance criteria are the ability of the controller to reduce the top floor displacements.

$$J_3 = \sigma_{x76} / \sigma_{x76_0} \tag{13}$$

$$J_4 = \frac{1}{7}\sum_i \left(\sigma_{x_i} / \sigma_{x_{io}}\right) \qquad \text{for i = 50, 55, 60, 65, 70, 75 and 76} \tag{14}$$

where σ_{x_i} and $\sigma_{x_{io}}$ are RMS displacements of the ith floor with and without control respectively. The aforementioned performance criteria are used to evaluate the performance of the structure at peak responses as follows:

$$J_5 = \max\left(\ddot{x}_{p_1}, \ddot{x}_{p_{30}}, \ddot{x}_{p_{50}}, \ddot{x}_{p_{55}}, \ddot{x}_{p_{60}}, \ddot{x}_{p_{65}}, \ddot{x}_{p_{70}}, \ddot{x}_{p_{75}}\right) / \ddot{x}_{p_{75o}} \tag{15}$$

$$J_6 = \frac{1}{6}\sum_i \left(\ddot{x}_{p_i} / \ddot{x}_{p_{io}}\right) \qquad \text{for i = 50, 55, 60, 65, 70 and 75} \tag{16}$$

$$J_7 = \frac{1}{7}\sum_i \left(x_{p_i} / x_{p_{io}}\right) \qquad \text{for i = 50, 55, 60, 65, 70, 75 and 76} \tag{17}$$

in which x_{p_i} and $x_{p_{io}}$ are the peak displacements of the ith floor with and without control; $\ddot{x}_{p_i}$ and $\ddot{x}_{p_{io}}$ are the peak accelerations of the ith floor with and without control respectively. From the definitions, the better the performance of the controller, the smaller the values of the performance indices are.

5. NUMERICAL RESULTS AND DISCUSSION

The designed fuzzy controller is applied to the benchmark structure. The building is subjected to wind excitations on one side. Although the wind tunnel data are available for one hour, a duration of 250 sec is used to reduce computational efforts. The time histories of wind forces acting on the 30th, 50 th, and 75th floor are shown in Fig. 8.

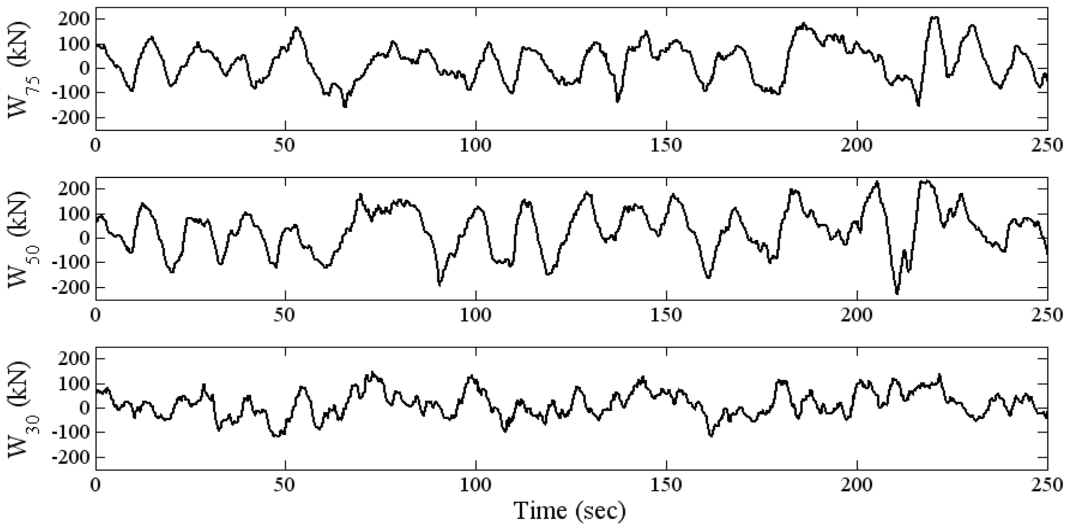

Fig. 8. Time histories of wind load on floors 30, 50, and 75

The maximum value of the damping of the semi-active device for the passive controlled case is chosen to be the maximum value of the damping which the fuzzy controller can take on. From Fig. 7, this maximum value is 3.51×10^9 Ns/m. Using the performance criteria introduced in the previous section, the efficiency of different methods is evaluated. The schematic block diagram of the building model with the fuzzy controller is shown in Fig. 9.

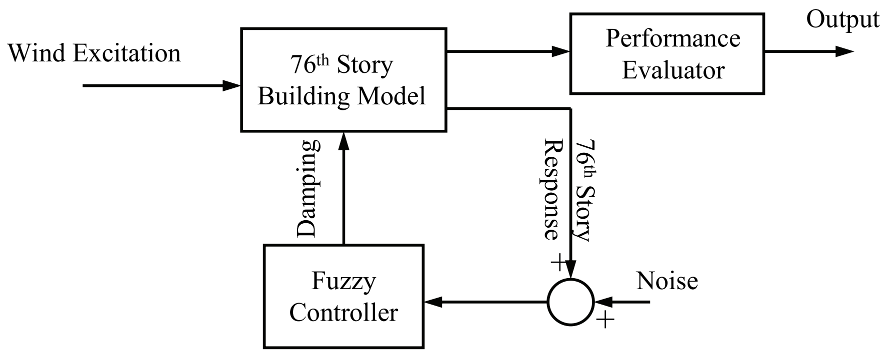

Fig. 9. Block diagram of the structure-controller system

Robustness of the fuzzy controller to uncertainties in structural parameters is evaluated for multiplicative perturbations in the stiffness of the building. Comparisons between the displacement responses of the uncontrolled, passive controlled and fuzzy controlled structures to wind excitation for 0, -15 and +15% uncertainty in the stiffness are shown in Fig. 10. The fuzzy controller is seen to have a good performance in reducing the responses, even at the presence of perturbations in the stiffness matrix. Since the structure is assumed to remain linear during wind excitations and semi-active dampers used here are inherently stabilizing, the structure will be stable and also preserves robust stability in the presence of small perturbations. However, the robustness in the performance is not clear beforehand and a set of time history analyses performed in the study in the presence of ±15% stiffness uncertainty has shown that the semi-active fuzzy controller has satisfactory robustness to uncertainties.

Detailed RMS and peak responses are presented in Tables 3 through 5. Table 3 compares the RMS and peak displacement and acceleration of the uncontrolled structure, the structure with passive damper, and the structure controlled with fuzzy logic controller, in the case with 0% stiffness uncertainty. The passive damper reduces the 76th floor RMS displacement and acceleration response by nearly 37% and 40% respectively, when compared to the uncontrolled case, while these reductions by the fuzzy controller are 42% and 48% respectively. Further reduction in the case of the fuzzy controller is a 5% response reduction in displacement and an 8% response reduction in acceleration compared with the passive controller. Peak displacement and acceleration responses are also presented in Table 3. Reductions in the 76th peak floor displacement and acceleration response are 25% and 27%, in the case of passive control, when compared to the uncontrolled case; these reductions in the case of the fuzzy controller are 37% and 15% respectively. The fuzzy controller reduces the 76th peak floor displacement by 12% but increases acceleration by 18% toward the passive case.

Table 3. Root mean square (RMS) and peak response of the building for 0% stiffness uncertainty, in three cases: without control, passive and fuzzy control

Floor No.		30	50	55	60	65	70	75	76
RMS displacement (mm)	W/O	25.047	60.579	70.845	81.444	92.342	103.4	114.86	117.42
	Passive	15.207	37.694	44.19	50.888	57.763	64.731	71.947	73.564
	Fuzzy	14.539	35.122	41.02	47.09	53.309	59.605	66.124	67.584
Peak displacement (mm)	W/O	59.674	143.01	166.79	191.24	216.4	241.96	268.42	274.35
	Passive	42.113	104.97	123.16	141.9	161.14	180.86	201.61	206.25
	Fuzzy	36.63	88.158	103.35	119.2	135.79	152.64	170.1	174.01
RMS acceleration (mm/s^2)	W/O	21.852	50.973	59.477	68.337	77.598	87.224	97.445	99.762
	Passive	12.821	29.639	34.624	39.895	45.505	51.462	57.908	59.383
	Fuzzy	12.08	25.992	30.253	34.912	39.735	44.717	50.584	52.04
Peak acceleration (mm/s^2)	W/O	57.764	123.3	139.82	158.79	181.71	207.53	234.22	240.2
	Passive	40.486	88.482	99.198	113.82	130	146.46	169.97	175.26
	Fuzzy	38.75	86.08	99.917	118.05	139.79	150.21	184.97	209.53

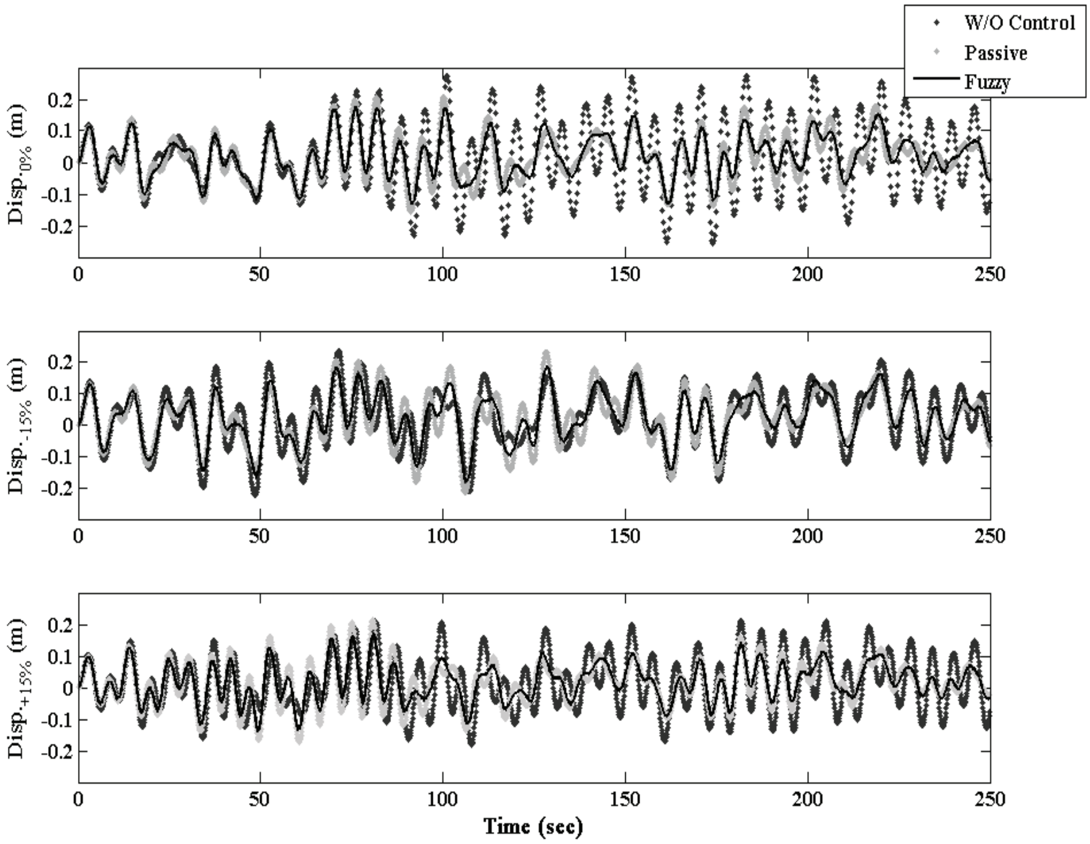

Fig. 10. 76th floor displacement for three cases with 0%, -15%, and +15% uncertainty

The RMS and peak of the displacement and acceleration responses for uncontrolled, passive controlled and fuzzy controlled cases for stiffness uncertainty of -15% are presented in Table 4. The passive damper reduces the 76th floor RMS displacement and acceleration response by nearly 11% and 8% respectively, while the fuzzy controller reduces these responses by 18% and 23% respectively, when compared to the uncontrolled case. Further reduction in the case of the semi-active fuzzy controller is 7% in displacement and 15% in acceleration responses. The reductions in the 76th floor displacement and acceleration peak response are nearly 2% and 13%, in the case of the passive controller, when compared to the uncontrolled case; these reductions in the case of the fuzzy controller are 21% and 15% respectively. Therefore, the fuzzy controller reduces the 76th peak floor displacement and acceleration by 19% and 2% further toward the passive case.

Table 5 compares the RMS and peak displacement and acceleration of the uncontrolled structure, the structure with passive dampers, and the structure controlled with the fuzzy logic controller, in the case with +15% stiffness uncertainty. The passive damper reduces the 76th floor RMS displacement and acceleration response by 21% and 23% respectively, when compared to the uncontrolled case. Reductions obtained in the same measures with the fuzzy controller are 33% and 36% respectively, when compared to the uncontrolled case. Through the application of the semi-active fuzzy controller, 12% and 13% further response reductions are achieved in RMS displacement and acceleration responses. Also presented in Table 5 are the peak displacement and acceleration responses of the structure for +15% uncertainty in stiffness. Reductions in the top floor displacement and acceleration peak responses are -2% and -4% in the case of the passive controller when compared to the uncontrolled case, while the fuzzy controller reduces these responses by 80% and 18% respectively. As a consequence, the fuzzy controller reduces the top floor peak displacement and acceleration by 82% and 22% further compared with the passive case.

Table 4. Root mean square (RMS) and peak response of the building for -15% stiffness uncertainty, in three cases: without control, passive and Fuzzy control

Floor No.		30	50	55	60	65	70	75	76
RMS displacement (mm)	W/O	20.359	49.065	57.317	65.82	74.543	83.381	92.533	94.584
	Passive	17.447	43.322	50.801	58.512	66.426	74.446	82.752	84.613
	Fuzzy	16.747	40.468	47.265	54.259	61.422	68.673	76.18	77.862
Peak displacement (mm)	W/O	49.68	121.01	141.7	163.14	185.44	208.11	231.61	236.87
	Passive	46.439	117.24	137.9	159.21	181.08	203.24	226.18	231.32
	Fuzzy	39.39	95.348	111.62	128.38	145.79	163.49	181.86	185.98
RMS acceleration (mm/s^2)	W/O	14.909	31.339	36.217	41.469	47.199	53.476	60.45	62.065
	Passive	12.454	28.321	33.052	38.061	43.423	49.186	55.505	56.96
	Fuzzy	11.501	23.888	27.593	31.522	35.895	40.811	46.527	47.944
Peak acceleration (mm/s^2)	W/O	50.083	86.43	98.571	109.69	119.06	142.11	167.87	173.67
	Passive	36.552	74.87	84.322	94.925	109.13	126.02	147.11	151.9
	Fuzzy	37.966	73.568	82.982	91.524	102.73	128.89	141.73	147.82

Table 5. Root mean square (RMS) and peak response of the building for +15% stiffness uncertainty

Floor No.		30	50	55	60	65	70	75	76
RMS displacement (mm)	W/O	19.116	46.206	54.023	62.09	70.379	78.788	87.499	89.45
	Passive	14.414	35.869	42.09	48.511	55.11	61.803	68.737	70.29
	Fuzzy	12.637	30.907	36.167	41.586	47.145	52.777	58.611	59.918
Peak displacement (mm)	W/O	44.891	109.02	127.52	146.6	166.21	186.1	206.7	211.32
	Passive	43.717	109.68	128.91	148.78	169.21	189.95	211.44	216.25
	Fuzzy	34.273	85.147	99.851	115.46	131.82	148.52	165.9	169.8
RMS acceleration (mm/s^2)	W/O	19.979	46.076	53.719	61.729	70.142	78.896	88.181	90.286
	Passive	14.375	34.745	40.765	47.063	53.663	60.532	67.827	69.481
	Fuzzy	13.008	28.722	33.413	38.371	43.749	49.364	55.81	57.397
Peak acceleration (mm/s^2)	W/O	54.174	103.18	116.96	134.56	156.36	178.65	202.24	207.57
	Passive	43.717	109.68	128.91	148.78	169.21	189.95	211.44	216.25
	Fuzzy	34.273	85.147	99.851	115.46	131.82	148.52	165.9	169.8

The force-velocity response of the semi-active variable damper and passive damper are shown in Fig. 11. As seen, the damping coefficient varies between an upper and a lower bound showing the variation imposed by the fuzzy controller. Also shown in this figure is the fact that neither the high nor the low damping coefficients are optimal. However the higher density of the damping force at the upper bound implies the optimal damping is closer to the upper bound. It is also observed that the damping coefficient increases as the magnitude of the perturbed stiffness matrix increases such that the damping coefficient is the smallest for the case with -15% and the largest for the case with +15% perturbations in the stiffness matrix. Since the increase in the magnitude of the stiffness matrix has resulted in smaller displacements (Tables 3,4,5), the increase in the damping coefficient can be related to the increase in the velocity response of the structure as the magnitude of the stiffness matrix increases.

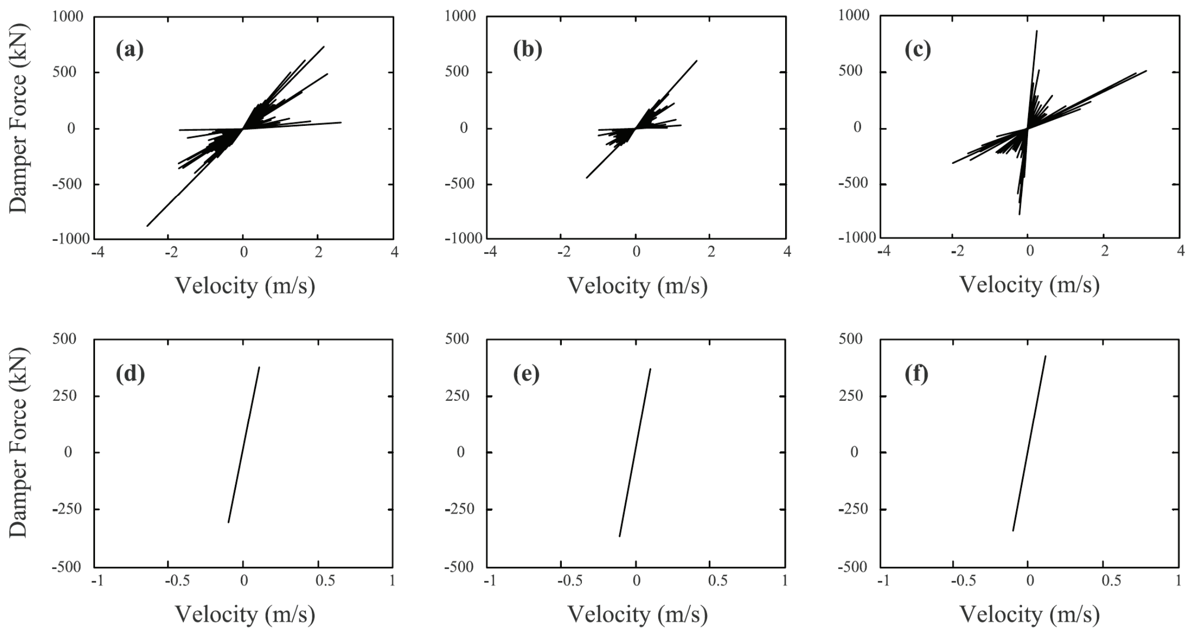

Fig. 11. Force-velocity behavior: (a), (b), and (c) semi-active variable damper for 0, -15, and 15% stiffness uncertainty; (e), (f), and (g) passive damper for 0, -15, and 15% stiffness uncertainty, respectively

The performance criteria J_1 through J_7 for the passive and fuzzy controller cases with different stiffness uncertainties, ΔK=0% and ±15%, are presented in Table 6. Similar performances in the passive and fuzzy controller cases can be observed in this table.

Table 6. Performance criteria for the passive and fuzzy control cases in the presence of uncertainties in the stiffness

Uncertainty Percent		J_1	J_2	J_3	J_4	J_5	J_6	J_7
0	Passive	0.59	0.59	0.63	0.63	0.73	0.72	0.74
	Fuzzy	0.52	0.51	0.58	0.58	0.77	0.75	0.63
-15	Passive	0.92	0.92	0.89	0.89	0.88	0.88	0.97
	Fuzzy	0.77	0.76	0.82	0.82	0.84	0.86	0.79
15	Passive	0.77	0.76	0.79	0.78	1.05	1.08	1.02
	Fuzzy	0.63	0.62	0.67	0.67	0.82	0.84	0.79

In most cases, the fuzzy controller has a better performance, especially in J_7, the average of the RMS displacement response. The reduction achieved in this criterion for the fuzzy controller is 37%, 21%, and 21% for 0%, -15%, and +15% stiffness uncertainty respectively, while for the passive controller the reductions are 26%, 3%, and -2% respectively. However, the fuzzy controller reduces the average of peak acceleration response J_6 less than the passive controller for 0% and -15% stiffness uncertainties. From Table 6, it is evident that the passive controller increases the maximum and average peak of the acceleration response and also the average of the displacement response, J_5, J_6, and J_7.

6. CONCLUSION

The application of semi-active variable dampers for wind response control of tall buildings was studied in this paper. A fuzzy controller was developed to determine the damping of the device in real time. Inputs to the fuzzy controller were the displacement and velocity of the 76th floor. Simulation results showed the passive damper reduces the 76th floor RMS displacement and acceleration response by 37% and 40% respectively, while the fuzzy controller reduced the same responses by 42% and 48% respectively, when compared to the uncontrolled case. Different performance criteria were used to evaluate the performance of the controller. In most cases, the fuzzy controller had a better performance, especially in J_7, the average of the RMS displacement response. The reduction obtained in this metric for the fuzzy control case was 37%, 21%, and 21% for 0%, -15%, and +15% stiffness uncertainty respectively, while for the passive control case these reductions were 26%, 3%, and -2% respectively. Considering all the results, the fuzzy controller is seen to be more effective than the passive controller in retuning the damping of the semi-active device and reducing the structural response to wind excitations.

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