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Active Control of Cross Wind Response of 76-Story Tall Building Using a Fuzzy Controller

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Abstract: This paper focuses on the benchmark problem application regarding the vibration control of tall buildings under cross wind excitation. The building under consideration is the 76-story, 306-m tall reinforced concrete office tower proposed for the city of Melbourne, Australia. The adopted control scheme consists of an active tuned mass damper (ATMD) where the control action is achieved by a fuzzy logic controller (FLC). The main advantage of the FLC is its inherent robustness and ability to handle any nonlinear behavior of the structure and the fact that its implementation does not require a mathematical model of the structure. This benchmark study is based on specified design constraints for the ATMD to be considered in the design of the proposed control scheme. The performance of the controller has been demonstrated through the uncertainty in stiffness (+15 and −15% variation from initial stiffness) of the building. The results of the simulation show a good performance by the fuzzy controller for all cases tested. Also the results show that the fuzzy controller performance is similar to the linear quadratic Gaussian (LQG) controller, while possessing several advantages over the LQG controller.

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CE Database subject headings: Active control; Wind forces; Fuzzy sets; Buildings, high-rise; Vibration control; Damping.

Introduction

Environmental loads on tall structures; such as those stemming from wind and earthquake can cause human discomfort, motion sickness, and sometimes endanger structural safety and integrity. Passive, semiactive, and active control schemes are becoming an integral part of the structural systems over the last 2 decades. Active tuned mass damper (ATMD) systems have been a popular area of research for some time and significant progress has been made in this area (Soong and Hanson 1993; Nerves and Krishnan 1995; Battaini et al. 1998a). The main objective of this study is to apply the fuzzy logic controller to the benchmark building defined in the problem definition paper. The building is excited by cross wind loads obtained from the wind tunnel tests at the University of Sydney.

Fuzzy logic algorithm is adopted in this study and validated through computer simulation. Fuzzy logic controller has been investigated for the active control of civil engineering structures (Casciati et al. 1996; Faravelli and Yao 1996; Subramanian et al. 1996; Ayyub et al. 1997; Battaini et al. 1998b; Naghdy et al. 1998; Al Dawod et al. 1999a,b,c) and the current study builds on previous work in this area.

A fuzzy logic controller is robust and capable of handling any nonlinear behavior of the structure. The main advantages in adopting a fuzzy control algorithm are summarized in Battaini et al. (1998a), namely,

1. The uncertainties of input data are treated in a much easier way by fuzzy control theory than by classical control theory. Fuzzy logic, which is the basis of the fuzzy controller, intrinsically accounts for such uncertainties. The implementation of fuzzy controllers makes use of linguistic synthesis and therefore they are not affected by the selection of a specific mathematical model. As a consequence the resulting fuzzy controller possesses inherent robustness.
2. The whole fuzzy controller can be easily implemented in a fuzzy chip, which guarantees immediate reaction time and autonomous power supply.

The knowledge base identifies the actual variables driving the control process. In the specific benchmark problem developed throughout the paper only two variables must be measured and estimated in order to implement the controller. The advantages of employing an intelligent controller against classical controller and the robustness of the fuzzy controller will be highlighted in this paper. The fuzzy controller will be described and the results presented and analyzed.

Structural Model

The model used in this study is the benchmark building of 76 stories, 306-m tall office tower proposed for the city of Melbourne, Australia (defined in the problem definition paper). The building is slender with a height to width ratio (aspect ratio) of $306/42=7.3$; therefore, it is wind sensitive. The total mass of the

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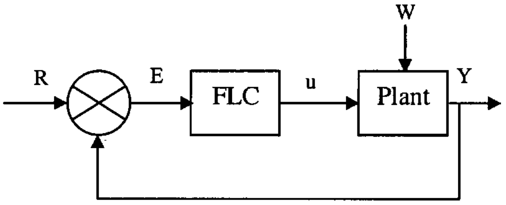

Fig. 1. Fuzzy logic control system

building, including heavy machinery in the plant rooms, is 153,000 t. The 76 story tall building is modeled as a vertical cantilever beam. The first five natural frequencies are 0.16, 0.765, 1.992, 3.790, and 6.395 Hz, respectively. Damping ratios for the first five modes are assumed to be 1% of critical for the proportional damping matrix. Through a model reduction process, the final model possesses only 23 degrees of freedom for the uncontrolled system. A tuned mass damper (TMD) with an inertial mass of 500 t is installed on the top floor. The damper natural frequency is tuned to 0.16 Hz and its damping ratio is set at 20% of critical.

For more details, including performance criteria, refer to the benchmark problem definition paper.

Fuzzy Logic Controller

Fuzzy logic, introduced by Zadeh (1965), enables the use of linguistic directions as a basis for control. Generally very robust and capable of handling nonlinear systems, fuzzy logic controllers (FLCs) usually require expert knowledge in their construction.

A FLC is incorporated into a closed-loop control system similar to conventional controllers as shown in Fig. 1, where, R is the reference input; E the input signal (error); u the output control force; W is the wind excitation, and Y the response after control. The most widely used fuzzy control inference M is the "if-then" rule, which can be written as follows when two input data are used in their antecedent parts (Wang 1994)

M^i: if $X_1 = A_i$ and $X_2 = B_i$ then $Y = C_i$

where i = number of control rules; X_1 and X_2 = variables of the antecedent parts; Y = variable of the sequent part; and A_i, B_i, and C_i = fuzzy variables. The basic structure of a typical FLC is illustrated in Fig. 2. Various components of this controller are defined as follows:

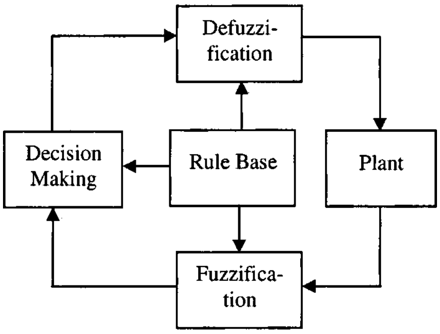

Fig. 2. Basic structure of fuzzy logic controller

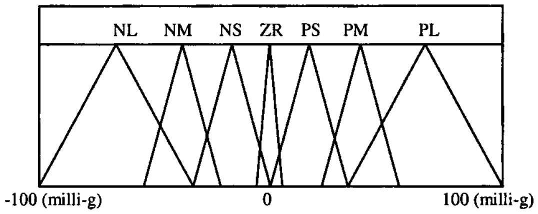

Fig. 3. Membership function for acceleration at L50 and L76

Fuzzification

This unit maps the measured inputs, which may be in the form of crisp values, into fuzzy linguistic values using fuzzy reasoning mechanism.

Rule Base

This is a collection of the expert control rules (knowledge) needed to achieve the control goal.

Decision Making

This unit is the fuzzy reasoning mechanism, which performs various fuzzy logic operations to infer the control action for a given fuzzy input.

Defuzzification

The inferred fuzzy control action is converted into required crisp control value in this unit.

In this paper, the preliminary design of the controller will couple the Larsen's maximum product rule (Yan et al. 1994), to combine the membership values for each rule, with the center of gravity defuzzification scheme, to obtain the output crisp value.

Fuzzy Controller Design

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.

The controller is designed using two input variables, each one having seven membership functions, and one output variable with 11 membership functions. The membership functions chosen for the input and output variables are triangular shaped as illustrated in Figs. 3 and 4, respectively. The fuzzy variables used to define

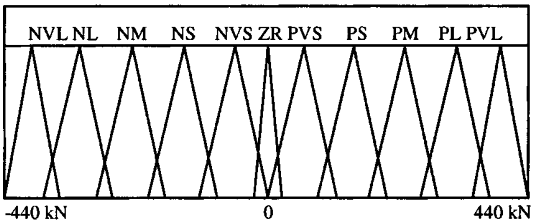

Fig. 4. Membership function for control force

Table 1. Fuzzy Variables

Variable	Definition
PVL	Positive and very large
PL	Positive and large
PM	Positive and medium
PS	Positive and small
PVS	Positive and very small
ZR	Zero
NVS	Negative and very small
NS	Negative and small
NM	Negative and medium
NL	Negative and large
NVL	Negative and very large

Table 2. Fuzzy Associative Memory of Fuzzy Controller

Acceleration of 76th floor	Acceleration of 50th floor						
u	NL	NM	NS	ZR	PS	PM	PL
NL	PVL	PVL	PL	PVS	ZR	ZR	ZR
NM	PL	PL	PM	PVS	ZR	ZR	ZR
NS	ZR	NVS	PM	PS	PVS	ZR	ZR
ZR	ZR	ZR	NVS	ZR	PVS	ZR	ZR
PS	ZR	ZR	NVS	NS	NM	PVS	ZR
PM	ZR	ZR	ZR	NVS	NM	NL	NL
PL	ZR	ZR	ZR	NVS	NL	NVL	NVL

Note: Definitions given in Table 1.

the fuzzy space are described in Table 1. The self-organizing fuzzy logic controller is used to find the final fuzzy associative memory as shown in Table 2.

The writers suggest using the acceleration of floors 50 and 76 as feedback variables for the fuzzy controller design because the response of the building is larger in the top floors compared to lower ones. The aim of using two input variables for the fuzzy controller is to show the performance of the fuzzy approach in the control problem. The small number of feedback variables means the use of fewer sensors; thus a simplification of the control system with advantages in terms of reliability and costs.

The control schemes provided in the benchmark study is used in the simulation and a deterministic context has been selected. The fuzzy controller is implemented into the *SIMULINK* program (see Fig. 5) using an integration time step of 0.001 s and the control signal is computed every 0.001 s.

Control Performance

The performance of the fuzzy controller is checked according to the evaluation criteria specified for the benchmark building (J_1–J_{12}), in the problem definition paper. Table 3 shows the results of peak and root mean square (RMS) uncontrolled and the passively controlled response (TMD) of the benchmark building. Tables 4, 5, and 6 show the results of the simulation using the fuzzy and linear quadratic Gaussian (LQG) controllers in terms of peak displacement and acceleration for the three cases of nominal building, the building with 15% higher stiffness, and the building with 15% lower stiffness, respectively. Tables 7, 8, and 9 show the results of the simulation using the fuzzy and LQG controllers in terms of RMS displacement and acceleration for the same cases, respectively.

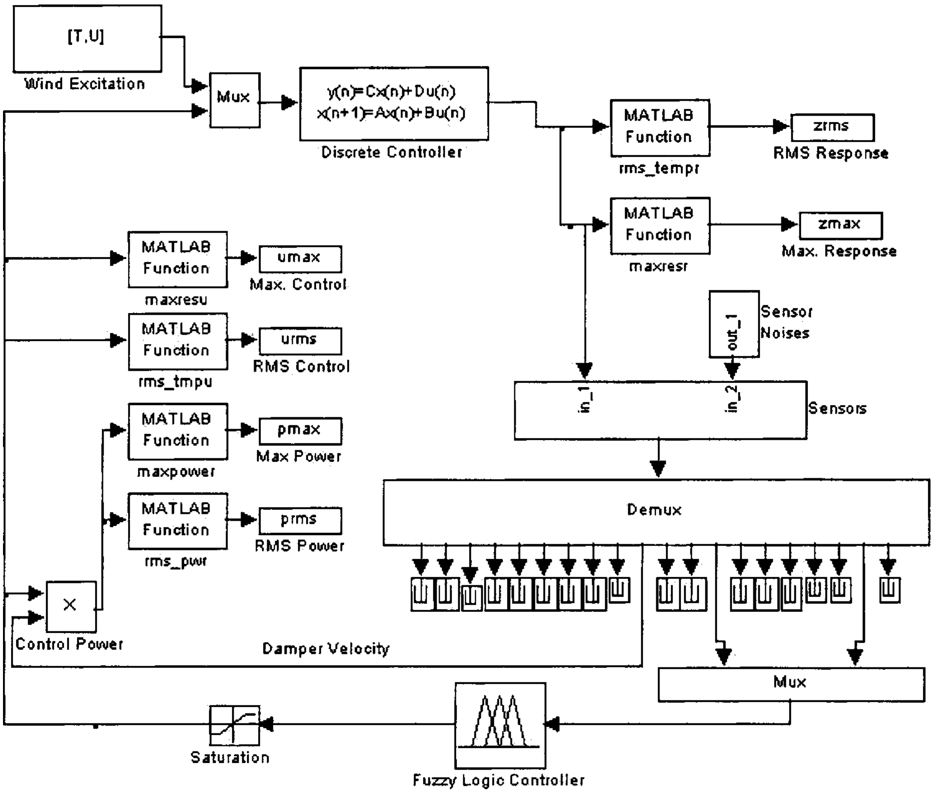

Fig. 5. *SIMULINK* model of building with fuzzy controller

Table 3. Root Mean Square (RMS) and Peak Response of 76-Story Building [No Control and Tuned Mass Damper (TMD)]

	RMS response no control		RMS response TMD		Peak response no control		Peak response TMD	
Floor no.	Displacement (mm)	Acceleration (m*g*)	Displacement (mm)	Acceleration (m*g*)	Displacement (mm)	Acceleration (m*g*)	Displacement (mm)	Acceleration (m*g*)
1	0.2	0.1	0.1	0.1	0.5	0.2	0.4	0.2
30	21.5	2.0	14.8	1.2	68.4	7.1	56.0	4.7
50	52.2	4.8	35.7	2.8	165.9	15.0	133.4	9.3
55	61.1	5.6	41.7	3.3	194.1	17.5	155.4	10.7
60	70.2	6.4	47.9	3.7	223.4	20.0	178.0	12.7
65	79.7	7.3	54.3	4.3	253.5	22.6	201.0	14.7
70	89.2	8.2	60.8	4.8	284.1	26.0	224.3	16.8
75	99.2	9.1	67.5	5.4	315.9	30.3	248.4	19.8
76	101.4	9.4	69.0	5.5	323.0	31.2	253.8	20.5
md	—	—	127.6	13.9	—	—	426.0	46.2

Table 4. Peak Response of 76-Story Nominal Benchmark Building Using Fuzzy and Linear Quadratic Gaussian (LQG) Controllers

	Fuzzy controller, peak control force=113.9 kN		LQG controller, peak control force=118.2 kN	
Floor no.	Displacement (mm)	Acceleration (m*g*)	Displacement (mm)	Acceleration (m*g*)
1	0.4	0.2	0.4	0.2
30	50.7	3.5	51.4	3.4
50	120.4	6.6	122.2	6.7
55	140.1	8.0	142.2	8.1
60	160.3	9.0	162.7	8.9
65	180.9	10.0	183.7	10.1
70	201.7	10.3	204.8	10.7
75	223.1	11.0	226.7	11.6
76	227.9	15.4	231.6	15.9
md	726.3	72.1	742.9	72.7

Table 5. Peak Response of 76-Story Building (with +15%) Stiffness Using Fuzzy and Linear Quadratic Gaussian (LQG) Controllers

	Fuzzy controller, peak control force=110.9 kN		LQG controller, peak control force=105.6 kN	
Floor no.	Displacement (mm)	Acceleration (m*g*)	Displacement (mm)	Acceleration (m*g*)
1	0.3	0.2	0.3	0.2
30	43.7	3.4	43.5	3.4
50	103.9	6.3	103.5	6.6
55	121.0	7.8	120.4	8.0
60	138.5	8.7	137.8	9.1
65	156.3	10.0	155.5	10.1
70	174.3	10.6	173.4	11.6
75	192.9	11.3	191.8	12.5
76	197.1	16.1	196.0	15.9
md	606.6	70.6	598.3	60.9

Table 6. Peak Response of 76-Story Building (with −15%) Stiffness Using Fuzzy and Linear Quadratic Gaussian (LQG) Controllers

	Fuzzy controller, peak control force=135.7 kN		LQG controller, peak control force=164.3 kN	
Floor no.	Displacement (mm)	Acceleration (m*g*)	Displacement (mm)	Acceleration (m*g*)
1	0.4	0.2	0.4	0.2
30	55.5	3.7	55.4	3.6
50	131.6	7.5	131.2	7.9
55	153.0	9.5	152.7	9.9
60	175.0	10.8	174.7	11.1
65	197.4	12.3	197.1	12.6
70	220.1	13.5	220.0	14.0
75	243.6	12.9	243.4	14.8
76	248.9	20.1	248.7	18.8
md	841.7	80.8	916.0	79.1

Table 7. Root Mean Square (RMS) Response of 76-Story Nominal Benchmark Building Using Fuzzy and Linear Quadratic Gaussian (LQG) Controllers

	Fuzzy controller, RMS control force=37.2 kN		LQG controller, RMS control force=34.1 kN	
Floor no.	Displacement (mm)	Acceleration (m*g*)	Displacement (mm)	Acceleration (m*g*)
1	0.1	0.1	0.1	0.1
30	12.1	0.9	12.6	0.9
50	29.2	1.9	30.4	2.0
55	34.1	2.2	35.5	2.4
60	39.1	2.6	40.8	2.8
65	44.3	2.9	46.2	3.2
70	49.5	3.1	51.7	3.4
75	55.0	2.9	57.4	3.3
76	56.2	4.6	58.6	4.7
md	244.3	24.7	233.0	22.4

As observed from the results in Tables 4–9, the performance of the fuzzy controller is similar and in some cases better than the LQG controller. These tables also show that both controllers perform better when stiffness is increased by 15% but their performance is not as good when stiffness is decreased by 15%. Table 10 shows the comparison of the performance indices $J_1 - J_{12}$ including the actuator actions between the fuzzy and the LQG controllers.

The results of the simulation show that the fuzzy controller can satisfy the design requirements of the benchmark problem. The constraints on the actuator requirements (RMS control force$\leqslant$100 kN, RMS actuator stroke$\leqslant$300 mm, peak control

Table 8. Root Mean Square (RMS) Response of 76-Story Building (with +15%) Stiffness Using Fuzzy and Linear Quadratic Gaussian (LQG) Controllers

	Fuzzy controller, RMS control force=45.9 kN		LQG controller, RMS control force=28.3 kN	
Floor no.	Displacement (mm)	Acceleration (mg)	Displacement (mm)	Acceleration (mg)
1	0.1	0.1	0.1	0.1
30	10.2	0.9	10.7	0.9
50	24.5	1.8	25.7	2.0
55	28.6	2.1	30.0	2.4
60	32.9	2.5	34.4	2.7
65	37.2	2.8	39.0	3.1
70	41.6	2.9	43.6	3.3
75	46.2	2.8	48.3	3.3
76	47.2	4.5	49.4	4.5
md	210.0	23.3	183.7	19.2

Table 9. Root Mean Square (RMS) Response of 76-Story Building (with −15%) Stiffness Using Fuzzy and Linear Quadratic Gaussian (LQG) Controllers

	Fuzzy controller, RMS control force=39.7 kN		LQG controller, RMS control force=44.3 kN	
Floor no.	Displacement (mm)	Acceleration (mg)	Displacement (mm)	Acceleration (mg)
1	0.1	0.1	0.1	0.1
30	15.0	1.0	15.5	1.0
50	36.2	2.0	37.3	2.1
55	42.3	2.4	43.6	2.6
60	48.6	2.8	50.1	3.0
65	55.0	3.2	56.8	3.3
70	61.6	3.3	63.5	3.5
75	68.4	3.1	70.5	3.4
76	69.9	5.0	72.1	5.1
md	264.3	24.3	274.7	24.3

force$\leq$300 kN, and peak actuator stroke$\leq$950 mm), are all satisfied for all cases using the fuzzy controller. Also, the maximum allowable floor acceleration of 15 milli-g (or a RMS value of 5 milli-g) is satisfied. In comparison with the closed-loop response of the nominal structure, the displacement response, actuator stroke, active control force, and control power for the +15% building with fuzzy controller reduce by 16, 14.1, 3.4, and 12.7%, respectively. On the other hand, for the LQG controller the corresponding reductions are 15.7, 20.2, 17.0, and 29.4%, respectively. For the −15% building with fuzzy controller, the displacement response, actuator storke, active control force, and control power increase by 24.4, 8.1, 6.8, and 5.9%, respectively, and increase by 23, 19.3, 30.1, and 38.5%, respectively, when using the LQG controller. The big advantage of using fuzzy controller over the LQG controller is the power consumption as witnessed by much smaller J_6 index. In this study the RMS of control power for fuzzy controller is less than half of that for the LQG controller and is almost constant for all three cases with varying stiffness. This is not, however, the case for the LQG controller and the RMS of control power varies in the range of 20–40 kN m.

Another aspect of the fuzzy controller robustness is the ability to control the system with different time steps (for both integration and computation of control signal). Table 11 shows the performance of the fuzzy controller when the time step changes from 0.001 to 0.01 s, with almost identical results. However, the LQG controller becomes unstable when the time step changes from the 0.001 to 0.01 s. Therefore, the fuzzy controller has more flexibility and robustness not only under system uncertainty but also computationally with respect to varying sample time. Furthermore, in the implementation of the fuzzy controller, only two sensors are used, compared to three sensors used by LQG controller, and this made the system simpler with advantages in terms of reliability and cost.

In this comparison, the fuzzy controller performance is fairly similar to the LQG controller in terms of the building response, the active control force required, and the stroke of the actuator,

Table 10. Evaluation Criteria Comparison: Fuzzy Controller versus Linear Quadratic Gaussian (LQG) Controller

	Fuzzy controller			LQG controller		
Evaluation criteria	+0% stiffness	+15% stiffness	−15% stiffness	+0% stiffness	+15% stiffness	−15% stiffness
J_1	0.334	0.322	0.366	0.369	0.365	0.388
J_2	0.380	0.365	0.414	0.417	0.409	0.438
J_3	0.554	0.465	0.689	0.578	0.487	0.711
J_4	0.556	0.467	0.691	0.580	0.489	0.713
J_5	2.410	2.072	2.608	2.272	1.812	2.710
J_6	13.853	12.086	14.666	29.38	20.74	40.69
J_7	0.363	0.372	0.444	0.381	0.411	0.488
J_8	0.426	0.421	0.512	0.432	0.443	0.539
J_9	0.706	0.610	0.770	0.717	0.607	0.770
J_{10}	0.714	0.617	0.780	0.725	0.614	0.779
J_{11}	2.249	1.878	2.606	2.300	1.852	2.836
J_{12}	65.198	64.892	91.318	71.96	52.69	118.33
Root mean square control force (kN)	37.18	35.92	39.71	34.07	28.29	44.33
Root mean square actuator stroke (mm)	244.4	210.0	264.3	230.3	183.7	274.7
Root mean square control power (kN m)	13.85	12.09	14.67	29.38	20.74	40.69
Peak control force (kN)	113.88	110.9	135.71	118.24	105.58	164.33
Peak actuator stroke (mm)	726.3	606.6	841.7	742.9	598.2	916.0
Peak control power (kN m)	65.20	64.89	91.32	71.96	52.69	118.3

Table 11. Evaluation Criteria for Fuzzy Controller with Different Time Steps

Evaluation criteria	Fuzzy controller, Time step = 0.001			Fuzzy controller, Time step = 0.001		
	+0% stiffness	+15% stiffness	−15% stiffness	+0% stiffness	+15% stiffness	−15% stiffness
J_1	0.334	0.322	0.366	0.334	0.322	0.366
J_2	0.380	0.365	0.414	0.379	0.365	0.414
J_3	0.554	0.465	0.689	0.554	0.465	0.689
J_4	0.556	0.467	0.691	0.556	0.467	0.691
J_5	2.410	2.072	2.608	2.411	2.072	2.608
J_6	13.853	12.086	14.666	13.849	12.080	14.661
J_7	0.363	0.372	0.444	0.364	0.371	0.442
J_8	0.426	0.421	0.512	0.425	0.421	0.511
J_9	0.706	0.610	0.770	0.706	0.610	0.770
J_{10}	0.714	0.617	0.780	0.714	0.617	0.780
J_{11}	2.249	1.878	2.606	2.249	1.878	2.606
J_{12}	65.198	64.892	91.318	63.363	63.683	90.672
Root mean square control force (kN)	37.18	35.92	39.71	37.13	35.86	39.66
Root mean square actuator stroke (mm)	244.4	210.0	264.3	244.4	210.0	264.4
Root mean square control power (kN m)	13.85	12.09	14.67	13.84	12.08	14.66
Peak control force (kN)	113.88	110.91	135.71	112.25	107.23	134.39
Peak actuator stroke (mm)	726.3	606.6	841.7	726.3	606.5	841.8
Peak control power (kN m)	65.20	64.89	91.32	63.36	63.68	90.67

but is much better with respect to the number of sensors required for the system and the required control power. These results show that the adopted fuzzy controller has great potential for active structural control.

Stability of Fuzzy Controller

Often the designers are concerned about the stability of the fuzzy controller system because the fuzzy controller does not have a mathematical model to be used to check its stability. Up to now there has been no general solution to this problem, but there is a number of stability analysis criteria proposed in the literature, (Yan et al. 1994). One of the proposed methods to ensure stability is the phase plane trajectory, which is a technique to reflect graphically the dynamic properties of a control system in a phase plane.

The control stability can be checked through the ability of the controlled system to return to rest conditions following oscillations caused by an external disturbance. In practice one runs the dynamic simulation, selects the state variable that seems to show the most severe response, and then runs the controlled system using the extreme values of the selected state variables. The test consists of checking the ability of the controller to reduce the response and to drive the system to the rest condition after the initial transient phase (Casciati 1997). The stability tests are performed considering the system with particular initial conditions on the state vector x and checking the ability of the controller to reach equilibrium after the initial transient phase. Figs. 6–8 show the stability tests of the fuzzy controller in terms of the control force, control power, and the acceleration response, respectively. These figures show the ability of the fuzzy controller to drive the system to the rest position after an initial excitation (free vibration) and converge to zero, which means the system is stable.

Conclusions

In this paper, the studies on the benchmark building defined in the problem definition paper, regarding the vibration control of the building under cross wind excitation, was reported. The fuzzy logic controller for structural control application was adopted to drive the ATMD to control the system. The advantages of employing an intelligent controller against classical controller have been highlighted.

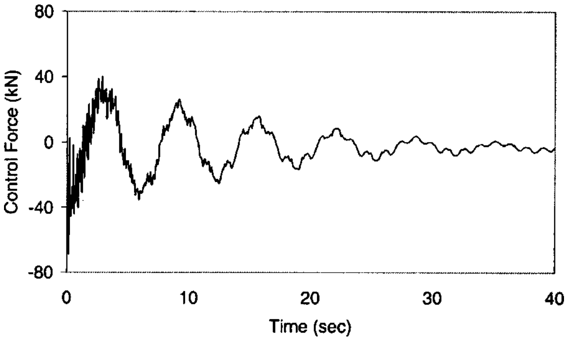

Fig. 6. Fuzzy controller stability test in terms of control force

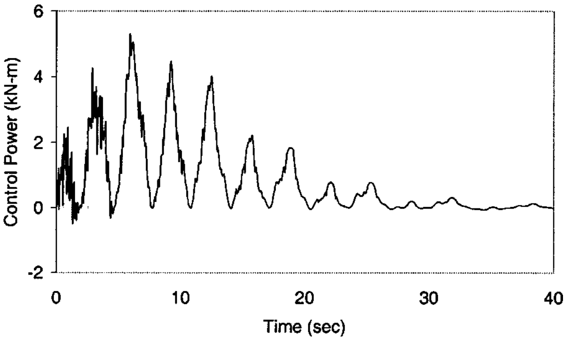

Fig. 7. Fuzzy controller stability test in terms of control power

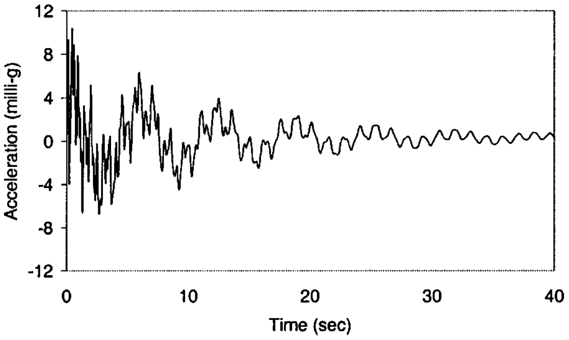

Fig. 8. Fuzzy controller stability test in terms of acceleration response

The results show that, the fuzzy controller performs fairly similarly to the LQG controller in terms of the building response, the active control force required, and the stroke of the actuator, but performs much better in terms of required control power and also requires fewer number of sensors for the system. These results show that the adopted fuzzy controller has great potential in active structural control.

In the next stage of the work, the adopted fuzzy logic controller will be tested experimentally by using a shake table and the benchmark model of 5 stories at the Univ. of Technology, Sydney (Samali 1999).

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