1999 IEEE International Fuzzy Systems Conference Proceedings
August 22-25, 1999, Seoul, Korea

Active Control of Wind Excited Structures Using Fuzzy Logic

M. Aldawod[1], F. Naghdy[2], B. Samali[1], and K. C. S. Kwok[3]

1. Centre for Built Infrastructure Research
Faculty of Engineering, University of Technology Sydney, NSW, 2007, Australia
(Email: Maldawod@eng.uts.edu.au)

2. School of Electrical, Computer Engineering, & Telecommunication Engineering, University of Wollongong, NSW, 2500, Australia

3. Department of Civil Engineering, University of Sydney, NSW, 2006, Australia

Abstract

The first stage in the development of a fuzzy controller for active control of vibration in a wind excited tall structure is reported. The initial rule base of the fuzzy controller is developed based on the input/output data obtained from the performance of the system under a state feedback controller. The performance of the developed controller is validated through computer simulation. The controller is applied to both the building model from which the rule base is extracted and another building with similar dynamics but different parameters. The developed controller has significantly outperformed a state feedback controller and a previously developed intuitive fuzzy controller in terms of the maximum required control force. The amplitude of the steady state oscillation produced by the state feedback controller has, however, proved to be marginally better than the other two controllers. In the next stage of the work, the rule base will be enhanced by including the rules obtained by observing the behavior of the system including qualitative characteristics of the building and other dynamics, which cannot be mathematically expressed.

1. Introduction

Environmental loads in tall structures, such as wind and earthquake can cause human discomfort or motion sickness and, sometimes-unsafe conditions. Passive, semi-active, and active 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 and a significant progress has been made in this area [1,3,4,6].

A true mathematical model of a tall building is usually non-linear. In addition, such a model does not fully represent the behaviour of the building when subjected to wind or earthquake. Such models particularly do not include disturbances caused by large displacements or material non-linearity and damage. Practically, the system is partly unstructured due to model uncertainties, control system constraints, and dynamic loading.

The main objective of this work is to develop a more effective method of active control of the excited structure using fuzzy logic [2,3]. A general method for combining both the numerical and linguistic information into a common framework- fuzzy rule base is adopted. The experience of human controller is usually expressed as some linguistic "IF-THEN" rules that state in what situation(s) which action(s) should be taken. The sampled input-output pairs are some numerical data that give the specific values of the input data and the corresponding successful output [2].

A new fuzzy control is developed to control the vibration of the building when excited by wind. The result of the simulation of the fuzzy controller is compared against a previously developed intuitive fuzzy controller and a conventional pole-placement controller.

In the first stage of the work, the rule base of the fuzzy controller is developed based on the input/output data obtained from the performance of the system under a state feedback controller. The controller is applied to both the building model from which the rule base is extracted and another building with similar dynamics but different parameters.

The developed controller has significantly outperformed a state feedback controller and a previously developed intuitive fuzzy controller in terms of the maximum required control force. The amplitude of the steady state oscillation produced by the state feedback controller has, however, proved to be marginally better than the other two controllers. In the next stage of the work, the rule base will be enhanced by including the rules obtained by observing the behavior of the system including qualitative characteristics of the building and other dynamics which cannot be mathematically expressed .

The first model used in the development of the fuzzy controller is a building of 76 stories and a height of 306 meters, proposed for the city of Melbourne, Australia. The second model is the structure used by Fertis [5] in his work.

The advantages of employing an intelligent controller against conventional methods will be highlighted in this paper. The designed fuzzy controller will be described and the results presented and analysed.

0-7803-5406-0/99/$10.00 ©1999 IEEE

2. Background

Control of vibration in a tall structure as a result of wind and earthquake has been a popular area of research over the last two decades. A tall structure generally oscillates at its fundamental frequency when excited. The most common method used to dampen such oscillation has been a passive device known as a Tuned Mass Damper (TMD) system [4]. In this process, the TMD system is mainly dependent on its inherent energy absorption capacity to compensate for the excitation. This can place limitations on the ability of the controller to provide adequate control to compensate for a disturbance.

In order to overcome the shortcoming of the TMD systems, active control methods have been developed. Masato [7] has developed a semi-active tune mass damper system by adding an external energy source in the form of an actuator to speed up the movement of TMD and to enhance its effectiveness. The semi-active device has performed more effectively than the passive device to reduce the vibration in an excited building. In practice, however, the required control force is so large that it cannot be generated by an actuator.

Chang [6] has further improved the TMD system by introducing an active control. The actuator employed in the system activates both the TMD system and the tendons to counteract the induced motion in the building by a disturbance. It was demonstrated that the building experiences smaller displacements when controlled by the active system. The required control force in this case is also very large.

In another work, C. Nerves and R. Krishnan [4] investigated the effects of various control strategies on the behaviour of an excited structure. The control strategies applied varied from classical methods such as PID control to modern schemes such as sliding mode, Neural Network and adaptive Fuzzy Control. It was shown that Sliding-Mode control method produced the best performance but the required control signal was much larger than the signal needed by the other methods.

3. Structure Model

Two models have been used in this study to design the controller and validate its performance. The first model is a 76 story, 306-meter tall office tower proposed for the city of Melbourne. The building has a total mass of 153,000 tonnes and its fundamental frequency is calculated to be 0.16 Hz (1rad/sec). A sliding type active tuned mass damper configuration is proposed for the building as illustrated in Figure 1.

This ATMD system is essentially intended to suppress the wind-induced motion in the fundamental sway mode. The parameters of this system are defined as:

m_1 = mass of the building
k_1 = The lateral stiffness of the building
b_1 = The damping constant of the building in the first mode.
m_2 = The mass of TMD
k_2 = The spring constant of TMD
b_2 = The damping constant of TMD
u = The control force
F_w = The wind force
y_1 = The displacement of the building
y_2 = The displacement of TMD

This ATMD structure system has only two-degrees of freedom [5], as the building is modelled as an idealized single degree of freedom system.

The equation of motion of the system is derived by applying the Newton's second law. The state space equation of the building will be derived as [4]:

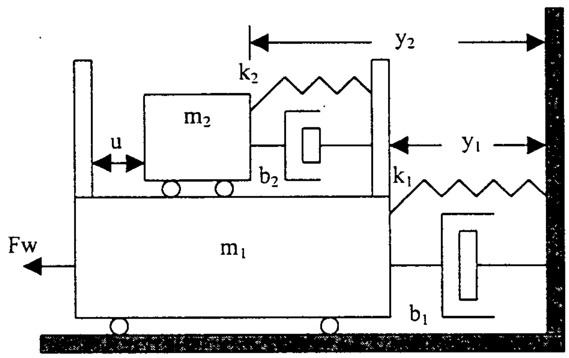

Figure 1 - TMD structure system

$$\dot{x} = Ax + B_1 u + B_2 F_w$$
$$y = Cx + Du$$

$$x = \begin{bmatrix} y_1 \\ z \\ \dot{y}_2 \\ \dot{z} \end{bmatrix}; B_2 = \begin{bmatrix} 0 \\ 0 \\ \frac{1}{m_1} \\ -\frac{1}{m_1} \end{bmatrix}; B_1 = \begin{bmatrix} 0 \\ 0 \\ -\frac{1}{m_1} \\ \frac{1}{m_1+m_2} \end{bmatrix};$$

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ \frac{-k_1}{m_1} & \frac{k_2}{m_1} & \frac{-b_1}{m_1} & \frac{b_2}{m_1} \\ \frac{k_1}{m_1} & -k_2(\frac{1}{m_1}+\frac{1}{m_2}) & \frac{b_1}{m_1} & -b_2(\frac{1}{m_1}+\frac{1}{m_2}) \end{bmatrix};$$

$$C = [1 \quad 0 \quad 0 \quad 0]; \; D = [0]$$

The second model has a similar TMD structure and dynamic model. The system parameters are, however, different. The parameters of both models are illustrated in Table 1.

Table 1 - Parameters of the building and TMD for the two models

Parameter	First Model	Second Model
m_1	$1.53x10^8$ Kg	$1.81x10^7$ Kg
k_1	$1.53x10^8$ N/m	$1.81x10^7$ N/m
b1	$3.06x10^6$ N/m	$3.62x10^5$ N/m
m_2	$3.06x10^6$ Kg	$3.62x10^5$ Kg
k_2	$2.55x10^6$ N/m	$3.01x10^5$ N/m
b_2	$2.01x10^5$ N/m	$0.238x10^5$ N/m

The simulated wind force time history is illustrated in Figure 2. The behavior of the uncontrolled structure system for the first and the second models are shown in Figures 3 and 4 respectively.

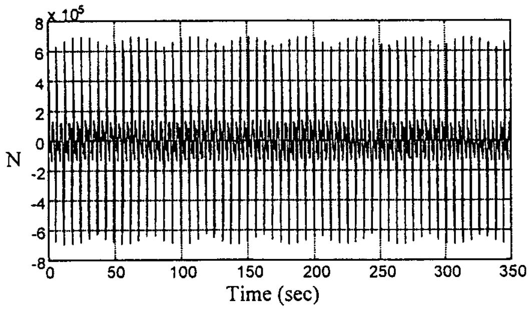

Figure 2 - Simulated wind force

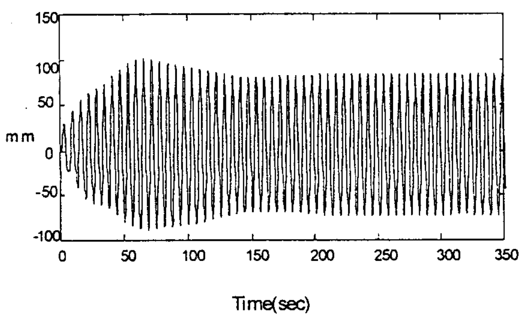

Figure 3 - Displacement of the uncontrolled building (first model)

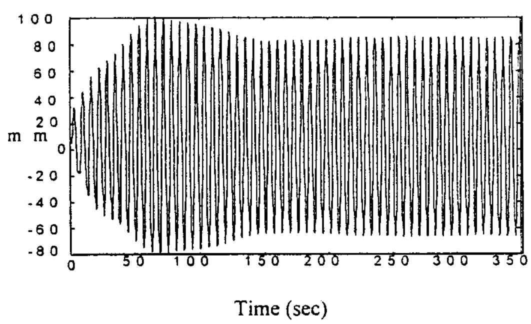

Figure 4 - Displacement of the uncontrolled building (second model)

4. Fuzzy Controller

A fuzzy logic controller is incorporated into closed-loop control system similar to conventional controllers as shown in Figure 5.

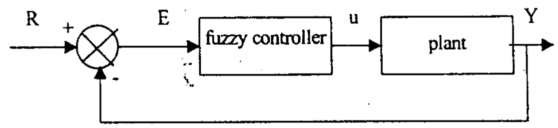

Figure 5 - adaptive fuzzy logic control system

Where, R is the response; E is the input signal; U is the output control force and Y is the response after control.

The fuzzy controller is designed based on both the input/output data and intuitive knowledge about the behavior of the system. At this stage, no input/output data was available from the actual building to be used in the extraction of the rules.

In order to overcome this problem, a state feedback was applied to control the oscillation of the building. The input/output data obtained from the controlled system has been used to build the first stage of the rule base of the system.

The method proposed by Wang and Mendel [2] is employed to extract the fuzzy rules. Let's assume that the following set of desired input-output data pairs are given:

$$(x_1^{(1)}, x_2^{(1)}, y^{(1)}), (x_1^{(2)}, x_2^{(2)}, y^{(2)}), \text{--------} \quad (1)$$

Where x_1 and x_2 are the inputs to the system and y is the output. The task here is to generate a set of fuzzy rules, which can map from input space to the output space. This is achieved through the following five steps:

i. Divide the input/output spaces into fuzzy regions such as small, medium, big. Assign a fuzzy membership function of triangular shape to each region.

ii. Generate fuzzy rules from given data pairs; first, determine the degree of given x_1, x_2, and y in different regions. Second, assign a given x_1, x_2, or y to a region with maximum degree. Finally, obtain a rule for the data pair based on the maximum degrees of membership.

iii. Assign a degree to each rule, as there are usually many data pairs and each one generates one rule. It is highly probable that there will be some conflicting rules, ie, rules that have the same IF part but a different THEN part. One way to resolve this conflict is to assign a degree to each rule generated from data pair, and accept only the rule from a conflict group that has maximum degree. In this way, not only is the conflict problem resolved, but also the number of rules is greatly reduced.

iv. Create a combined fuzzy rule base. The fuzzy rule base consists of the number of boxes that equal to the result of multiplying the number of membership functions of each input. The rule-base boxes are filled with fuzzy rules according to the following strategy: a combined fuzzy rule base is the assigned rules from either those generated from numerical data or linguistic rules (it is assumed that a linguistic rule also has a degree that is assigned by human expert and reflects the expert's belief of the importance of the rule). If there is more than one rule in one box of fuzzy rule base, use the rule that has maximum degree. In this way both numerical and linguistic information are codified into a common framework - the combined fuzzy rule base.

v. Determine a mapping based on the combined fuzzy rule base.

As illustrated above, this method is simple and straightforward in the sense that it is a one-pass building procedure and does not require time-consuming training.

In the fuzzy vibration control, the input of the system is chosen to be the building displacement (x) and the velocity of the building $(\dot{x})$. The output is the required control force (u). The membership functions are chosen to be triangular shaped as illustrated in Figures 6 - 8.

The fuzzy variables used to define the fuzzy space are ZR (Zero), PS (Positive and Small), PM (Positive and Medium), PL (Positive and Large), NS (Negative and Small), NM (Negative and Medium), and NL (Negative and Large).

In this work, 1271 pairs of input/output data, obtained from the system with a state feedback, have been used to generate the rule base. Since there are 7 fuzzy variables, the maximum number of rules required will be 7 x 7 or 49. In the first stage of the design of the rule base, 1271 rules have been generated. The reduction of the rules have been achieved by grouping the rules with the same IF part and accepting only the rules with a maximum membership value. The Fuzzy Associative Memory (FAM) illustrating the rules derived from the input/output pairs is illustrated in Figure 9.

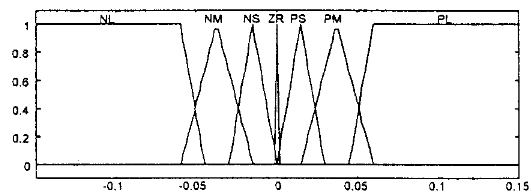

Figure 6 - Membership functions for displacement

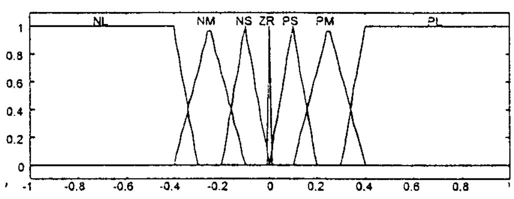

Figure 7 - Membership functions for velocity

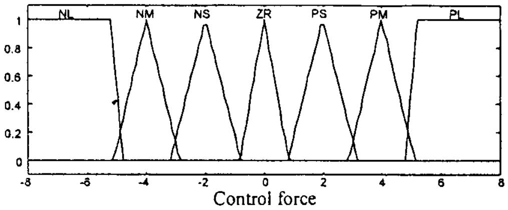

Figure 8 - Membership functions for control force

5 – Results

The behavior of the control system using the developed fuzzy controller is shown in Figures 10 and 11 in terms of the building displacement and the control force.

In order to check the robustness of the controller, which has been developed based on the first model, it is applied to the second model. The performance of the controller for the second model is illustrated in Figures 12, and 13.

For comparison, the behavior of the system for the first model under the state-feedback controller is illustrated in Figures 14 and 15. In order to realize the effectiveness of the developed controller, the behavior of the first model under the intuitive fuzzy controller, reported previously [2], is also illustrated in Figures 16 and 17.

The parameters of the three controllers are compared in Table 2 in terms of the amplitude of the steady state oscillation and the maximum control force required in the controller. According to these results, the performance of the proposed fuzzy controller in terms of building displacement is better than the intuitive fuzzy controller, but worse than the state feedback controller.

The table however, shows that the maximum control force required in the proposed fuzzy controller is significantly lower than the other two controllers. This is a very important outcome as the large magnitude of the required control force usually prevents the implementation of active controllers.

For the second model, the fuzzy controller developed based on the first model is used. The comparison carried out in Table 3 illustrates that the performance of the proposed fuzzy controller is superior to the other two controllers. Hence the developed rule base is robust to the variation of the parameters of a building. It is, however, required to investigate how this model performs when the building dynamics is significantly changed.

	NL	NM	NS	ZR	PS	PM	PL
NL	PL	PL	PL	PL	PL	PL	PL
NM	ZR	PS	PS	PS	PS	PM	PM
NS	ZR	ZR	PS	ZR	PS	PS	PS
ZR	NS	ZR	ZR	ZR	ZR	ZR	PS
PS	NS	NS	NS	ZR	NS	ZR	ZR
PM	NM	NM	NS	NS	NS	NS	ZR
PL	NL	NL	NL	NL	NL	NL	NL

Figure 9 - FAM of the fuzzy controller

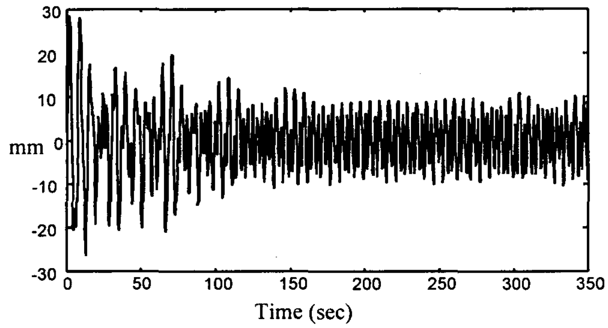

Figure 10 - Building displacement under the fuzzy controller (first model)

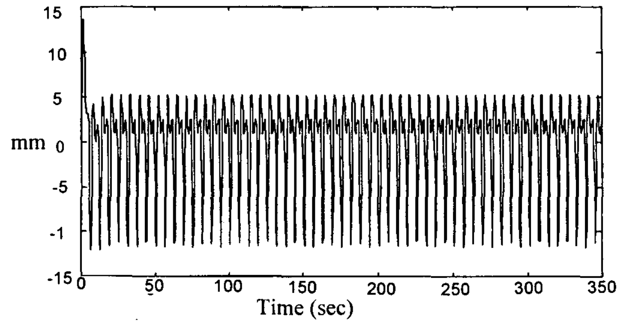

Figure 14 - Building displacement under state-feedback controller (first model)

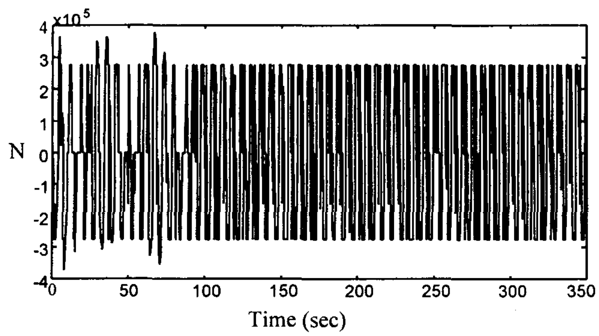

Figure 11 - Control force (N) under the fuzzy controller (first model)

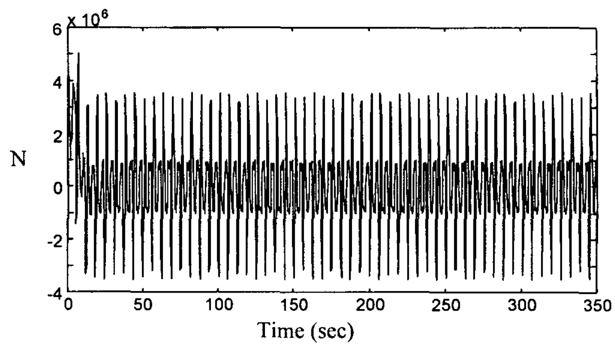

Figure 15 - Control force under state-feedback controller (first model)

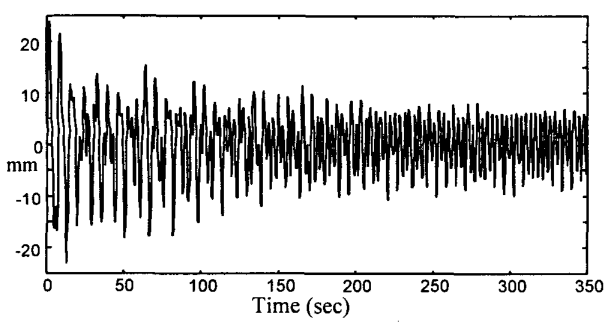

Figure 12 - Building displacement under the fuzzy controller (second model)

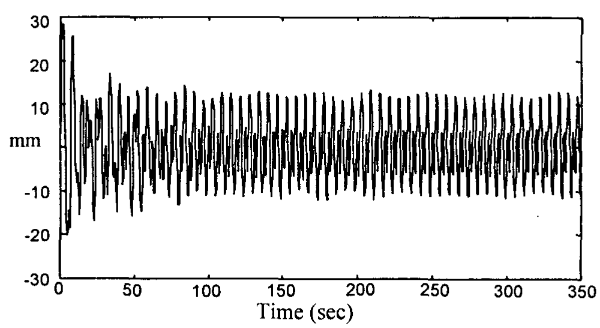

Figure 16 - Building displacement under intuitive fuzzy controller (first model)

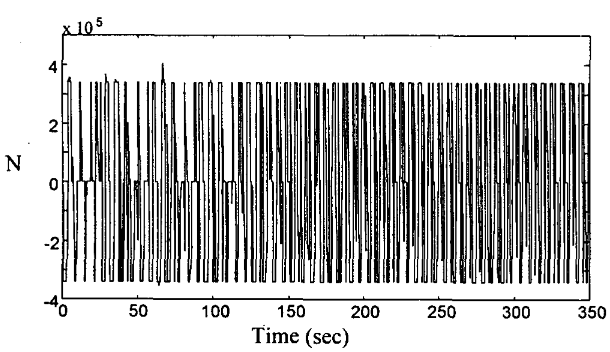

Figure 13 - Control force under the fuzzy controller (second model)

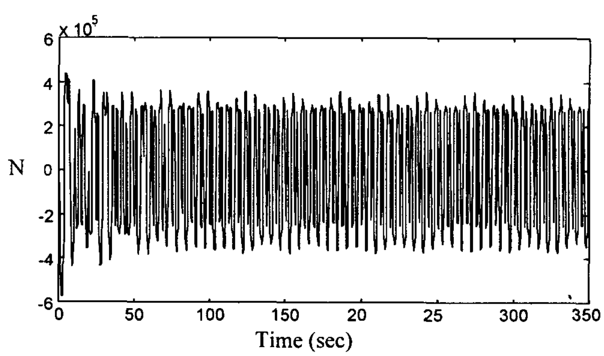

Figure 17 - Control force under intuitive fuzzy controller (first model)

Table 2 - Comparison between different controllers (first model)

Type of Controller	Steady State Amplitude of Oscillation (mm)	Maximum control Force (KN)
Fuzzy Controller	8	270
Intuitive Fuzzy Controller	10	400
State-Feedback Controller	5	3500
No Control	90	-------

Table 3 - Comparison between different controllers (second model)

Type of Controller	Steady State Amplitude of Oscillation (mm)	Maximum Control Force (KN)
Fuzzy Controller	6	35
Intuitive Fuzzy Controller	10	60
State-Feedback Controller	5	400
No Control	85	-------

6. Conclusion

In this paper, the first stage in the development of a fuzzy controller for active control of vibration in a wind excited tall structure was reported. The initial rule base of the fuzzy controller was developed based on the input/output data obtained from the performance of the system under a state feedback controller. In the next stage of the work, the rule base will be enhanced by including the rules obtained by observing the behavior of the system including qualitative characteristics of the building and other dynamics, which cannot be mathematically expressed.

The developed model will be also used in an adaptive fuzzy controller which will compensate for variation in the loading and other characteristics of the building such as the number of people occupying it at different times or variation in the ambient temperature.

The behavior of the excited building, controlled by a proposed fuzzy controller was compared with the building behavior under an intuitive fuzzy controller developed previously and a state-feedback controller. The results show that the steady state amplitude of oscillation of the proposed fuzzy controller was less than the amplitude of the fuzzy controller, but more than the amplitude of a state-feedback controller. However, the maximum required control force in the proposed controller was significantly less than the other two controllers. The rule base of the developed fuzzy controller seems to be robust to variation of the parameters of the model. It is necessary to investigate how the developed model will perform when the dynamics of the building is changed.

References

1. C. Nerves and R. Krishnan (1994), "Active Control Of Wind-Induced Vibrations In Tall Building Using Neural Networks", Proc. IECON, IEEE Los Alamitos, CA, USA, 94CH3319-1, Vol. 2, pp. 1292-1297.
2. Li-Xin Wang and J. M. Mendel (1992), "Generating Fuzzy Rules By Learning From Examples", IEEE Transactions on system, Man, and Cybernetics, Vol. 22, No. 6, pp. 1414-1427.
3. F. Naghdy, B. Samali, K. C. S. Kwok, and V. H. Lam (1998), "Intelligent Active Control Of Wind Excited Structures", Proc. of the Fourth International Conference on Motion and Vibration Control, Zurich, Switzerland, pp.1195-1199.
4. C. Nerves and R. Krishnan (1995), "Active Control Strategies for Tall Civil Structures", Proc. IECON, IEEE Los Alamitos, CA, USA, 94CH3319-1,Vol. 2, pp. 962-967.
5. G. Fertis (1973), "Dynamics and Vibration of Structures", Wiley Interscience.
6. H. Chang (1980), "Structural Control Using Active Tuned Mass Dampers", Journal of Engineering Mechanics ASCE, Vol.106, pp. 1091-1098.
7. Abe, and Masato (1996), "Semi-active tuned mass dampers for seismic protection of civil structures", IEEE Earthquake Engineering and Structural Dynamics, Vol. 25, No. 7, pp. 743-749.