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Active control for seismic response reduction using modal-fuzzy approach

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Abstract

An active modal-fuzzy control method using hydraulic actuators is presented for seismic response reduction. In the proposed control system, a new fuzzy controller designed in the modal space produces the desired active control force. This type controller has all advantages of the fuzzy control algorithm and modal approach. Since it is very difficult to select input variables used in fuzzy controller among numerous state variables in the active fuzzy control system, the presented algorithm adopts the modal control algorithm to be able to consider information of all state variables in civil structures that are usually dominated by first few modes. In other words, all information of the whole structure can be considered in the control algorithm evaluated to reduce seismic responses and it can be efficient for civil structures especially. In addition, the presented algorithm is expected to magnify utility and performance caused by efficiency that the fuzzy algorithm can handle complex model more easily. An active modal-fuzzy control scheme is applied together with a Kalman filter and a low-pass filter to be applicable to real civil structures. A Kalman filter is considered to estimate modal states and a low-pass filter was used to eliminate spillover problem. The results of the numerical simulations for a wide amplitude range of loading conditions and for historic earthquake show that the proposed active modal-fuzzy control system can be beneficial in reducing seismic responses of civil structures.

Keywords: Modal-fuzzy control; Fuzzy control; Modal control; Vibration control

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1. Introduction

In the field of civil engineering, many different techniques for actively controlling vibrations of seismically excited structure have been developed and applied to civil structures. Active control system reduces the structural response by using external energy supplied by actuators to impart forces on the structures, generally depending on a sizeable power supply. It is considerably more flexible to reduce the structural responses for a wide variety of loading conditions. Although in the past researches of civil structures were often treated separately, the fields have now been interfaced to combine two or more algorithms for reducing effectively and treating more realistically.

Fuzzy theory has been recently proposed for the active structural control of civil engineering systems. Active vibration control of structural systems using fuzzy set theory has been widely investigated in the past years (Zadeh, 1965; Mamdani, 1974; Brown and Yao, 1983; Juang and Elton, 1986; Battaini et al., 1998; Teng et al., 2000; Wang and Lee, 2002). The fuzzy set theory was introduced by Zadeh (1965). Mamdani (1974), by applying Zadeh's theories of linguistic approach and fuzzy inference, successfully used the 'IF–THEN' rule on the automatic operating control of steam generator. In civil engineering, the fuzzy set theory was applied by Brown and Yao (1983), Juang and Elton (1986), Battaini et al. (1998), Teng et al. (2000) and Wang and Lee (2002). Since especially buildings in civil engineering are getting so higher and bridges are getting so longer that those structures are very complex systems of multi-degree of freedom, it is very difficult to find an exact mathematical model to describe the behavior of the structures. Because the fuzzy controller does not rely on the analysis and synthesis of the mathematical model of the process, the uncertainties of input data from the external loads and structural responses sensors are treated in a much easier way by the fuzzy controller than by classical control theory. Moreover, it offers a simple and robust structure for the specification of nonlinear control laws that can accommodate uncertainty and imprecision (Subramanian et al., 1996).

Modal control algorithm represents one control class in which the vibration behavior is reshaped by merely controlling some selected vibration modes. Modal control approach has been demonstrated to have advantages over the design in physical space, in that it demands far less computer storage, reduces the computational effort significantly, and allows a larger choice of control algorithms, including nonlinear control. Moreover, because civil structures has hundred or even thousand degrees of freedom and its vibration is usually dominated by first few modes, modal control algorithm is especially desirable for reducing vibration of civil engineering structure. In other words, all information of the whole structure can be considered in the control algorithm evaluated to reduce seismic responses and it can be efficient for especially civil structures.

However, it is impossible to measure all state responses to apply modal controller for real civil structure having hundred or even thousand degrees of freedom. Moreover, since real sensors may not estimate full modal states directly or the system may be expensive to prepare the sensors for full states, an observer for modal state estimation should be provided. Therefore, modal control scheme that uses modal state estimation is desirable. To estimate the full controlled modal states from the sensor outputs, a Luenberger observer (Meirovitch, 1990; Luenberger, 1971) and a Kalman–Bucy filter can be considered. Luenberger observers are to be used for low noise-to-signal ratios and Kalman–Bucy filters for high noise-to-signal ratios. In this paper, a Kalman–Bucy filter is used as an observer. The control system designed cannot lose stability due to control spillover from the modes controlled to those uncontrolled by using the modal control approach. However, that a small amount of damping inherent in the structure is often sufficient to overcome the observation spillover effect (Meirovitch and Baruh, 1983).

In this work reported here, a new fuzzy control approach designed in the modal space is presented. The design of the fuzzy controller began to select the response quantities to be used as inputs to the fuzzy controller and then what control functions are needed is defined as output variable. However, for civil structures having hundred or even thousand degrees of freedom, it is very difficult to select input variables used in fuzzy controller among numerous state variables. This can be just selected by expert's experience. If the modal approach having all information of the whole structure is used to fuzzy controller, it may be very possible for general civil structures usually dominated by just first few modes. In other words, the proposed modal-fuzzy algorithm is very easy to select fuzzy input variables by means of just first few modal coordinates and is also able to consider information of all degree of freedoms to design control system. The proposed method maintains robustness of fuzzy controller and serviceability of modal approach, simultaneously. In the case of combination of fuzzy and modal approach, an active modal-fuzzy control algorithm proposed can be magnified efficiency caused by belonging their' own advantages simultaneously.

2. Active modal-fuzzy control strategy

2.1. Modal control system

Consider a seismically excited structure controller with m control devices. Assuming that the forces provided by the control devices are adequate to keep the response of the primary structure from exiting the linear region, the equations of motion can be written as

$$\boldsymbol{M}\ddot{\boldsymbol{x}}(t) + \boldsymbol{C}\dot{\boldsymbol{x}}(t) + \boldsymbol{K}\boldsymbol{x}(t) = \boldsymbol{\Gamma}\boldsymbol{f}(t) - \boldsymbol{M}\boldsymbol{\Lambda}\ddot{\boldsymbol{x}}_{\mathrm{g}}, \tag{1}$$

where $\boldsymbol{M}$, $\boldsymbol{C}$, and $\boldsymbol{K}$ are the $(n \times n)$ mass, damping, and stiffness matrices, respectively; $\boldsymbol{x}$ is the n-dimensional vector of the displacements of the floors of the structure relative to the ground; $\boldsymbol{f}$ is the vector of measured control forces generated by m control devices; $\ddot{\boldsymbol{x}}_{\mathrm{g}}$ is ground acceleration; $\boldsymbol{\Gamma}$ is the matrix determined by the placement of control devices in the structure; $\boldsymbol{\Lambda}$ is the column vector of ones. This equation can be written in state-space form as

$$\dot{\boldsymbol{z}} = \boldsymbol{A}\boldsymbol{z} + \boldsymbol{B}\boldsymbol{f} + \boldsymbol{E}\ddot{\boldsymbol{x}}_{\mathrm{g}}, \tag{2a}$$

$$\boldsymbol{y} = \boldsymbol{C}\boldsymbol{z} + \boldsymbol{D}\boldsymbol{f} + \boldsymbol{v}, \tag{2b}$$

where $\boldsymbol{z}$ is a state vector; $\boldsymbol{y}$ is the vector of measured outputs; and $\boldsymbol{v}$ is a measurement noise vector. The next step is to transform Eq. (2) into a set of modal equations. Let us use the expansion theorem and express the solution of Eq. (2) as a linear combination of the right eigenvectors multiplied by time-dependent modal coordinates as follows:

$$\boldsymbol{x}(t) = \sum_{i=1}^{n} \eta_i(t)\phi_i = \boldsymbol{\Phi}\boldsymbol{\eta}(t), \quad i = 1, 2, \ldots, n, \tag{3}$$

where $\eta_i(t)$ $(i = 1, 2, \ldots, n)$ are the modal coordinates; $\boldsymbol{\eta}(t)$ is the corresponding vector; ϕ_i is the ith right eigenvector; $\boldsymbol{\Phi}$ is an right eigenvector set. The eigenvectors are orthogonal and they are assumed to be normalized so as to satisfy the orthonormality relations. The orthonormality relations can be written in the compact form

$$\phi_s^{\mathrm{T}}\boldsymbol{M}\phi_r = \delta_{sr}, \quad \phi_s^{\mathrm{T}}\boldsymbol{K}\phi_r = \omega_r^2\delta_{sr}, \tag{4a}$$

$$\boldsymbol{\Phi}^{\mathrm{T}}\boldsymbol{\Phi} = \boldsymbol{I}, \quad \boldsymbol{\Phi}^{\mathrm{T}}\boldsymbol{A}\boldsymbol{\Phi} = \boldsymbol{\Lambda}, \tag{4b}$$

where $\boldsymbol{\Phi} = [\phi_1 \;\; \phi_2 \;\; \cdots \;\; \phi_n]$ and $\boldsymbol{\Lambda} = \mathrm{diag}\,\lambda_i$ is the diagonal matrix of the eigenvalues. where δ_{sr} is the Kronecker delta and ω_r is the natural frequency.

Inserting Eq. (3) into Eq. (1), multiplying on the left by ϕ_r^{T} and considering Eq. (4), we obtain the modal equation

$$\ddot{\boldsymbol{\eta}}_r + 2\zeta_r\omega_r\dot{\boldsymbol{\eta}}_r + \omega_r^2\boldsymbol{\eta}_r = \phi_r^{\mathrm{T}}\boldsymbol{\Gamma f} - \phi_r^{\mathrm{T}}\boldsymbol{M\Lambda}\ddot{\boldsymbol{x}}_{\mathrm{g}}, \tag{5}$$

where ζ_r are modal damping ratios.

Modal equations that is similar form to Eq. (5) for whole system can be written in the matrix form as

$$\ddot{\boldsymbol{\eta}} + \boldsymbol{\Delta}\dot{\boldsymbol{\eta}} + \boldsymbol{\Omega\eta} = \overline{\boldsymbol{\Gamma}}\boldsymbol{f}(t) - \overline{\boldsymbol{\Lambda}}\ddot{\boldsymbol{x}}_{\mathrm{g}}, \tag{6}$$

where $\boldsymbol{\Delta}$ is the diagonal matrix listing $2\zeta_r\omega_r$; $\boldsymbol{\Omega}$ is the diagonal matrix listing $\omega_1^2, \omega_2^2, \ldots, \omega_n^2$; $\overline{\boldsymbol{\Gamma}} = \boldsymbol{\Phi}^{\mathrm{T}}\boldsymbol{\Gamma}$; and $\overline{\boldsymbol{\Lambda}} = \boldsymbol{\Phi}^{\mathrm{T}}\boldsymbol{M\Lambda}$. This equation can be written in state-space form as

$$\dot{\boldsymbol{w}}(t) = \overline{\boldsymbol{A}}\boldsymbol{w}(t) + \overline{\boldsymbol{B}}\boldsymbol{f}(t) + \overline{\boldsymbol{E}}\ddot{\boldsymbol{x}}_{\mathrm{g}}(t), \tag{7a}$$

$$\boldsymbol{y}(t) = \overline{\boldsymbol{C}}\boldsymbol{w}(t), \tag{7b}$$

where $\boldsymbol{w}(t) = \begin{bmatrix}\eta^{\mathrm{T}} & \dot{\eta}^{\mathrm{T}}\end{bmatrix}^{\mathrm{T}}$ is the modal state vector and

$$\overline{\boldsymbol{A}} = \begin{bmatrix}\mathbf{0} & \boldsymbol{I} \\ -\boldsymbol{\Omega} & -\boldsymbol{\Delta}\end{bmatrix}, \quad \overline{\boldsymbol{B}} = \begin{bmatrix}\mathbf{0} \\ \overline{\boldsymbol{\Gamma}}\end{bmatrix}, \quad \text{and} \quad \overline{\boldsymbol{E}} = \begin{bmatrix}\mathbf{0} \\ -\overline{\boldsymbol{\Lambda}}\end{bmatrix}. \tag{8}$$

For linear feedback control, the control vector is related to the modal state vector according to

$$\boldsymbol{F}(t) = -\boldsymbol{G}\boldsymbol{w}(t), \tag{9}$$

where $\boldsymbol{G}$ is an $m \times 2\infty$ control gain matrix. Determination of infinite-dimensional gain matrices is not possible, so the control of the entire infinity of modes is not feasible, nor is it necessary. Indeed, higher modes have only minimal participation in the motion and especially the motion of civil structure with hundred or even thousand DOFs is usually dominated by first few modes, as they are difficult to excite. Practically in modal control, only a limited number of lower modes are controlled. In view of the above, we propose to control l modes only. The l controller modes can be selected with $l < n$ and the displacement may be partitioned into controller and uncontrolled parts. Retracing the steps leading to Eq. (7), we obtain

$$\dot{\boldsymbol{w}}_{\mathrm{C}}(t) = \overline{\boldsymbol{A}}_{\mathrm{C}}\boldsymbol{w}_{\mathrm{C}}(t) + \overline{\boldsymbol{B}}_{\mathrm{C}}\boldsymbol{f}(t) + \overline{\boldsymbol{E}}_{\mathrm{C}}\ddot{\boldsymbol{x}}_{\mathrm{g}}, \tag{10a}$$

$$\boldsymbol{y}_{\mathrm{C}}(t) = \overline{\boldsymbol{C}}_{\mathrm{C}}\boldsymbol{w}_{\mathrm{C}}(t), \tag{10b}$$

where $\boldsymbol{w}_{\mathrm{C}}$ is a $2l$-dimensional modal state vector by the controller modes and

$$\overline{\boldsymbol{A}}_{\mathrm{C}} = \begin{bmatrix}\mathbf{0} & \boldsymbol{I}_{\mathrm{C}} \\ -\boldsymbol{\Omega}_{\mathrm{C}} & -\boldsymbol{\Delta}_{\mathrm{C}}\end{bmatrix}, \quad \overline{\boldsymbol{B}}_{\mathrm{C}} = \begin{bmatrix}\mathbf{0} \\ \overline{\boldsymbol{\Gamma}}_{\mathrm{C}}\end{bmatrix}, \quad \text{and} \quad \overline{\boldsymbol{E}}_{\mathrm{C}} = \begin{bmatrix}\mathbf{0} \\ -\overline{\boldsymbol{\Lambda}}_{\mathrm{C}}\end{bmatrix}, \tag{11}$$

are $2l \times l$ and $2l \times m$ matrices and $2l \times 1$ vector, respectively. In this case Eq. (9) must be replaced by

$$\boldsymbol{F}(t) = -\boldsymbol{G}_{\mathrm{C}}\boldsymbol{w}_{\mathrm{C}}(t), \tag{12}$$

where $\boldsymbol{G}_{\mathrm{C}}$ is an $m \times 2l$ control gain matrix. Note that, in using the control law given by Eq. (12), the closed-loop modal equations are not independent, so that this procedure represents coupled control (Meirovitch, 1990).

2.2. Fuzzy control system

Fig. 1 shows an algorithm of fuzzy control inference. It consists of three basic parts; fuzzification where continuous input variables are transformed into linguistic variables, fuzzy rule inference that handles rule inference consisting of fuzzy IF–THEN rules, and defuzzification that ensures exact and physically interpretable values for control variables. The design of fuzzy control may include; the definition of input

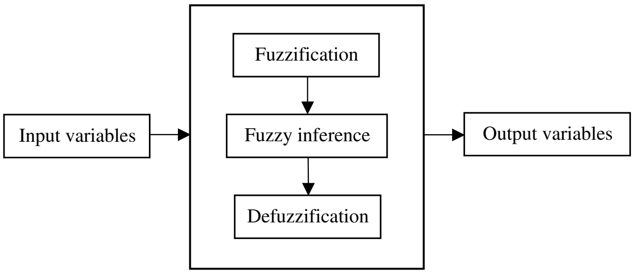

Fig. 1. The algorithm of fuzzy control inference.

and output variables, the selection of data manipulation method, the membership function design and the rule base design. Using fuzzy rules and membership functions, fuzzy control converts linguistic variables into numerical values required in most applications.

The design of the fuzzy controller began to select the response quantities to be used as inputs to the fuzzy controller and the distribution and type of membership functions to be used for the selected input variables. Moreover, we must consider what control functions are needed, and then define them as output variables.

Then, fuzzy inference rule is completely based on the selected input variables. Usually, we use the form 'If (a set of condition to be satisfied) Then (a set of consequences to be inferred)' to describe the expert knowledge. For example, the multiple-input multiple-output IF–THEN rules of the fuzzy control are shown in the form:

$$R^j: \quad \text{If } x_1 \text{ is } A_1^j \text{ and} \cdots \text{and } x_p \text{ is } A_p^j \quad \text{Then } y_1 \text{ is } B_1^j \text{ and} \cdots \text{and } y_m \text{ is } B_m^j, \tag{13}$$

where R^j denotes the jth rule of the fuzzy inference rule, $j = 1, 2, \ldots, q$, $x_1, x_2, \ldots, x_p$ are the inputs of the fuzzy controller, A_i^j is linguistic value with respect to x_i of rule j, $y_1, y_2, \ldots, y_m$ are the outputs of the fuzzy controller and B_i^j is a fuzzy singleton function defined by experts.

Then, the inference conclusion obtained via fuzzification is defuzzified into a crisp output. This paper adopts the center-of-gravity (COG) method among the defuzzification methods. COG method is defined as follows:

$$y_j = \frac{\sum_{l=1}^{N} B_l^j \left[\prod_{i=1}^{p} \mu_{A_i^j}(x_i)\right]}{\sum_{l=1}^{N} \left[\prod_{i=1}^{p} \mu_{A_i^j}(x_i)\right]}, \tag{14}$$

where $\mu_{A_i^j}$ is the membership function of A_i^j.

2.3. Active modal-fuzzy control system

The strategy of the active modal-fuzzy control algorithm for seismic protection is presented in Fig. 2. Though it is difficult to select input variables used in active fuzzy controller among numerous state variables, the proposed active modal-fuzzy algorithm uses only modal coordinates corresponding selected first few modes as input variables and produces the desired control force. It is very effective for civil structures usually dominated by just first few modes. In other words, the proposed algorithm is easy to select fuzzy input variables by means of just first few modal coordinates and is also able to consider information of all degree of freedoms to construct control system. The proposed method has advantages over the design in physical space, in that it demands far less computer storage, reduces the computational effort significantly, and handle more easily. The proposed algorithm has robustness and easiness of fuzzy controller and serviceability of modal approach, simultaneously. In other words, in this case of combination of fuzzy

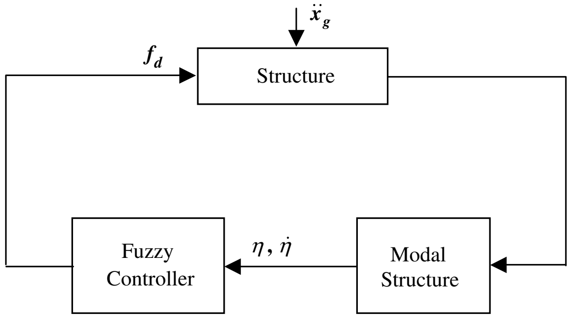

Fig. 2. Control diagram for the active modal-fuzzy control system.

and modal approach, a modal-fuzzy control algorithm proposed can be magnified the efficiency caused by belonging their' own advantages simultaneously.

2.4. Modal state estimation and elimination of observable spillover

An observer for modal state estimation should be provided, since real sensors may not estimate the full modal states directly or the system may be expensive to prepare the sensors for the full states. An active modal-fuzzy control system using full state feedback may not be practical for a structural system involving a large number of DOFs, since the control implementation may requires a large amount of sensors. Therefore, a modal-fuzzy control scheme, which uses modal state estimation, is desirable. Moreover, accurate measurement of displacements and velocities is difficult to achieve directly in full-scale applications, particularly during seismic activity, since the foundation of the structure is moving with ground. Hence, it is ideal to use acceleration feedback because accelerometers can readily provide reliable and inexpensive measurements of accelerations at arbitrary points on the structure (Dyke et al., 1996a,b). In this paper, the acceleration feedback is implemented for the modal state estimation using a Kalman–Bucy filter.

Note that the observer designed normally may cause observer spillover effect. This effect can produce instability in the residual modes. However, a small amount of damping inherent in the structure is often sufficient to overcome the observation spillover effect (Meirovitch and Baruh, 1983). At any rate, observation spillover can be eliminated if the sensor signals are prefiltered so as to screen out the contribution of the uncontrolled modes (Meirovitch, 1990). To improve for eliminating the observable spillover, a low-pass filter is introduced to measure the filtered response. In an active modal-fuzzy system modified like this, the observable spillover does not occur in this controlled system. Hence, the controlled modal states be suppressed by a well-designed control input, and the residual modal states may be also attenuated by their natural damping.

3. Numerical example

To verify the effectiveness of the proposed active modal-fuzzy control systems, a set of numerical simulations is performed. Then, simulation results of the proposed control system are compared to those of an uncontrolled system, optimal control system, active fuzzy control system, and active modal-fuzzy control system using hydraulic actuators.

3.1. Six-story shear building structure

A model of a six-story shear building that is controlled with two hydraulic actuators is performed. This system is a simple model of the scaled, six-story, test structure adopted by Jansen and Dyke (2000). One device is rigidly connected between the ground and the first floor, and the other device is rigidly connected between the first and second floors, as shown in Fig. 3. The governing equations can be written in the form of Eq. (1) by defining the mass of each floor m_i as 0.0227 N/(cm/s^2), the stiffness of each floor k_i as 297 N/cm, and a damping ratio for each mode of 0.5%.

The various control algorithms were evaluated using a set of evaluation criteria based on those used in the second-generation linear control problem for buildings (Dyke et al., 1996a). The first evaluation criterion is a measure of the normalized maximum floor displacement relative to the ground, given as

$$\boldsymbol{J}_1 = \max_{i,j}\left(\frac{|\boldsymbol{x}_i(t)|}{x^{\max}}\right), \tag{15}$$

where $\boldsymbol{x}_i(t)$ is relative displacement of the ith floor over the entire response; and $x^{\max}$ denotes the uncontrolled maximum displacement. The second evaluation criterion is a measure of the reduction in the interstory drift. The maximum of the normalized interstory drift is

$$\boldsymbol{J}_2 = \max_{i,j}\left(\frac{|\boldsymbol{d}_i(t)/h_i|}{d_{\mathrm{n}}^{\max}}\right), \tag{16}$$

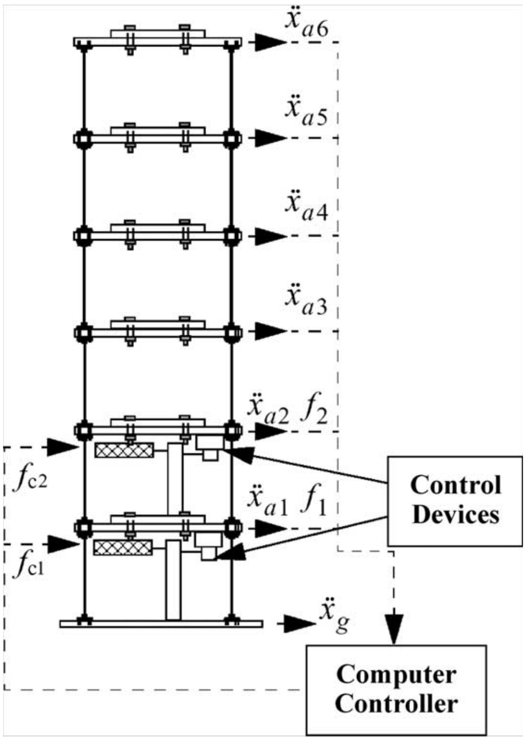

Fig. 3. Schematic diagram of the control devices implementation (Jansen and Dyke, 2000).

where h_i is the height of each floor (30 cm); $\boldsymbol{d}_{\mathrm{i}}(t)$ is the interstory drift of the above ground floors over the response history; and $d_{\mathrm{n}}^{\max}$ denotes the normalized peak interstory drift in the uncontrolled response. The third evaluation criterion is a measure of the normalized peak floor accelerations, given by

$$\boldsymbol{J}_3 = \max_{i,j}\left(\frac{|\ddot{\boldsymbol{x}}_{\mathrm{a}i}(t)|}{\ddot{x}_{\mathrm{a}}^{\max}}\right), \tag{17}$$

where the absolute accelerations of the ith floor $\ddot{\boldsymbol{x}}_{\mathrm{a}i}(t)$ are normalized by the peak uncontrolled floor acceleration, denoted $\ddot{x}_{\mathrm{a}}^{\max}$.

The final evaluation criteria considered in this study is a measure of the maximum control force per device, normalized by the weight of the structure, given by

$$\boldsymbol{J}_4 = \max_{i,j}\left(\frac{|\boldsymbol{f}_i(t)|}{W}\right), \tag{18}$$

where W is the total weight of the structure (1335 N).

The corresponding uncontrolled responses under North–South component of the 10% scaled El Centro earthquake are as follows: $\ddot{x}^{\max} = 1.313$ cm, $d_{\mathrm{n}}^{\max} = 0.00981$ cm, and $\ddot{x}_{\mathrm{a}}^{\max} = 146.95$ cm/s^2.

3.2. Optimal control system design

An optimal control system is performed to compare with proposed algorithm and to use as reference of this simulation. The LQR (linear quadratic regulator) control system with output weighting is very efficient and traditional linear optimal controller. The optimal control approach is to design a linear optimal controller gain vector that calculates a vector of desired control forces $\boldsymbol{f}_{\mathrm{c}} = [f_{\mathrm{c}1}\ f_{\mathrm{c}2}]^{\mathrm{T}}$ based on the measured structural responses and the measured control force vector $\boldsymbol{f}$ applied to the structure.

For the control design, an infinite horizon performance index is chosen

$$\boldsymbol{J} = \lim_{\tau\to\infty}\frac{1}{\tau}\boldsymbol{E}\left[\int_0^{\tau}\{\boldsymbol{y}^{\mathrm{T}}\boldsymbol{Q}\boldsymbol{y} + \boldsymbol{f}_{\mathrm{c}}^{\mathrm{T}}\boldsymbol{R}\boldsymbol{f}_{\mathrm{c}}\}\mathrm{d}t\right]. \tag{19}$$

A wide variety of controllers were evaluated. The best results through many iterations were obtained using $\boldsymbol{R} = \boldsymbol{I}_{2\times2}$ and placing a weighting 9000 (cm^{-2}) on the relative displacements of all floors.

The usual LQR is very efficient classical control algorithm. However, it is difficult to select weighting matrices ($\boldsymbol{Q}$ and $\boldsymbol{R}$) and to design control system. And although it gives good performance, it is not guaranteed robustness.

3.3. Active fuzzy control system design

An active fuzzy control system as another simulation reference is performed. The design issue of the active fuzzy controller began to select the response quantities to be used as input to the fuzzy controller and the distribution and type of membership functions to be used for the selected input variables. However, it is difficult to be selected input variables used in fuzzy controller among numerous state variables (i.e., 6 displacement, 6 velocity, and 6 acceleration variables) in this example. According to selected input variables, control performance can be increased or decreased. This can be just selected by expert's experience. In this case, the controller is designed using two input variables (i.e., they are displacement and velocity of floor that a controller is located), each one having five membership functions, and one output variable (i.e., desired control force) with seven membership functions. The membership functions chosen for the input and output variables are triangular shaped as illustrated in Fig. 4. The definitions of the fuzzy variables of input and output membership function are as follows: NL = negative large, NS = negative small, ZE = zero, PS = positive small and PL = positive large. A reasonable range of input and output values must be

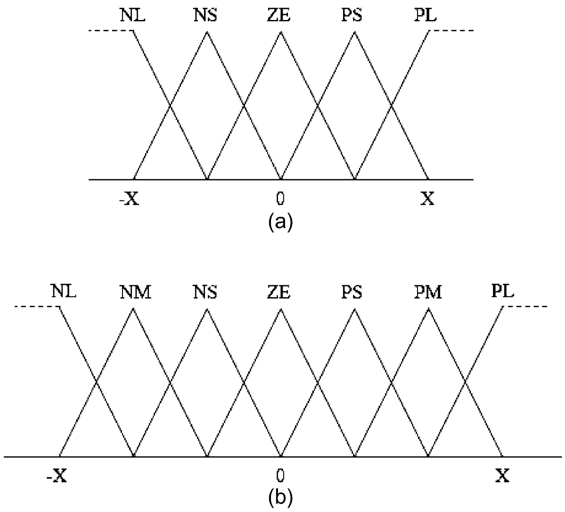

Fig. 4. Input (a) and output (b) membership functions.

selected according to purposed of the controller. However, if the range is too large and too small, the outermost membership functions will rarely and essentially be utilized respectively and thus limit the variability of the control system. The definitions of the fuzzy variables of output membership function are as follows: NL = negative large, NM = negative medium, NS = negative small, ZE = zero, PS = positive small, PM = positive medium and PL = positive large.

Fuzzy inference rule is completely based on the structural displacement and velocity of the floor that a controller is located. The basic concept of inference rule is that if the displacement and velocity are very large, then the output force is large. The fuzzy inference rule is shown in Table 1.

3.4. Active modal-fuzzy control system design

Though the design of the active modal-fuzzy controller began to select the quantities to be used as input to the fuzzy controller, the active modal-fuzzy control system proposed needs not to select input variables among numerous state variables. Since, especially, in civil structure like this example, the lowest one or two modes has information of the whole structure system, it is very possible for fuzzy control system designed with the lowest one or two modes to reduce seismically excited vibration without difficulty.

In six-story shear building structure presented, the uncontrolled responses of the first and sixth floors are shown in Figs. 5 and 6, respectively, in frequency domain. These figures also show that the lowest few modes are dominant in structural motion and especially we can find that the first mode is dominant in

Table 1
Fuzzy inference rule

	NL	**NS**	**ZE**	**PS**	**PL**
NL	PL	PL	PM	PS	ZE
NS	PL	PM	PS	ZE	NS
ZE	PM	PS	ZE	NS	NM
PS	PS	ZE	NS	NM	NL
PL	ZE	NS	NM	NL	NL

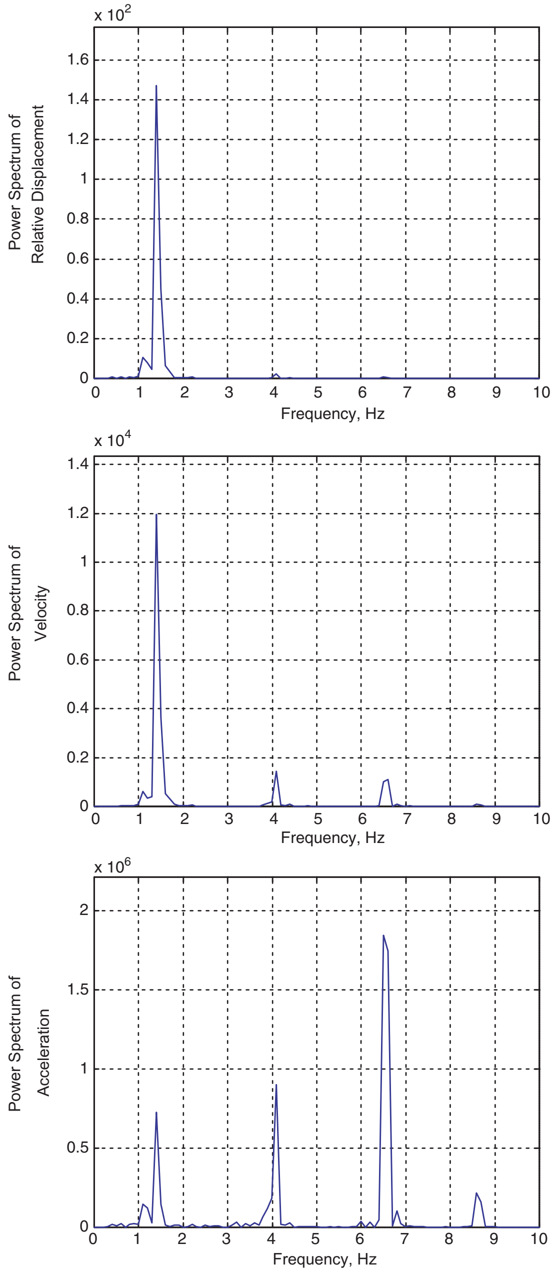

Fig. 5. Frequency responses of the first floor for the uncontrolled structures under the scaled El Centro earthquake.

all responses of the sixth floor. Thus, it may be possible to reduce the responses through modal control combining fuzzy control algorithm.

In this active modal-fuzzy case, two kinds of control design are considered. One (i.e., type A) is based a focus to reduce the structural displacement, and the other (i.e., type B) is based a focus to reduce the structural acceleration.

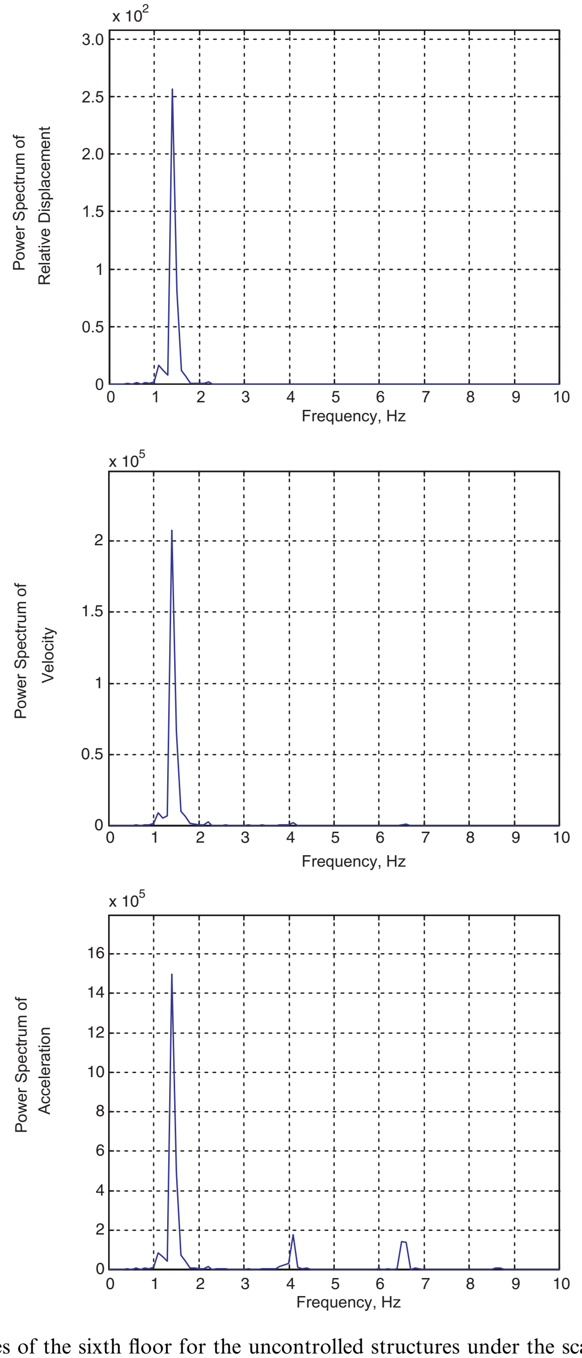

Fig. 6. Frequency responses of the sixth floor for the uncontrolled structures under the scaled El Centro earthquake.

Type A controller is designed using two input variables (i.e. one is first mode displacement coordinate and the other is first mode velocity coordinate), each one having five membership functions, and one output variable (i.e. desired control force) with five membership functions. The membership functions chosen for

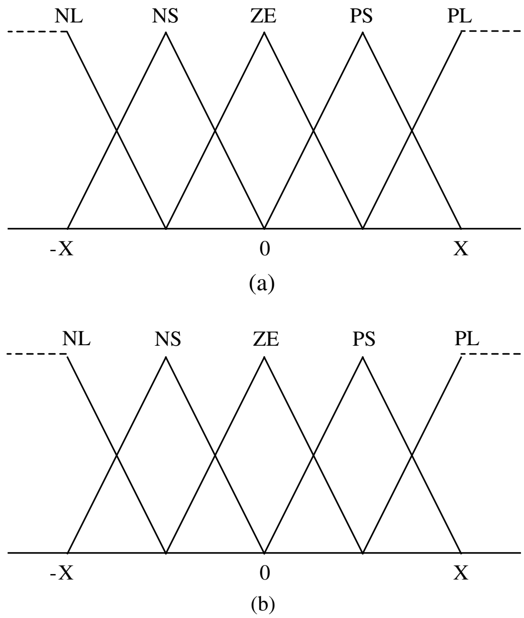

Fig. 7. Input (a) and output (b) membership functions.

the input and output variables are triangular shaped as illustrated in Fig. 7. The definitions of the fuzzy variables of input and output membership function are as follows: NL = negative large, NS = negative small, ZE = zero, PS = positive small and PL = positive large.

Type B controller is similar to Type A except the number of membership functions output variable, having seven membership functions. The membership functions chosen for the input and output variables are the same as those of active fuzzy control system.

Fuzzy inference rule is completely based on the structural first mode displacement coordinate and first mode velocity coordinate. The fuzzy inference rules are shown in Table 2 for type A controller and the same as that of active fuzzy control system.

3.5. Control results

Table 3 summarizes the results of the high (120%), medium (100%) and low (80%) scaled El Centro earthquake excitation simulations. Additionally, to compare the performance of the control algorithms considered the peak of the interstory drift and absolute acceleration responses for all floors were examined. Fig. 8 shows the peak interstory drift and the peak absolute acceleration responses of each floor when the medium (100%) scaled El Centro earthquake is used as input excitation.

In the medium excitation simulation, the ratios of the normalized maximum responses in the optimal control system, active fuzzy control system and active modal-fuzzy control system (Type B) are 0.48, 0.60, 0.55 for the displacement ($\boldsymbol{J}_1$), 0.63, 0.76, 0.64 for the interstory drift ($\boldsymbol{J}_2$) and 0.69, 0.66, 0.60 for the acceleration ($\boldsymbol{J}_3$), respectively. As seen the results, the overall performance of the system employing the active modal-fuzzy control system (Type B) is slightly better than the active fuzzy system and comparable to the optimal control system. However, even though the active modal-fuzzy control system based a focus to reduce the structural displacement performs significantly better than other systems restricted within the displacement and interstory drift, the performance of the normalized peak floor acceleration

Table 2
Fuzzy inference rule

	NL	**NS**	**ZE**	**PS**	**PL**
NL	PL	PL	PS	PS	ZE
NS	PL	PS	PS	ZE	NS
ZE	PS	PS	ZE	NS	NS
PS	PS	ZE	NS	NS	NL
PL	ZE	NS	NS	NL	NL

Table 3
Normalized controlled maximum responses due to high (120%), medium (100%), and low (80%) amplitude scaled El Centro earthquake

Input excitation	Control strategy	J_1	J_2	J_3	J_4
High amplitude (120%)	LQR	0.479	0.610	0.912	0.0178
	Active fuzzy	0.621	0.724	0.782	0.0178
	Modal-fuzzy A	0.374	0.594	1.545	0.0178
	Modal-fuzzy B	0.607	0.623	0.701	0.0134
Medium amplitude (100%)	LQR	0.479	0.626	0.685	0.0178
	Active fuzzy	0.600	0.756	0.660	0.0178
	Modal-fuzzy A	0.343	0.562	1.186	0.0178
	Modal-fuzzy B	0.548	0.635	0.601	0.0134
Low amplitude (80%)	LQR	0.474	0.657	0.586	0.0178
	Active fuzzy	0.591	0.785	0.663	0.0178
	Modal-fuzzy A	0.289	0.573	1.386	0.0178
	Modal-fuzzy B	0.504	0.624	0.773	0.0134

are not good. In addition, Fig. 8 also shows similar phenomenon. This occurs because a trade-off is established between the various control objectives. It means that the building behaves in a more rigid manner, consequently decreasing the amount of interstory drift of the structure, and at the same time, increased rigidly results in higher floor accelerations within the building. However, a well designed active modal-fuzzy control system (Type B) balances the benefits of the different objectives within the requirements of the specific design scenario.

At high and low excitations, the performance results show similar trend to the medium case. It is demonstrated that the active modal-fuzzy control system that information of all state variables and the whole structure system is considered, without difficulty to select input variables used in fuzzy controller among numerous state variables is very effective in reducing the structural responses due to the earthquake excitation and is applicable to real civil structures.

Consequently, the results of the numerical simulations for a wide amplitude range of loading conditions and for historic earthquake show that the proposed active modal-fuzzy control system can be beneficial in reducing seismic responses of civil structures. The proposed algorithm gives comparable performances to active fuzzy controller and optimal controller and moreover, it is much easier to design control system than those controllers.

3.6. Stability of proposed control system

An active control is used to attenuate the effects of external disturbances of significant intensity but of transient character. The control stability must be checked through the ability of the controlled system to

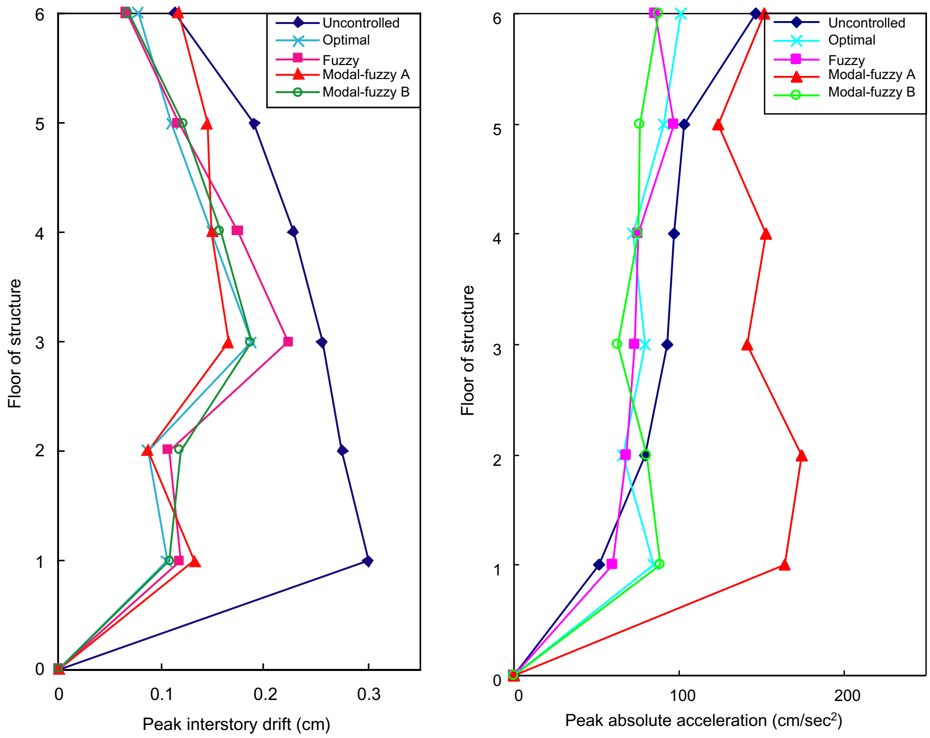

Fig. 8. Peak responses of each floor of structure to scaled El Centro earthquake.

return to rest conditions following oscillations caused by an external disturbance (Casciati, 1997). Since 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 (Casciati, 1997).

The stability tests are performed considering the system with particular initial conditions on the state vector $\boldsymbol{x}$ and checking the ability of the controller to reach equilibrium after the initial transient phase (Battaini et al., 1998). Figs. 9–11 show that the stability tests of the proposed control system in terms of

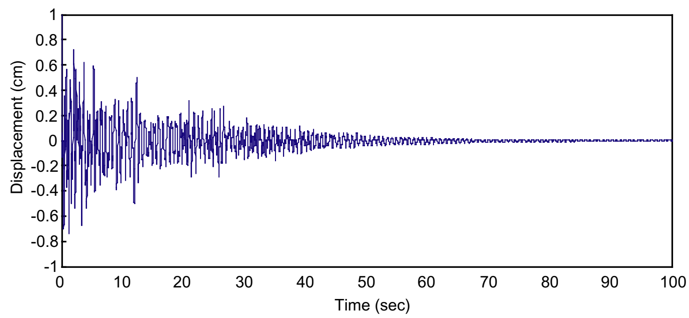

Fig. 9. Stability test in terms of the floor displacement response.

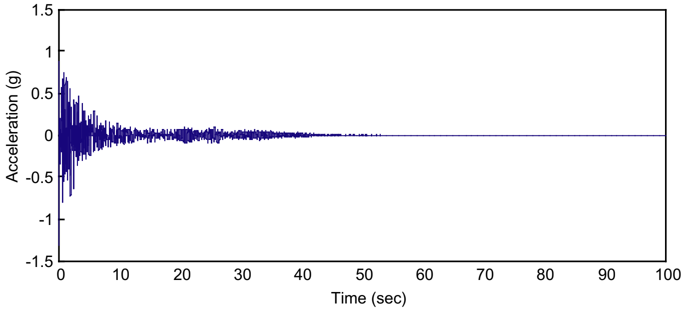

Fig. 10. Stability test in terms of the floor acceleration response.

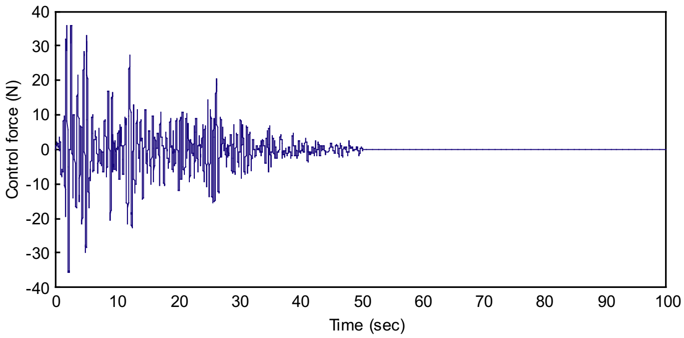

Fig. 11. Stability test in terms of the control force.

the displacement response, acceleration response, and control force, respectively. These figures show that the ability of the proposed controller to drive the system to the rest position after an initial excitation and converge to zero, which means that the system is stable.

4. Conclusions

An active modal-fuzzy control method is presented for seismic response reduction. The major issue in this study is based on the fuzzy algorithm adding modal approach for seismic response reduction. In the case of only active fuzzy control system, it is very difficult to select input variables used in fuzzy controller among numerous state variables. However, the fuzzy theory has advantages to treat in a much easier way is the uncertainties of input data from the external loads and structural responses sensors and offer a simple and robust structure for the specification of nonlinear control laws. The modal approach has advantages over the design in physical space, in that it demands far less computer storage, reduces the computational effort significantly, allows a larger choice of control algorithms, including nonlinear control and is especially desirable for handling of civil structures that dominated by first few modes. In the case of combination of fuzzy and modal approach, the proposed algorithm is very easy to select fuzzy input variables by means of just first few modal coordinates having information of all state variables and the whole system. In other words, a modal-fuzzy control algorithm proposed can be magnified the efficiency caused by belonging their' own advantages simultaneously. To this end, a modal-fuzzy control scheme is applied together with a Kalman filter and a low-pass filter to be applicable to real civil structures. A Kalman filter is considered to estimate modal states and a low-pass filter was used to eliminate spillover problem. The effectiveness of the proposed method in reducing the structural responses for a wide amplitude range of loading conditions and for historic earthquake has been demonstrated via a six-story building structure with hydraulic actuators. Numerical simulation results show that the proposed algorithm is quite effective to reduce seismic responses. The results of this investigation, therefore, indicate that the active modal-fuzzy control strategy could be used for control of seismically excited structures.

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