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VIBRATION CONTROL OF EARTHQUAKE-EXCITED STRUCTURES USING INDEPENDENT MODAL SPACE FUZZY TECHNIQUE

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SUMMARY

This paper proposes a hybrid controller-design technique, which consists of designing optimal controllers and a fuzzy tuner. For an improved seismic performance of the vibration control system, the tuner modulates the pre-designed static gain at every moment according to the contribution of the modal responses to the structural response. Numerical results for a six-floor building structure show the validity and effectiveness of the proposed independent modal space fuzzy control (IMSFC) method.

INTRODUCTION

Civil structures are susceptible to the exposure to excessive levels of vibration caused by strong winds or earthquakes. Especially, when large structures such as high-rise buildings and towers are subjected to this kind of earthquake excitation, their seismic responses mainly depend on a few lower structural modes. On the other hand, earthquake load includes different frequency contents that can be considered as wide-band and usually covers the structural dominant frequencies, which means that the seismic response varies with the frequency content of the earthquake load. The adaptability of conventional fixed gain approach may be insufficient to consider diversity or uncertainty of an earthquake load. Occasionally, desired performance could not be achieved. For earthquake-excited structures, an appropriate time-varying controller makes it possible to achieve optimum efficiency even though operating conditions could change with various earthquakes.

To effectively address this vibration control problem, an independent modal-space fuzzy control method is presented in this paper. For the active control of earthquake-excited structures, even though a structure has a large number of vibration modes, control performance can be efficiently achieved by controlling selected critical modes. Control algorithms based on modal synthesis [1], also known as modal space control, can be effectively used when only a few critical modes need to be controlled. In the proposed approach, each modal controller for a selected mode is separately designed first. Fuzzy logic [2-4] is then introduced to appropriately tune the pre-designed modal feedback gains according to the various operating conditions.

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Unlike conventional fuzzy control [5], control forces are not directly determined by fuzzy logic. Instead, modal control gains are modified by a fuzzy tuning process. This can simplify the construction of a fuzzy rule table and avoid the need to fine adjustments of the corresponding membership functions. It also alleviates the shortcomings of the conventional fuzzy logic controller, in which the characteristics cannot be pre-specified. A fuzzy tuner reassigns the most effective gain at every moment by converting simply designed static gain into a real-time variable dynamic gain via a fuzzy inference mechanism.

In this paper, example designs and numerical simulations were performed with a six-story building to prove the validity of the proposed control method. For the numerical simulations, historically recorded ground accelerations, i.e., the El Centro (1940) and Kobe (1995) earthquakes were considered as external disturbances. Finally, comparative results and discussions of other control methods are also presented.

SYSTEM MODELING

The equation of motion for a building structure with n-degrees of freedom subject to earthquake ground acceleration $\ddot{x}_g(t)$ and control forces $\mathbf{u}(t)$ can be expressed as,

$$\mathbf{M}\ddot{\mathbf{z}}(t)+\mathbf{C}\dot{\mathbf{z}}(t)+\mathbf{K}\mathbf{z}(t)=\mathbf{E}_1\mathbf{u}(t)-\mathbf{M}[\mathbf{1}]\ddot{x}_g(t) \tag{1}$$

where, $\mathbf{z}(t)=[z_1,\ z_2,\ \cdots,\ z_n]^{\mathrm{T}}$ is a displacement vector of order n relative to the ground motion, $\mathbf{u}(t)=\left[u_1,\ u_2,\ \cdots,\ u_{n_c}\right]^{\mathrm{T}}$ is a control force vector of n_c actuators and $\ddot{x}_g(t)$ is a ground acceleration. **M**, **C** and **K** are $n\times n$ mass, damping and stiffness matrices of the building, respectively. $\mathbf{E}_1$ represents an $n\times n_c$ matrix denoting the location of actuators and $[\mathbf{1}]=[1\quad 1\quad \cdots\quad 1]^{\mathrm{T}}$ has $n\times 1$ dimension.

When the state space variable $\mathbf{x}(t)=[\mathbf{z}(t)^{\mathrm{T}}\quad \dot{\mathbf{z}}(t)^{\mathrm{T}}]^{\mathrm{T}}$, Eq. (1) can be transformed into the standard state space equation as follows,

$$\dot{\mathbf{x}}(t)=\mathbf{A}\mathbf{x}(t)+\mathbf{B}_u\mathbf{u}(t)+\mathbf{B}_w\ddot{x}_g(t) \tag{2}$$

where, **A** is a $2n\times 2n$ system matrix, $\mathbf{B}_u$ is a $2n\times n_c$ control matrix and $\mathbf{B}_w$ is a $2n\times 1$ disturbance matrix. They can be expressed as follows:

$$\mathbf{A}=\begin{bmatrix}\mathbf{0} & \mathbf{I}\\ -\mathbf{M}^{-1}\mathbf{K} & -\mathbf{M}^{-1}\mathbf{C}\end{bmatrix},\ \mathbf{B}_u=\begin{bmatrix}\mathbf{0}\\ \mathbf{M}^{-1}\mathbf{E}_1\end{bmatrix},\ \mathbf{B}_w=\begin{bmatrix}\mathbf{0}\\ -[\mathbf{1}]\end{bmatrix} \tag{3}$$

Considering state feedback, the control force vector $\mathbf{u}(t)$ becomes

$$\mathbf{u}(t)=-\mathbf{G}\mathbf{x}(t)=-[\mathbf{G}_z\quad \mathbf{G}_{\dot{z}}]\cdot\left[\mathbf{z}(t)^{\mathrm{T}}\quad \dot{\mathbf{z}}(t)^{\mathrm{T}}\right]^{\mathrm{T}} \tag{4}$$

where, **G** is the feedback gain matrix and $\mathbf{G}_z$ and $\mathbf{G}_{\dot{z}}$ are the displacement and velocity parts of **G**, respectively.

To obtain the state space equation in the modal space, we assume the coordinate transformation as

$$\mathbf{z}=\mathbf{\Phi}\mathbf{q} \tag{5}$$

where $\mathbf{q}=[q_1,q_2,\cdots q_n]^{\mathrm{T}}$ is a modal displacement vector, $\mathbf{\Phi}$ is an $n\times n$ eigenvector matrix of the system, which satisfies the following relations

$$\mathbf{\Phi}^{\mathrm{T}}\mathbf{M}\mathbf{\Phi}=\mathbf{I},\mathbf{\Phi}^{\mathrm{T}}\mathbf{K}\mathbf{\Phi}=\mathrm{diag}\left(\omega_1^2,\ \omega_2^2,\ \cdots,\ \omega_n^2\right)=\mathbf{\Omega}^2,\mathbf{\Phi}^{\mathrm{T}}\mathbf{C}\mathbf{\Phi}=\mathbf{C}_m=\mathrm{diag}\left(2\xi_1\omega_1,\ 2\xi_2\omega_2,\ \cdots,\ 2\xi_n\omega_n\right) \tag{6}$$

where ω_i and ζ_i are the natural frequency and the modal damping ratio of the i-th mode, respectively.

By using Eqs. (1), (5) and (6), we obtain

$$\ddot{\mathbf{q}}+\mathbf{C}_m\dot{\mathbf{q}}+\mathbf{\Omega}^2\mathbf{q}=\mathbf{\Phi}^{\mathrm{T}}\mathbf{E}_1\mathbf{u}-\mathbf{\Phi}^{\mathrm{T}}\mathbf{M}[\mathbf{1}]\ddot{x}_g \tag{7}$$

When the modal state vector $\mathbf{y} = \begin{bmatrix} \mathbf{q}^{\mathrm{T}} & \dot{\mathbf{q}}^{\mathrm{T}} \end{bmatrix}^{\mathrm{T}}$ and the modal control force vector $\mathbf{u}_m(t) = \mathbf{\Phi}^{\mathrm{T}}\mathbf{E}_1\mathbf{u}(t)$ are introduced, Eq. (7) can be transformed into the state space equation in modal space as follows.

$$\dot{\mathbf{y}}(t) = \begin{bmatrix} \mathbf{0} & \mathbf{I} \\ -\mathbf{\Omega}^2 & -\mathbf{C}_m \end{bmatrix} \mathbf{y}(t) + \begin{bmatrix} \mathbf{0} \\ \mathbf{I} \end{bmatrix} \mathbf{u}_m(t) - \begin{bmatrix} \mathbf{0} \\ \mathbf{\Phi}^{\mathrm{T}}\mathbf{M}[\mathbf{1}] \end{bmatrix} \ddot{x}_g(t) \tag{8}$$

DESIGN OF CONTROL SYSTEM IN MODAL SPACE

For control algorithms based on a modal synthesis [1], a control system can be designed in the reduced modal space. Considering that Eq. (8) is a set of n decoupled modal state equations, and adopting only n_{mc} $(n_{mc} < n)$ modal equations from Eq. (8), we can obtain n_{mc} independent state space equations as in the following form.

$$\dot{\mathbf{y}}_i = \mathbf{A}_{mi}\mathbf{y}_i + \mathbf{B}_{mi}u_{mi} \tag{9}$$

where, $\mathbf{y}_i$, $\mathbf{A}_{mi}$ and $\mathbf{B}_{mi}$ are 2×1 state vector, 2×2 system matrix and 2×1 control matrix of the i-th mode selected for control, respectively. They are expressed as

$$\mathbf{y}_i = \begin{bmatrix} q_i \\ \dot{q}_i \end{bmatrix},\ \mathbf{A}_{mi} = \begin{bmatrix} 0 & 1 \\ -\omega_i^2 & -2\xi_i\omega_i \end{bmatrix},\ \mathbf{B}_{mi} = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \tag{10}$$

Let $\mathbf{G}_{mi}$ denote the 1×2 i-th modal control gain matrix, the i-th modal control force can then be rewritten as Eq. (11) considering feedback control law.

$$u_{mi} = -\mathbf{G}_{mi}\mathbf{y}_i = -\begin{bmatrix} G_{q_i} & G_{\dot{q}_i} \end{bmatrix} \cdot \begin{bmatrix} q_i & \dot{q}_i \end{bmatrix}^{\mathrm{T}} \tag{11}$$

The modal control gain $\mathbf{G}_{mi}$ can be determined by using LQR control theory [6]. In this study, the modal control gain was obtained by minimizing a quadratic modal performance index J_i of the form

$$J_i = \int_0^{\infty} \left\{ \mathbf{y}_i^{\mathrm{T}}\mathbf{Q}_i\mathbf{y}_i + u_{mi}^{\mathrm{T}}R_i u_{mi} \right\} \tag{12}$$

where, $\mathbf{Q}_i$ and R_i are weighting matrices for the i-th modal state vector and the modal control force, respectively. The i-th modal control gain $\mathbf{G}_{mi}$ can then be determined as,

$$\mathbf{G}_{mi} = R_i^{-1}\mathbf{B}_{mi}^{\mathrm{T}}\mathbf{P}_i \tag{13}$$

where $\mathbf{P}_i$ is 2×2 semi-positive definite matrix obtained from Riccati equation [7] taking the form of

$$\mathbf{A}_{mi}^{\mathrm{T}}\mathbf{P}_i + \mathbf{P}_i\mathbf{A}_{mi} - \mathbf{P}_i\mathbf{B}_{mi}R_i^{-1}\mathbf{B}_{mi}^{\mathrm{T}}\mathbf{P}_i + \mathbf{Q}_i = \mathbf{0} \tag{14}$$

By substituting a solution of Eq. (14) into Eq. (13), the modal control gains are obtained as

$$G_{q_i} = -\omega_i^2 + \omega_i\sqrt{\omega_i^2 + R_i^{-1}}\ ,\ G_{\dot{q}_i} = -2\xi_i\omega_i + \sqrt{4\xi_i^2\omega_i^2 + 2G_{q_i} + R_i^{-1}} \tag{16}$$

From Eq. (16), determination of R_i leads to the corresponding modal control gain.

If the first n_{mc} modes are selected, the modal control gain matrix $\mathbf{G}_m$ and $\mathbf{u}_m$ can be expressed as

$$\mathbf{G}_m = \begin{bmatrix} \mathbf{G}_{mq} & \mathbf{G}_{m\dot{q}} \end{bmatrix} \tag{17}$$

$$\mathbf{u}_m(t) = -\mathbf{G}_m\mathbf{y}(t) = \mathbf{\Phi}_{mc}^{\mathrm{T}}\mathbf{E}_1\mathbf{u}(t) \tag{18}$$

where, $\mathbf{G}_{mq} = \left[\mathrm{diag}\left(G_{q_1},\ G_{q_2},\ \cdots,\ G_{q_{n_{mc}}}\right) \ \vdots\ \mathbf{0}_{n_{mc}\times(n-n_{mc})} \right]$, $\mathbf{G}_{m\dot{q}} = \left[\mathrm{diag}\left(G_{\dot{q}_1},\ G_{\dot{q}_2},\ \cdots,\ G_{\dot{q}_{n_{mc}}}\right) \ \vdots\ \mathbf{0}_{n_{mc}\times(n-n_{mc})} \right]$ and $\mathbf{\Phi}_{mc}$ is an $n \times n_{mc}$ matrix of the selected n_{mc} eigenvectors.

By substituting Eq. (4) into Eq. (18) the modal gain matrix $\mathbf{G}_m$ can be expressed as follows,

$$\mathbf{G}_m = \mathbf{LG\Psi} \tag{19}$$

where, $\mathbf{L} = \mathbf{\Phi}_{mc}^{\mathrm{T}} \mathbf{E}_1$ is a modal participation matrix and $\mathbf{\Psi} = \begin{bmatrix} \mathbf{\Phi} & \mathbf{0} \\ \mathbf{0} & \mathbf{\Phi} \end{bmatrix}$, respectively.

Note that the dimension of the modal participation matrix $\mathbf{L}$ is $n_{mc} \times n_c$, where n_{mc} is the number of controlled modes and n_c the number of controllers. If $n_{mc} \neq n_c$, the inverse of $\mathbf{L}$ does not exist but the physical gain matrix $\mathbf{G}$ can be approximated as follows by performing a pseudo-inverse of $\mathbf{L}$.

$$\begin{aligned} \mathbf{G} = \begin{bmatrix} \mathbf{G}_z & \mathbf{G}_{\dot{z}} \end{bmatrix} &= \mathbf{L}^{-1} \mathbf{G}_m \mathbf{\Psi}^{-1}, \ (n_{mc} = n_c) \\ &= \mathbf{L}^{+} \mathbf{G}_m \mathbf{\Psi}^{-1}, \ (n_{mc} \neq n_c) \end{aligned} \tag{20}$$

DESIGN OF FUZZY TUNER

The next stage of IMSFC is to obtain a fuzzy tuner, which identifies the current behavior of the structural system from measured responses and determines the way to modify the pre-designed controllers. Once the fuzzy tuner is obtained, it continuously modulates the modal gains in real-time in order to enhance the control performance. In the proposed approach, the modified modal control forces or fuzzy-tuned modal control force, u_{mi}^{tuned}, is defined by Eq. (21) by introducing $\alpha_i(t)$, the i-th modal gain's contribution factor, which is a positive real number and varies with time.

$$u_{mi}^{tuned}(t) = \alpha_i(t)\, u_{mi}(t) = -\alpha_i(t)\ \mathbf{G}_{mi}\ \mathbf{y}_i(t) \tag{21}$$

As shown in Figure 1, a fuzzy tuner is composed of four elements, i.e., fuzzification, an inference mechanism, a rule-base and defuzzification. The fuzzy tuning mechanism including determination process of the contribution factor α_i is described later in this chapter.

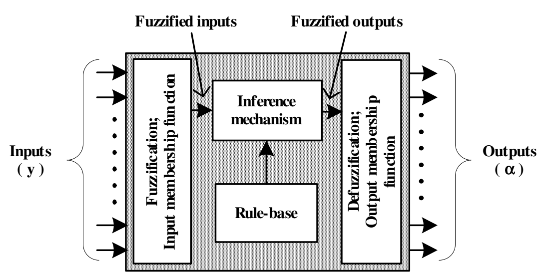


Figure 1. Fuzzy operation procedure

In the fuzzification or defuzzification process, an interface of some form is required to relate the infinite number of crisp values to the finite number of linguistic values or fuzzy variables. This is accomplished by membership functions. The input membership function converts modal responses into fuzzy numbers so that the inference mechanism can easily exploit them to activate and to apply pre-assigned rules. In addition, the output membership function converts the conclusions of the inference mechanism into the contribution factor which is the actual input into the control system. Membership functions are specified in a heuristic manner, based on the designer's experience or intuition, and as a result, it is possible to obtain wider choices for the shape of the membership function. In this paper, triangular input and output membership functions were used, as shown in Figures 2 and 3, respectively. The set of linguistic values defined over the universe of discourse is listed as follows:

Set of Input Linguistic Values; $\Omega_{\tilde{q}}$ or $\Omega_{\tilde{\dot{q}}}$ = {NL, NS, Zero, PS, PL}

Set of Output Linguistic Values; $\Omega_{\tilde{\alpha}}$ = {VS, S, M, L, VL}

where N(negative), P(positive), S(small), M(medium), L(large), V(very) and Zero are used as abbreviations to represent each qualitative meaning. The universe of discourse of each input membership function is defined according to the level of modal response, and that of the output membership function is chosen to maintain a reasonable operation.

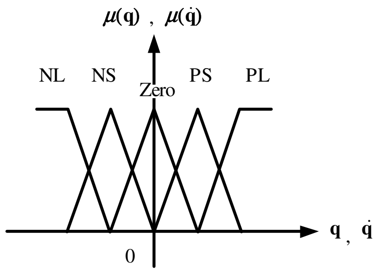


Figure 2. Input membership function

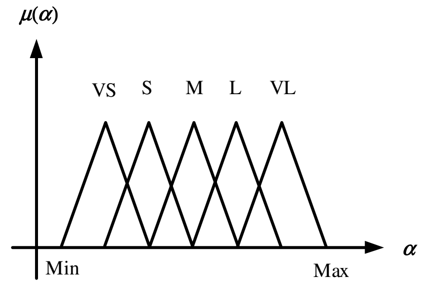


Figure 3. Output membership function

The fuzzification module quantifies the modal responses to the fuzzy numbers with membership functions as follows

$$\mu(q)=\begin{cases}\mu_q^i(q) & \text{if } q\in\left[q_{\min}^i \quad q_{\max}^i\right] \\ 0 & \text{otherwise}\end{cases}, \quad \mu(\dot{q})=\begin{cases}\mu_{\dot{q}}^i(\dot{q}) & \text{if } \dot{q}\in\left[\dot{q}_{\min}^i \quad \dot{q}_{\max}^i\right] \\ 0 & \text{otherwise}\end{cases} \tag{22}$$

where, $q, \dot{q}$ are modal displacement and velocity, and $\mu_q^i(q), \mu_{\dot{q}}^i(\dot{q})$ are i-th input membership functions, $\left[q_{\min}^i \quad q_{\max}^i\right], \left[\dot{q}_{\min}^i \quad \dot{q}_{\max}^i\right]$ are ranges in which the i-th membership functions are defined.

The rule base module is constructed by specifying a set of 'If-Then' statements that captures the expert's knowledge of the way to modify the contribution factor. In this study, we consider a linguistic rule with the following form.

j-th rule for i-th modal controller: ***If*** $\tilde{q}_i$ *is* $\Omega_{\tilde{q}_i}^j$ *and* $\tilde{\dot{q}}_i$ *is* $\Omega_{\tilde{\dot{q}}_i}^j$ ***then*** $\tilde{\alpha}_i$ *is* $\Omega_{\tilde{\alpha}_i}^j$

where $\tilde{q}_i$, $\tilde{\dot{q}}_i$ are the input fuzzy variables corresponding the modal displacement and velocity, $\tilde{\alpha}_i$ the output fuzzy variable for the contribution factor, and $\Omega_{\tilde{q}_i}^j$, $\Omega_{\tilde{\dot{q}}_i}^j$ and $\Omega_{\tilde{\alpha}_i}^j$ the linguistic values of the respective fuzzy variables, respectively. As an example, when $\Omega_{\tilde{q}_i}^j$ = "PL," $\Omega_{\tilde{\dot{q}}_i}^j$ = "PL" and $\Omega_{\tilde{\alpha}_i}^j$ = "VL," the If-Then statement represents a rule as:

If *modal displacement is <u>positive large</u> and modal velocity is <u>positive large</u>* ***then*** *the contribution factor is <u>very large</u>.*

The tabular representation of one possible set of rules is shown in Table 1, although we can establish some of valid and reasonable rule bases considering system dynamics.

Table 1. Fuzzy rule table

$\tilde{\alpha}$		$\tilde{q}$				
		NL	**NS**	**Zero**	**PS**	**PL**
$\tilde{\dot{q}}$	**NL**	VL	L	M	L	VL
	NS	L	M	S	M	L
	Zero	M	S	VS	S	M
	PS	L	M	S	M	L
	PL	VL	L	M	L	VL

The inference mechanism determines the extent to which each rule is relevant to the current situation characterized by the fuzzy input variables, and it draws conclusions using the current inputs and the information in the rule-base. The current situation means the structural response that varies with the earthquake load. Therefore, the conclusions drawn by fuzzy inference reflect the diversity and uncertainty of earthquake loads. The conclusion implied by the rule, that is, the aggregation of the implied fuzzy sets are defined by the *min* method and the aggregation of the implied fuzzy sets is combined by means of the *max* method.

Defuzzification operates on the implied fuzzy sets produced by the inference mechanism and combines their effects in order to tune the modal gains. In this study, we adopted the "center of gravity" (COG) defuzzification method for combining the recommendations represented by the implied fuzzy sets from all the rules. For example, let $b_i^{(j)}$ denote the center of the output membership function of the consequent of j-th rule for i-th modal responses and N_R denote the number of rules applied to the given input. Then, the COG method computes α_i to be

$$\alpha_i = \left(\sum_{j=1}^{N_R} b_i^{(j)} \int \mu_i^{(j)}\right) \Big/ \left(\sum_{j=1}^{N_R} \int \mu_i^{(j)}\right) \tag{23}$$

The schematic organization of the IMSFC is shown in Figure 4. The state vector is transformed into modal responses that can be used to generate appropriate feedback control forces through the fuzzy tuner. From the aforementioned feedback control law, control forces transmitted to the structure can be calculated by inserting α_i of Eq. (23) into Eq. (21).

$$u_{mi}^{tuned} = -\alpha_i \mathbf{G}_{mi} \mathbf{y}_i = -\left(\sum_{j=1}^{N_R} b_i^{(j)} \int \mu_i^{(j)}\right) \Big/ \left(\sum_{j=1}^{N_R} \int \mu_i^{(j)}\right) \mathbf{G}_{mi} \mathbf{y}_i \tag{24}$$

Then, by replacing u_{mi} in Eq. (9) with u_{mi}^{tuned} and considering earthquake excitation, the state space equation in the modal space for a fuzzy tuned time-varying modal control system can be written as,

$$\dot{\mathbf{y}}_i(t) = \begin{bmatrix} 0 & 1 \\ -\left(\omega_i^2 + \alpha_i(t) G_{q_{mi}}\right) & -\left(2\xi_i \omega_i + \alpha_i(t) G_{\dot{q}_{mi}}\right) \end{bmatrix} \mathbf{y}_i(t) - \begin{bmatrix} 0 \\ \phi_i^{\mathrm{T}} [\mathbf{1}] \end{bmatrix} \ddot{x}_g(t) \tag{25}$$

where, ϕ_i is an $n \times 1$ i-th mode vector.

Accordingly, the state space equation in physical coordinate can be also expressed as,

$$\dot{\mathbf{x}}(t) = \left(\mathbf{A} - \mathbf{B}_u \mathbf{L}^{+1} \left[\boldsymbol{\alpha}(t)\right] \mathbf{G}_m \boldsymbol{\Psi}^{-1}\right) \mathbf{x}(t) + \mathbf{B}_w \ddot{x}_g(t) \tag{26}$$

where, $\left[\boldsymbol{\alpha}(t)\right] = \mathrm{diag}\left(\alpha_1,\ \alpha_2,\ \cdots,\ \alpha_{n_{mc}}\right)$.

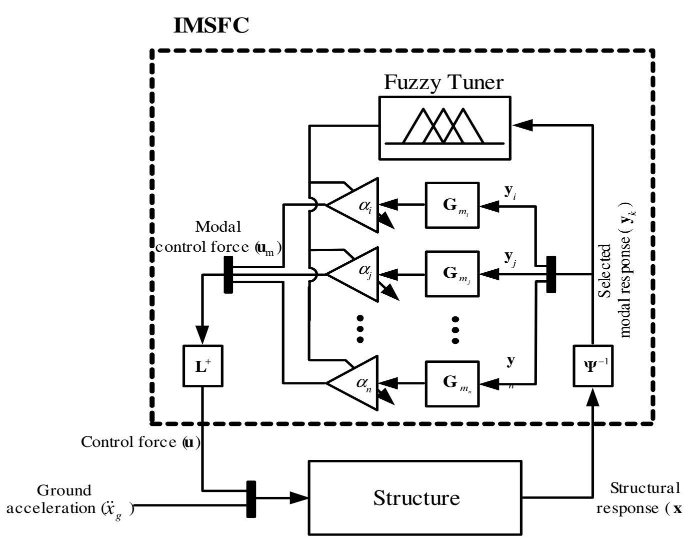


Figure 4. Schematic block diagram of IMSFC

NUMERICAL EXAMPLES

The control performance of the IMSFC was evaluated by comparing dynamic simulation results. Three types of controllers, i.e., a conventional LQR, a modal control without fuzzy tuning and the proposed method were considered for the purpose of comparison. As an example for illustrating the proposed method, a six-story building with an active tendon control system as shown in Figure 5 is considered. Each floor has the same mass of 34,560 kg and a stiffness of 12,000 kN/m respectively. The damping ratios and natural frequencies of the first three modes are 1.0%, 3.0%, 4.7% and 0.7Hz, 2.1Hz, 3.4Hz, respectively.

In order to evaluate the proposed control strategy for various earthquakes which have distinct frequency contents and magnitudes, one far-field and one near-field historical records were selected as input excitations: (i) *El Centro*. The N-S component recorded at the Imperial Valley Irrigation District substation in El Centro, California, during the Imperial Valley, California earthquake of May 18, 1940. (ii) *Kobe*. The N-S component recorded at the Kobe JMA station during the Hyogo-ken Nanbu earthquake of January 17, 1995. The peak acceleration of the earthquake records are 3.42m/sec^2, 8.18m/sec^2, respectively.

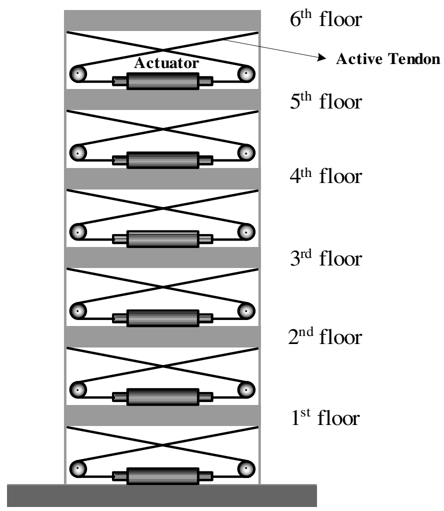


Figure 5. A six-story example building

The first step of the proposed approach is to design a control system in modal space. In the design of the modal controller, the first three modes were selected for the control in this example. The weighting parameters for the 1st, 2nd and 3rd modal control force, i.e., R_1, R_2 and R_3 were chosen using Eq. (27) by considering the acceptable maximum force levels of the actuators,

$$R_1 = 0.10,\ \ R_2 = 0.05,\ \ R_3 = 0.05 \tag{27}$$

By substituting R_i in Eq. (27) into Eq. (16), we could obtain the modal control gains.

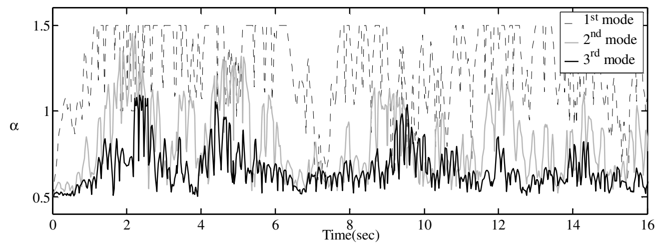
Note that the weighting matrix $\mathbf{Q}_i$ of the performance index in Eq. (12) was chosen so that it could weigh the modal energy of the i-th mode,

$$\mathbf{Q}_1 = \begin{bmatrix} 4.5^2 & 0 \\ 0 & 1 \end{bmatrix},\ \mathbf{Q}_2 = \begin{bmatrix} 13.2^2 & 0 \\ 0 & 1 \end{bmatrix},\ \mathbf{Q}_3 = \begin{bmatrix} 21.2^2 & 0 \\ 0 & 1 \end{bmatrix} \tag{29}$$

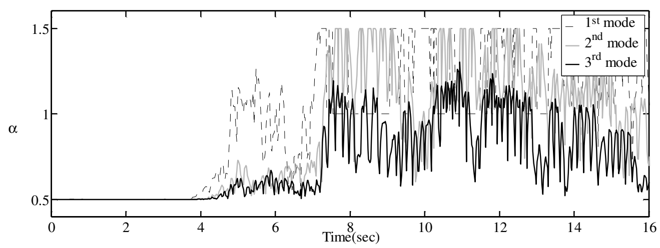
In order to obtain an appropriate fuzzy tuner, a rule surface that corresponds to the rule bases as presented in Table 1 was generated. This rule surface represents the relationship between the input modal responses and the output values α for the fuzzy system. In this example, the input ranges for the modal displacement and the velocity have their saturation points at ±3.2, ±9.5 respectively, and the output value

α is within the ranges between 0.5 and 1.5 such that each modal gain can be increased or decreased from its original value by 50%.

Numerical simulations were carried out for the example building subject to the two earthquakes. Figure 7 shows the generation history of α for each earthquake. For clarity, the first 16 seconds of α are plotted. For the El Centro earthquake, amplification of the first modal gain can be seen to dominate during the control action, and the third modal gain is activated to a lesser extent. On the other hand, the second modal gain is mainly amplified while the first modal gain is relatively deactivated in the case of the Kobe earthquake.



(a) El Centro case



(b) Kobe case

Figure 7. Time histories of the contribution factor generated by fuzzy tuning process

Simulation result of the top floor displacement is plotted in Figure 8. An effective reduction of the vibrations induced by the El Centro earthquake can be observed in the case of the proposed control method compared to the uncontrolled case. This suggests that the modal gains were successfully modified in real time according to the modal responses through the fuzzy gain tuner. In the simulation of controlled responses, performance degradation of the IMSFC due to spillover effects on residual modes is not observed.

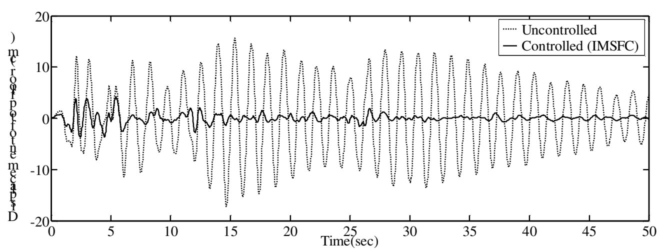


Figure 8. Controlled and uncontrolled displacement responses of the top floor (El Centro case)

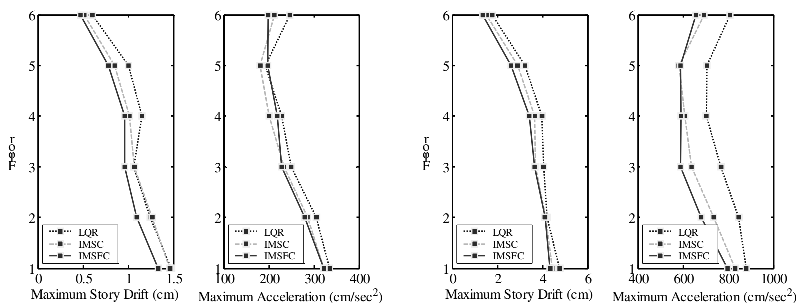
Comparative Results

To compare the performance of control systems, we also considered a conventional LQR method. The feedback gain matrix $\mathbf{G}$ in Eq. (4) is determined by minimizing a quadratic performance index J' of the form

$$J' = \int_0^\infty \left\{ \mathbf{x}^{\mathrm{T}} \mathbf{Q}' \mathbf{x} + \mathbf{u}^{\mathrm{T}} \mathbf{R}' \mathbf{u} \right\} dt \tag{30}$$

where, $\mathbf{Q}'$ and $\mathbf{R}'$ are the weighting matrix and are chosen as $\mathbf{Q}' = \mathbf{I}_{12\times12}$, $\mathbf{R}' = 5\times10^{-14}\times\mathbf{I}_{6\times6}$. Dynamic simulations for three controlled cases, i.e., (i) LQR, (ii) IMSC denoting independent modal space control without fuzzy tuning and (iii) the proposed IMSFC are performed and the simulation results are presented. Figure 9 (a) shows the maximum story drift and maximum acceleration response of each floor when the El Centro earthquake is used as input excitation. The 1st floor has the largest story drift and acceleration response for the three methods considered in this paper. The IMSC shows similar results with the LQR in the case of story drift of the 1~3rd floors, but the responses of the 4~6th floors are reduced substantially. On the other hand, the IMSFC reduces the displacement responses of all floors considerably. As a result, the maximum story drift for the 1st floor is seen to have decreased by 9.74% compared to the LQR and 8.71% compared to IMSC, and the story drift of the top floor are decreased by 21.87% and 8.39%, respectively. Though the IMSFC has larger acceleration responses for the 4th and 5th floors than those of IMSC, it maintains a lower level of acceleration response than the LQR.

Figure 9 (b) shows the results when the Kobe earthquake is used, which shows a similar performance to that for the El Centro earthquake. The proposed method reduces the top story drift by 22.64% compared to the LQR and 11.03% to IMSC, and 3rd floor acceleration is reduced by 23.82% and 8.08%, respectively.



(a) El Centro case (b) Kobe case

Figure 9. Maximum story drift and maximum acceleration response

The control efficiency of the methods was also evaluated by investigating required control efforts, which are represented by the maximum instantaneous control force, the maximum instantaneous power and the total required power. The maximum instantaneous control force implies the maximum required control force during an earthquake. The maximum instantaneous power indicates the maximum required power to control the structure when the actuators are in operation. Therefore, the maximum instantaneous power can be estimated by taking the maximum value of summations of the instantaneous power required by each actuator at every time step. The total work done by actuators or required energy was calculated by summing the integrations of the instantaneous powers with time. These values are summarized in Table 2. By comparing the IMSFC and IMSC results, we can see that the difference is not large. Compared to LQR, however, IMSFC requires smaller control forces and power levels than the LQR for the two earthquake excitations. The maximum instantaneous control force, maximum instantaneous power and total energy of IMSFC appear to be saved by 7.09%, 15.42% and 6.82%, respectively, in the case of El Centro earthquake. We could also observe similar amount of savings are also achieved in Kobe case. Based on the foregoing results, we can conclude that the appropriate fuzzy tuning of existing modal controllers can enhance the control performance of vibration suppression and, thereby suggesting that the proposed IMSFC has improved seismic performance while maintaining smaller or comparable level of required control efforts.

Table 2. Maximum instantaneous control force, maximum instantaneous power and total work

	El Centro			Kobe		
	LQR	IMSC	IMSFC	LQR	IMSC	IMSFC
Maximum instantaneous control force (kN)	302	282	280	927	850	855
Maximum instantaneous power (kW)	114	100	96	1034	913	916
Total work or required control energy ($J\times10^3$)	135	123	126	809	735	736

CONCLUSIONS

An independent modal space fuzzy control method has been developed to improve the seismic performance of the active control system. The method is comprised of a fuzzy tuner and several fixed gain controllers obtained by a modal synthesis. The state space equation is transformed into modal coordinates, and modal feedback gains are obtained by applying the optimal control theory. For an improved seismic performance of the vibration control system, a rule-based fuzzy tuner is introduced. The tuner continuously tunes the modal gains by evaluating the current situation of the structure according to the modal responses. Dynamic simulation results of a six-story building subjected to the El Centro and Kobe earthquakes showed that improved seismic control performance can be achieved by the simple fuzzy tuning of existing modal control gains.

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