Research on Intelligent Fuzzy Optimal Active and Hybrid Control Systems of Building Structures
- Verification of Optimization Method on Switching Rules of Control Forces -

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Summary

Recently, many reseraches on active control systems of building structures are preformed based on modern control theory and are installed real buildings. The authors have already proposed intelligent fuzzy optimal active control (IFOAC) systems. IFOAC systems imitate intelligent activities of human brains such as prediction, adaptation, decision-kaking and so on. In IFOAC systems, objective and subjective judgements on the active control can be taken into account. However, IFOAC systems are considered to be suitable for far-field erathquake and control effect becomes small in case of near-field earthqaukes which include a few velosity pules with large amplitudes. To improve control effect in case of near-souece earthquakes, the authors have also proposed hybrid control (HC) systems, in which IFOAC systems and fuzzy control system are combined. In HC systems, the fuzzy control systems are introduced as a reflective fuzzy active control (RFAC) system and imitates spinal reflection of human. In HC systems, active control forces are activated to buildings in accordance with switching rules on active control forces. In this paper, optimizations on fuzzy control rules in RFAC system and switching rules of active control forces in HC system are performed by Parameter-Free Genetic Algorithms (PfGAs). Here, the optimization is performed by using different earthquake inputs. The results of digital simulations show that the HC system can reduce maximal response displacements under restrictions on strokes of the actuator effectively in case of a near-source earthquake and the effectiveness of the proposed HC system is discussed and clarified.

1 Introduction

Recently, buildings become high-rise and intelligent, and brand-new seismic technologies such as active control systems and base-isolation systems are applied to real buildings. Many researches (Leipholz 1979 and Casciati and Magonette 2000) on active control systems are carried out based on modern control theory.

To develop effective active control system of buildings, it is necessary to take account of not only uncertainties including in earthquake inputs and structural responses but also subjective judgments of users, owners and/or engineers on seismic safety and habitability, and so on (Yao 1972). The authors have already proposed an intelligent fuzzy optimal active control (IFOAC) system (Kawamura and Yao 1990) which can take account of these special features, and the effectiveness of proposed system is verified and proved by digital simulations (Tani and Kawamura 1992 and Mitsui, Tani, Kawamura and Takizawa 2002) and shaking table tests (Tani, Nishimura, Ryu, Nishihata and Kawamura 2000 and Fujita, Tani, Kawamura and Takizawa

2002). IFOAC systems imitate intelligent activities of human brains such as prediction, adaptation, decision-kaking and so on.

However, in IFOAC system, a certain interval is employed as a control interval, and predictions of earthquake inputs and structural responses in the next step are performed in each control interval. So, IFOAC system is considered to be suitable for far-field earthquake motions which show relatively continuous variation. On the other hand, near-source earthquakes have distinguished features such as a few velocity pulses with relatively large amplitudes and long periods. Examples of typical near-source earthquakes are Northridge earthquake (1994) and Hyogoken-nanbu earthquake (1995). Therefore, it is considered that the control effect of IFOAC system becomes small. To correspond to near-source earthquakes, the authors have already proposed hybrid control (HC) systems (Mitsui, Ryu, Tani, Kawamura and Yao 2000, Jibatake, Mitsui, Tani, Kawamura and Takizawa 2001 and Takagi, Tani, Kawamura and Takizawa 2002) in which IFOAC system and a reflective fuzzy active control (RFAC) system which imitates a spinal reflection of human are combined. As for RFAC system, usual fuzzy control rules (Pedrycz 1989) are employed.

In this paper, the limit of the performance of the control device is set up. Under the assumed setting, the control results of a single control (IFOAC and RFAC) and hybrid control are compared and examined, in order to verify the effectiveness of hybrid control by digital simulation. In verification, the tuning of fuzzy control rules in RFAC system and the optimization of switching rules of active control forces in HC system are performed by Genetic Algorithms (GAs) (Holland 1993 and Goldberg 1989). Here, Parameter-Free Genetic Algorithms (PfGAs) (Sawai, Kidu and Adachi 2000) are employed.

2 Basic Assumpton

An objective structure is assumed to be five-degree-of-freedom system with visco-elastic restoring force characteristics with active mass driver (AMD) at the top floor as shown in Fig.2-1. As for structural characteristics, following values are employed in digital simulations, i.e.; mass m=500/980 tf*sec^2/cm, stiffness k=500 tf/cm for the same values in each story. Calculated first predominant period is 0.705 sec. As for structural characteristics of AMD, additional mass m_d, and stiffness k_d are assumed to be 75 tf* sec^2/cm, 0.1 tf/cm, respectively. Damping ratios of the objective structure and AMD are assumed to be 0.01 and damping factors in each story are calculated under the assumption that the damping factor is proportional to the stiffness in each story.

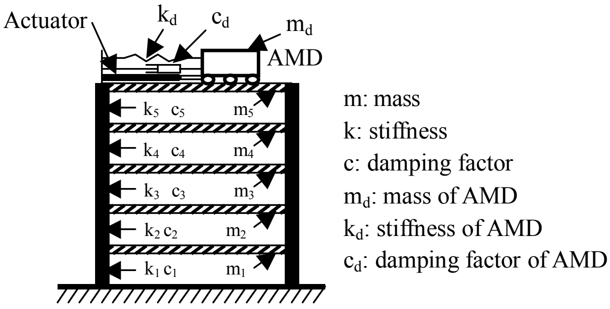


Figure 2-1 Objective Structures

In this research, at first, limit values of the performance of the actuator is assumed by parametric study and following values are determined, i.e.; stroke of the actuator (drive distance of AMD) limit =150cm and control force limit =200tf. Under these settings, the control effect of each control method can be examined within the limits of the actuator performance restricted.

In this simulation, four earthquake input waves such as El Centro (1940, NS), JMA Kobe (1995, NS), Hachinohe (1968, NS), and Taft (1952, EW), and the standard wave (Homepage of the Buiding Center of Japan) of the Building Center of Japan (BCJ-wave). The maximal acceleration of each earthquake wave is regulated into 350 gal. BCJ-wave is proposed as the standard wave in structral designs by the Buiding Center of Japan.

Equations of motions are shown in Eqs. (2-1)-(2-4). As for numerical integration method, the linear acceleration method is employed. As for an activation method of active control forces in IFOAC system, an equivalent variable damping method is employed as shown in Eq. (2-5).

$$m_1\ddot{y}_1 + c_1\dot{y}_1 - c_2(\dot{y}_2 - \dot{y}_1) + k_1 y_1 - k_2(y_2 - y_1) = -m_1\ddot{x} \tag{2-1}$$

$$m_i\ddot{y}_i + c_i(\dot{y}_i - \dot{y}_{i-1}) - c_{i+1}(\dot{y}_{i+1} - \dot{y}_i) + k_i(y_i - y_{i-1}) - k_{i+1}(y_{i+1} - y_i) = -m_i\ddot{x} \quad (i = 2,3,4) \tag{2-2}$$

$$m_5\ddot{y}_5 + c_5(\dot{y}_5 - \dot{y}_4) - c_d(\dot{y}_d - \dot{y}_5) + k_5(y_5 - y_4) - k_d(y_d - y_5) + f = -m_5\ddot{x} \tag{2-3}$$

$$m_d\ddot{y}_d + c_d(\dot{y}_d - \dot{y}_5) + k_d(y_d - y_5) - f = -m_d\ddot{x} \tag{2-4}$$

$$f_I = u_I = \alpha \cdot \dot{y}_5 \qquad \text{(active control force by IFOAC system)} \tag{2-5}$$

Here, $\ddot{y}_i$, $\dot{y}_i$ and $y_i (1 \le i \le 5)$ denote relative response accelerations, velocities and displacements of the objective structure, respectively, and $\ddot{x}$ denotes earthquake input accelerations. $\ddot{y}_d$, $\dot{y}_d$ and y_d denote relative response accelerations, velocities and displacements of AMD, respectively. 'u_I' and 'α' in Eq. (2-5) denote active control forces in IFOAC system and control variables in case of the equivalent variable damping method.

Fig.2-2 shows a flowchart of the hybrid control system. In case of hybrid control system, the active control force 'f' is determined by switching rules of active control forces calculated by IFOAC system and RFAC system in real time. IFOAC system consists of following three intelligent systems (Kawamura and Yao 1990 and Tani and Kawamura 1992), i.e.; (1) prediction of earthquake inputs, (2) structural identification and prediction of structural responses, (3) fuzzy maximizing decision (Bellman and Zadeh 1970). In IFOAC system, a certain time interval Δt as a control interval is introduced as shown in Fig.2-3. Predictions of erathquake inputs and structurl responses, and fuzzy maximizing decision are preformed by using maximal absolute values in each Δt.

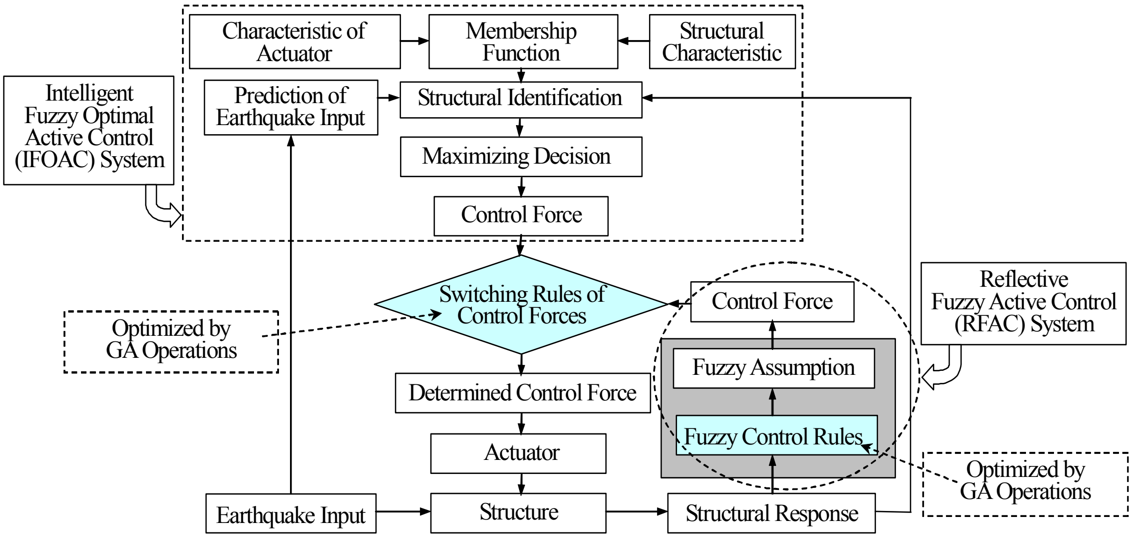


Figure 2-2 Flowchart of Hybrid Control System

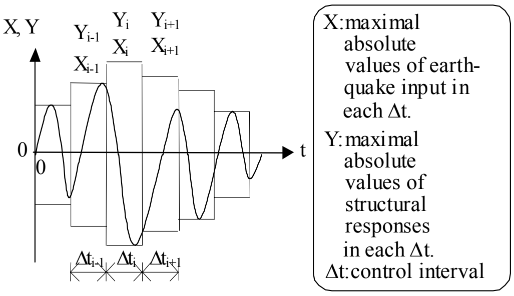


Figure 2-2 Assumptions and Responses (Kawamura and Yao 1990)

3 Outline of Intelligent Fuzzy Active Control (IFOAC) System

3.1 Prediction System of Earthqauke Inputs

Prediction of earthquake inputs is performed by using conditioned fuzzy set rules (Kawamura and Yao 1990 and Tani and Kawamura 1992) proposed by the authors. These rules are obtained by statistical operations of some observed data of earthquake input accelerations. In this method, maximal absolute values in each Δt are employed. First-order and second-order differences of observed data are calculated by using Eqs.(3-1) and (3-2). Next incremental value $\Delta\ddot{X}_{i+1}$ is determined by conditioned fuzzy set rules, and the predicted value $\ddot{X}^{P}_{i+1}$ in the next control interval is obtained by Eq.(3-3).

$$\Delta\ddot{X}_i = \ddot{X}_i - \ddot{X}_{i-1} \tag{3-1}$$

$$\Delta^2\ddot{X}_i = \ddot{X}_i - 2\cdot\ddot{X}_{i-1} + \ddot{X}_{i-2} \tag{3-2}$$

$$\ddot{X}^{P}_{i+1} = \ddot{X}_i + \Delta\ddot{X}_{i+1} \tag{3-3}$$

3.2 Structural Identification (Prediction System of Strcutural Responses)

Prediction of structural responses is performed by piece-wise linear response equations (Kawamura and Yao 1990 and Tani and Kawamura 1992) also proposed by the authors. These equations are assumed on the basis of qualitative characteristics among inputs, responses and control variables. As for an objective condition of active control, the structural response displacement at the top floor is employed as a control target. As for constraint conditions, the value of control force and the stroke of the actuator are employed as control targets. In this paper, piece-wise linear response equations are assumed as shown in Eqs.(3-4)-(3-6).

Structural response displacement: $$Y^{P}_{i+1} = a_{i+1}\cdot\ddot{X}^{P}_{i+1}/\alpha_{i+1} \tag{3-4}$$

Stroke of actuator: $$S^{P}_{i+1} = b_{i+1}\cdot\ddot{X}^{P}_{i+1} \tag{3-5}$$

Control forces: $$U^{P}_{i+1} = c_{i+1}\cdot\alpha_{i+1}\cdot\ddot{X}^{P}_{i+1} \tag{3-6}$$

$$a_{i+1} = \max\{a_{i-1}, a_i\} \tag{3-7}$$

$$b_{i+1} = \max\{b_{i-1}, b_i\} \tag{3-8}$$

$$c_{i+1} = \max\{c_{i-1}, c_i\} \tag{3-9}$$

Here, Y^{P}_{i+1}, S^{P}_{i+1} and U^{P}_{i+1} denote predicted maximal values of the response displacement at the top floor, the stroke of actuator and the control force in the i+1-th control interval. a_{i+1}, b_{i+1} and c_{i+1} are parameters and are identified by using observed data in past two control intervals as shown Eqs. (3-7)-(3-9), in which Eqs. (3-4)-(3-5) are applied to observed data, and parameters in i-1-th and i-th control intervals are determined.

3.3 Fuzzy Maximizing Decision

In IFOAC system, the optimal control variable in the next control interval is determined by fuzzy maximizing decision (Bellman and Zadeh 1970) by using assumed membership functions. In this system, three membership functions are assumed as shown in Fig.3-1. The structural response displacement D are employed as the objective condition, and the control force U and the stroke S are employed as constraint conditions. In Fig.3-1, values of Dh, Uh and Sh are defined as target values of the active control. By using assumed membership functions and predicted values of earthquake inputs, predicted structural responses are transformed into membership values μ and control variables α plane as shown in Fig.3-2. An optimal membership value μ^* and an optimal control variable α^* are determined by fuzzy maximizing decision as shown in Fig.3-2.

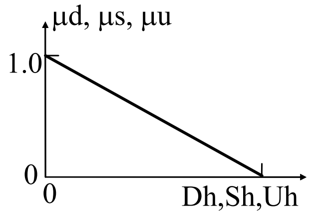


Figure 3-1 Membership Functions in IFOAC System

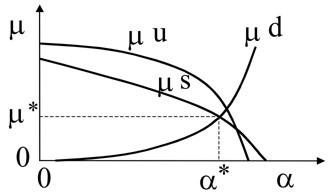


Figure 3-2 Fuzzy Maximizing Decision

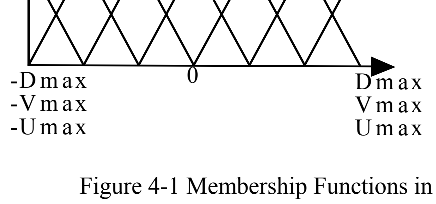
3.4 Setting of Membership Functions by Parametric Study

In this research, it is necessary to have the control performance which can control without maximal stroke and control force exceeding the limit of actuator performance for every assumed seismic waves when IFOAC is performed. Then the membership functions of IFOAC are determined as follows by parametric study (1cm unit to 1~15cm about Dh, 50cm unit to 50~100cm about Sh and 50tf unit to 50~150tf about Uh) for all assumed seismic waves. As the results, following values are determined as target values of membership functions; i.e.; Dh=14cm, Sh=100cm, Uh=150tf.

4 Outline of Reflective Fuzzy Active Control (RFAC) System

4.1 Fuzzy Control Rules

In RFAC system, each fuzzy control rule consists of IF (former=displacement and velocity) and THEN (latter=control force) as shown in Table4-1. Former means structural response displacements and velocities. Latter means control force in case of RFAC system. Seven triangle membership functions as shown in Fig.4-1 are assumed in accordance with linguistic representations in Table4-1. Max-min method is employed as an inference method. Center of gravity method is employed as a defuzzification method.



PB: positive big
PM: positive medium
PS: positive small
ZR: zero
NS: negative small
NM: negative medium
NB: negative big

Figure 4-1 Membership Functions in RFAC System

Table4-1 Fuzzy control rules

		DISPLACEMENT						
		NB	NM	NS	ZR	PS	PM	PB
VELOCITY	NB	PB	PB	PB	PB	PB	PB	PB
	NM	PM	PM	PM	PM	PM	PM	PM
	NS	PS	PS	PS	PS	PS	PS	PS
	ZR	ZR	ZR	ZR	ZR	ZR	ZR	ZR
	PS	NS	NS	NS	NS	NS	NS	NS
	PM	NM	NM	NM	NM	NM	NM	NM
	PB	NB	NB	NB	NB	NB	NB	NB

CONTROL FORCE

4.2 Tuning of Fuzzy Control Rules by GAs

In this research, RFAC system is required to have the control performance which can fully reduce a response to such a sudden changes of earthquake input. However, it is difficult and not realistic to employ control devices with huge active control forces. So, the fuzzy control rules are tuned up (optimized) by using GA in order to reduce responses appropriately within the limits of actuator performance. In this research, fuzzy control rule matrix and Dmax (displacement), Vmax (velocity), and Umax (control force) in the membership function are optimized. Here, as a rule matrix is shown in Table4-2, seven points of a~g, which are linguistic rules for control forces, are optimized, and an other rules are determined by liner interpolation. Dmax and Vmax are determined as shown in a Eqs. (4-1) and (4-2) on the basis of the maximal response displacement Dn and the maximal response velocity Vn without control in each seismic waves. Here, DR and VR are assumed to be the constants of [0, 1], and optimized.

$$\mathrm{Dmax} = \mathrm{Dn} \times \mathrm{DR} \tag{4-1}$$

$$\mathrm{Vmax} = \mathrm{Vn} \times \mathrm{VR} \tag{4-2}$$

Here, in order to determine Umax, following two cases are assumed.

[case1] The value of Umax is fixed to the limits of the maximal control force which is determined by actuator performance.

[case2] The value of Umax is optimized by GA within the limits of the maximal control force.

Table4-2 Fuzzy control rules as the object of optimization

		DISPLACEMENT						
		NB	NM	NS	ZR	PS	PM	PB
VELOCITY	NB	PB			a			b
	NM							
	NS							
	ZR	c			d			e
	PS							
	PM							
	PB	f			g			NB

CONTROL FORCE

4.2.1 Geno-Type (G-Type)

Assumed G-Type for optimization is shown in Fig.4-2 in [case2]. Each bit of a~g of G-Type expresses with the integer number of [0, 6] and made to correspond to the linguistic expression of a fuzzy control rules such as 0: NB, 1: NM, 2: NS, 3: ZR, 4: PS, 5: PM, 6: PB, respectively. Moreover, each bit of DR, VR, and Umax expresses with the integer number of [0, 9]. Every these bits of DR, VR, Umax are transformed to real values as shown in Fig.4-2. In addition, the portion of Umax is not used in [case1].

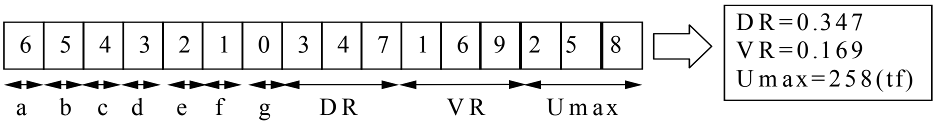


Figure 4-2 G-Type for Tuning of Fuzzy Control Rules

4.2.2 Evaluation Function

The evaluation function Eval_F used for optimization of a fuzzy control rules is assumed as shown Eq. (4-3). Evaluations are performed using three membership functions of maximal response displacement (D), the maximal stroke (S), and the maximal control force (U) as shown in Fig.4-3. GA is performed as a maximization problem of Eval_F.

$$\mathrm{Eval}_F = \mu_D \times \mu_S \times \mu_U \tag{4-3}$$

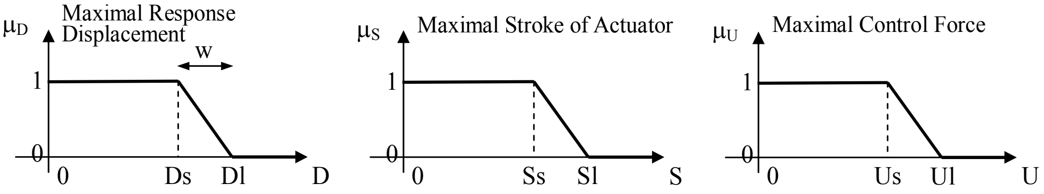


Figure 4-3Membership Functions for Eval_F

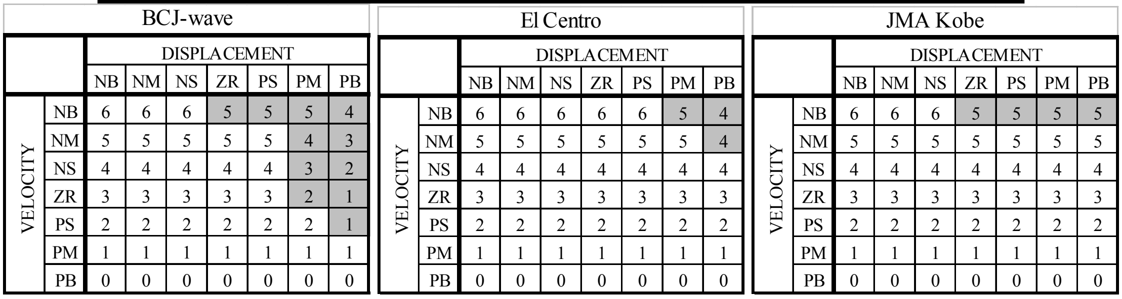
Here, Dl is taken as the maximal response displacement at the time of IFOAC (for RFAC reduces response displacement rather than IFOAC at least). Sl and Ul are taken as the limits of the assumed actuator performance. Moreover, target values Ss and Us are assumed in consideration of safety. In optimizing, the rules which can reduce response displacement are searched within the limits of actuator performance by enlarging w every 0.5cm.

4.2.3 Results of Tuning of Fuzzy Control Rules

As for the earthquake inputs used for optimization a BCJ-wave (Homepage of Buiding Centrer of Japan), El Centro, and JMA Kobe are employed. Here following values are assumed, i.e.; Sl=150cm, Ul=200tf (performance limit of an actuator), Ss=125cm, and Us=175tf (target values for safety). As for initial conditions of GA operations, total generations and number of families are assumed to be 10000 and 10, respectively. The results of optimization on [case1] and [case2] are shown in Tables 4-3 and 4-4, respectively. Moreover, the portion of the gray in control rule matrixes expresses the change portion by displacement.

Table4-3 Optimized fuzzy control rules by [case1]

Input earthquake	Dl (cm)	w (cm)	Eval	DR	VR	Dmax (cm)	Vmax (cm/sec)	Umax (tf)
BCJ-wave	13.54	5	0.986	0.833	0.39	20	86	200
El Centro	9.83	1	0.923	0.377	0.649	5	83	200
JMA Kobe	10.31	2	0.903	0.348	0.393	8	81	200



BCJ-wave

		DISPLACEMENT						
		NB	NM	NS	ZR	PS	PM	PB
VELOCITY	NB	6	6	6	5	5	5	4
	NM	5	5	5	5	5	4	3
	NS	4	4	4	4	4	3	2
	ZR	3	3	3	3	3	2	1
	PS	2	2	2	2	2	2	1
	PM	1	1	1	1	1	1	1
	PB	0	0	0	0	0	0	0

El Centro

		DISPLACEMENT						
		NB	NM	NS	ZR	PS	PM	PB
VELOCITY	NB	6	6	6	6	6	5	4
	NM	5	5	5	5	5	5	4
	NS	4	4	4	4	4	4	4
	ZR	3	3	3	3	3	3	3
	PS	2	2	2	2	2	2	2
	PM	1	1	1	1	1	1	1
	PB	0	0	0	0	0	0	0

JMA Kobe

		DISPLACEMENT						
		NB	NM	NS	ZR	PS	PM	PB
VELOCITY	NB	6	6	6	5	5	5	5
	NM	5	5	5	5	5	5	5
	NS	4	4	4	4	4	4	4
	ZR	3	3	3	3	3	3	3
	PS	2	2	2	2	2	2	2
	PM	1	1	1	1	1	1	1
	PB	0	0	0	0	0	0	0

Table4-4 Optimized fuzzy control rules by [case2]

Input earthquake	Dl (cm)	w (cm)	Eval	DR	VR	Dmax (cm)	Vmax (cm/sec)	Umax (tf)
BCJ-wave	13.54	6.5	0.965	0.256	0.22	6	49	175
El Centro	9.83	2	0.896	0.665	0.322	10	41	175
JMA Kobe	10.31	2.5	0.802	0.386	0.313	9	64	175

BCJ-wave								
		DISPLACEMENT						
		NB	NM	NS	ZR	PS	PM	PB
VELOCITY	NB	6	6	6	6	6	6	6
	NM	5	5	5	5	5	5	5
	NS	4	4	4	4	4	4	4
	ZR	3	3	3	3	3	3	2
	PS	2	2	2	2	2	2	2
	PM	1	1	1	1	1	1	1
	PB	0	0	0	0	0	0	0

El Centro								
		DISPLACEMENT						
		NB	NM	NS	ZR	PS	PM	PB
VELOCITY	NB	6	6	6	6	6	6	5
	NM	5	5	5	5	5	5	5
	NS	4	4	4	4	4	4	4
	ZR	3	3	3	3	3	3	2
	PS	2	2	2	2	2	2	2
	PM	1	1	1	1	1	1	1
	PB	0	0	0	0	0	0	0

JMA Kobe								
		DISPLACEMENT						
		NB	NM	NS	ZR	PS	PM	PB
VELOCITY	NB	6	6	6	6	6	6	6
	NM	5	5	5	5	5	5	5
	NS	4	4	4	4	4	4	4
	ZR	3	3	3	3	3	3	3
	PS	2	2	2	2	2	2	2
	PM	1	1	1	1	1	1	1
	PB	0	0	0	0	0	0	0

5 Switching Rules of Active Control Forces in Hybrid Control System

5.1 Switcing Rules of Active Control Forces in Hybrid Control System

In this paper, 'Hybrid' means combining IFOAC system and RFAC system. In preceding papers, switching rules of active control forces are proposed on the response displacements (Mitsui, Ryu, Tani, Kawamura and Yao 2000) or the response velocities (Jibatake, Mitsui, Tani, Kawamura and Takizawa 2001). In this paper, switching rules are set up on both the response displacements and the response velocities as shown in Table5-1. Here, 'a' and 'b' denote reference values of the response displacement and the response velocity, respectively. 'n0' and 'n1' correspond to IFOAC system or RFAC system, respectively.

Table5-1 Switching rules of control forces in hybrid control system

	$\lvert y \rvert \leq a$	$\lvert y \rvert > a$
$\lvert \dot{y} \rvert \leq b$	IFOAC system	n1
$\lvert \dot{y} \rvert > b$	n0	RFAC system

$y, \dot{y}$: response displacement (cm), response velocity (cm/sec) at the top floor

5.2 Optimization of Swichng Rules by GAs

Values of 'a' and 'b', and control methods of 'n0' and 'n1' in Table5-1 are optimized by using GA operations.

5.2.1 G-Type

Assumed G-Type is shown in Fig.5-1. First two bits are corresponded to 'n0' and 'n1' and are assumed as binary values, 0:IFOAC and 1:RFAC. Another 10 bits are corresponded to 'a' and 'b' and are assumed as decimal values and are transformed to real numbers as shown in Fig.5-1.

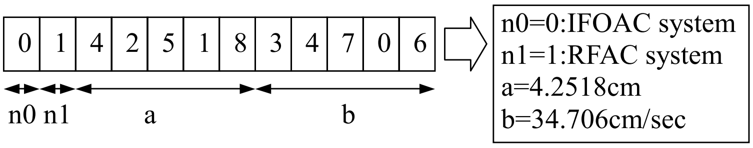


Figure 5-1 G-Type for Optimization of Switching Rules

5.2.2 Evaluation Function

The evaluation function Eval_H used for optimization of the switching rules by GA is assumed as shown Eq. (5-1). GA operations are performed as a maximization problem of Eval_H.

$$\mathrm{Eval}_H = \mathrm{Eval}_I \times \mathrm{Eval}_M \qquad (5\text{-}1)$$

Eval_I is the evaluation for every control interval, and is assumed as shown Eq. (5-2) using the membership function of IFOAC as shown in Fig.3-1. In this evaluation, minimal values of membership functions on response displacements, strokes and control forces in each control interval are summed up in all control interval.

$$\mathrm{Eval}_I = \sum_{i=1}^{n} \mathrm{Min}(\mu_d, \mu_s, \mu_u) \quad \text{n: total number of control interval} \qquad (5\text{-}2)$$

Eval_M evaluates to each maximal response values (response displacements, strokes and control forces) using the membership function shown in Fig.5-2, and Eval_M is assumed as shown Eq. (5-3). The same values mentioned in section 4.3 are used for Dl, Sl, and Ul in Fig.5-2.

$$\mathrm{Eval}_M = \mu_D \times \mu_S \times \mu_U \qquad (5\text{-}3)$$

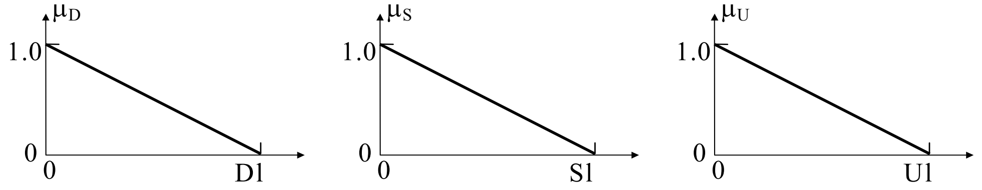


Figure 5-2 Membership Functions for Eval_M

5.2.3 Results of Optimization of Switching Rules

Initial conditions of optimization are the same as those of the case of a fuzzy control rules, and the result of optimization on [case1] and [case2] is shown in Tables5-2 and 5-3, respectively.

Table5-2 Optimized switching rules by [case1]

Input earthquake	Dl (cm)	Eval	a (cm)	b (cm/sec)	n0	n1
BCJ-wave	13.54	0.474	0.24	35	1	1
El Centro	9.83	0.3	1.59	4.8	1	1
JMA Kobe	10.31	0.691	0.58	48.5	1	1

Table5-3 Optimized switching rules by [case2]

Input earthquake	Dl (cm)	Eval	a (cm)	b (cm/sec)	n0	n1
BCJ-wave	13.54	0.452	0.23	74.8	1	1
El Centro	9.83	0.336	0.42	60.7	1	1
JMA Kobe	10.31	0.788	0.44	44	1	1

6 Results of Digital Simulations on Active Control

The results of the active control simulation using the optimal rules by a BCJ-wave and JMA Kobe (named 'BCJ rule' and 'Kobe rule', respectively) are shown in Figs.6-1 and 6-2. In Figs.6-1 and 6-2, the maximal response values are compared. Moreover, the results on the performance of active control in case of Taft and JMA Kobe using the Kobe rule are shown in Figs.6-3 and 6-4.

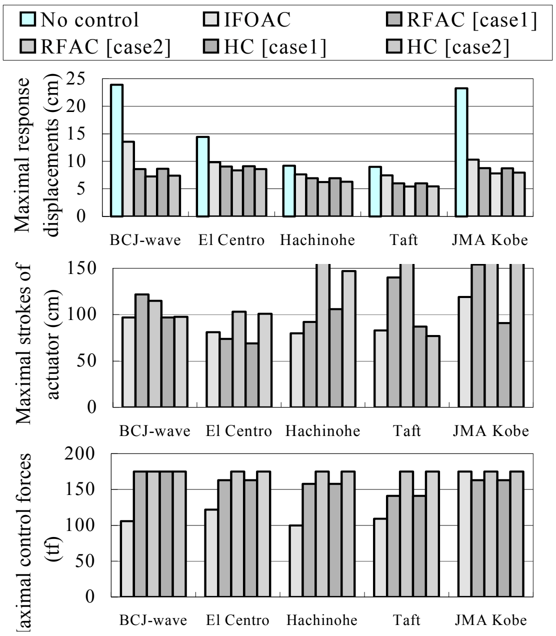


Figure 6-1 Control Results (BJC Rule)

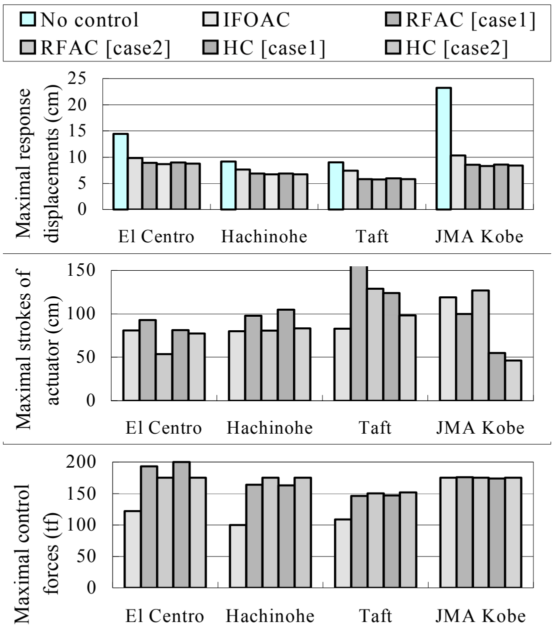


Figure 6-2 Control Results (Kobe Rule)

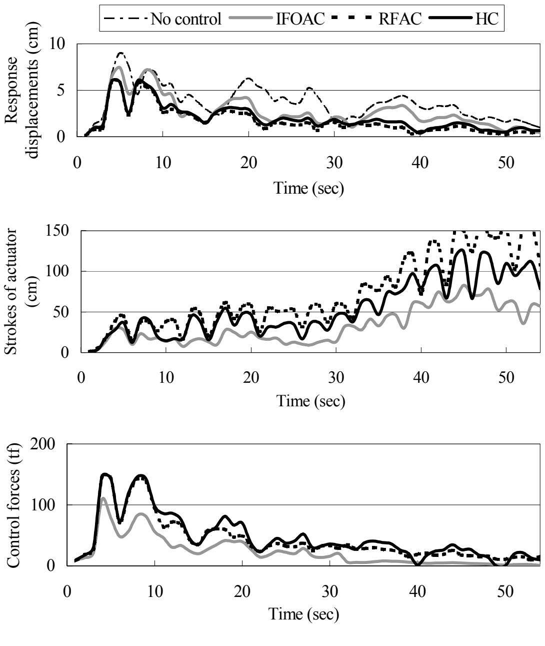


Figure 6-3 Control Results by Taft (Kobe Rule)

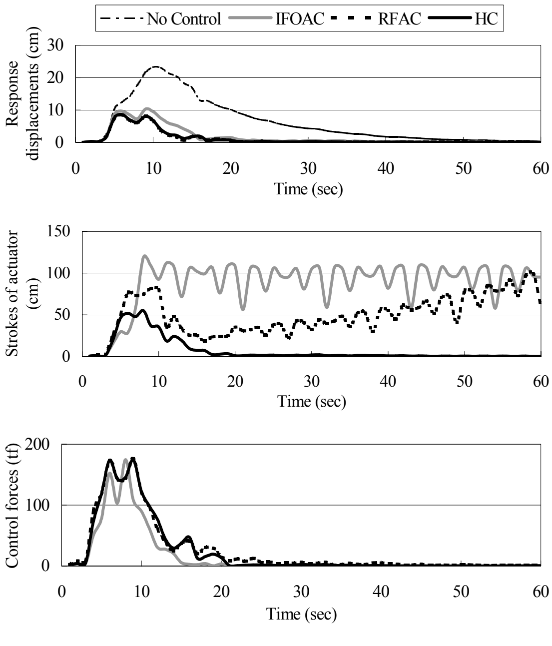


Figure 6-4 Control Results by Kobe (Kobe Rule)

7 Discussion

Each of optimized fuzzy control rules in Tables4-3 and 4-4 becomes a rule with the strong influence on response velocity. This features are observed strongly in the results of [case2].

The optimized switching rules of active control forces in Tables5-2 and 5-3, show that the active control force calculated by the RFAC system is considered to be selected in almost all cases, because the value of ‘a’ is small compared with the maximal response displacements and fuzzy control is chosen in both ‘n0’ and ‘n1’ in [case 1] and [case 2].

In comparison with the maximal responses as shown Fig.6-1 and 6-2, the order of maximal response displacements became in ‘non-controlling > IFOAC > RFAC’ in all cases. Moreover, in hybrid control, maximal response displacements became almost equivalent to RFAC. Therefore, in hybrid control, the reduction effect of the responses by RFAC is employed efficiently. Furthermore, in hybrid control, maximal strokes can be controlled smaller than that in RFAC in almost all cases. In many cases, maximal strokes become the middle values of IFOAC and RFAC such as Fig.6-3. Especially, to earthquake input of JMA Kobe, the reduction effect of response displacements in hybrid control is larger than that in IFOAC. In this case, the maximal stroke in hybrid control is smaller than that in IFOAC under the almost equivalent maximal control forces in hybrid control such as Fig.6-4. So, the effectiveness of the hybrid control to near-source earthquake such as JMA Kobe is verified. In comparison with [case1] and [case2], while the reduction effect of responses in [case2] is larger than tha in [case1], the strokes also become larger.

As mentioned above, in the range of this paper, it is considered that ‘Kobe rule’ is the optimal rule. Therefore, it is effective that optimizations are performed by using the earthquake inputs by which responses of structure become largest inside of the assumed earthquakes.

8 Conclusion

In this paper, in order to adapt structural control systems for near-source earthquakes, a hybrid control (HC) system is proposed, in which the intelligent fuzzy optimal active control (IFOAC) system and the reflective fuzzy active control (RFAC) system are combined. Optimizations on fuzzy control rules in RFAC system and switching rules of active control forces in HC system are performed by Genetic Algorithms (GAs). Digital simulations are carried out and following conclusions are obtained:

1) HC system, the effectiveness of both IFOAC and RFAC systems is obtained.
2) HC system can reduce maximal response displacements and can restrict strokes of the actuator effectively, especially in case of JMA Kobe, which is a typical near-source earthquake.
3) It is effective to perform the optimization supposing large earthquake when the safety of control equipments are taken into consideration.
4) As a future subject, performing multiplex optimizations of IFOAC, RFAC, and HC systems are mentioned.

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