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AN EVOLUTIONARY HYBRID CONTROL SYSTEM OF BUILDING STRUCTURES BY FUZZY AND GA LOGIC

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SUMMARY

In this paper, an evolutionary hybrid control system is proposed. The word “hybrid” means a combination of seismic intelligent and reflective fuzzy active control methods and the word “evolutionary” means that proposed system can be evolved by GA. In the former intelligent fuzzy control, adaptive fuzzy predictive and optimal methods are employed. In the latter, reflective fuzzy control, a structural system can be controlled by fuzzy set rules evolved by GA. Digital simulations are performed to compare the results of intelligent, fuzzy and hybrid control systems. Simulations show the following things: In case of the intelligent fuzzy control, responses of structural displacements, strokes of actuators and control forces can be restricted within allowable limits. In case of reflective fuzzy control, effectiveness of control is larger than intelligent fuzzy one for extremely large structural responses. However it can’t especially restrict the strokes of actuators. Therefore, it is concluded that hybrid active control system has both the merits of two kinds of control methods. Here, the effectiveness of the proposed evolutionary hybrid active control system is verified by digital simulations.

INTRODUCTION

The Hyougoken-Nanbu Earthquake, January 1995, Japan was a typical urban and near-source earthquake. Another example of such an earthquake was the American Northridge Earthquake that happened in January 1994.The most distinguished features observed from such earthquake were a few velocity pulses with relatively long periods and large amplitudes. On the other hand, far-field earthquake motions show relatively continous vibration types. The objective of this research is to develop an evolutionary intelligent seismic control system for building structures that can respond effectively to all kinds of earthquake including near-source and far-field ones.

The authors have already proposed an intelligent fuzzy control system, i.e., predictive, adaptive and optimal active control system based on fuzzy theory for building structures with AMD (active mass driver) type subjected to seismic loading [Zadeh, L. A., 1965] [Kawamura, H. and Yao, J. T. P., 1990] [Yao, J. T. P., 1972] [Kawamura, H., Tani, A., Watari, Y. and Yamada, M., 1990] [Tani, A. and Kawamura, H. 1992]. In this research improvements are intended.

(1) A hybrid fuzzy optimization system in which fuzzy control rules and fuzzy maximizing decision are used is studied. The former is suitable for accidental inputs and reflective control. The latter can perform optimization from the point of view of a total balance with given conditions.

(2) An evolutionary system with membership functions, i.e., objective assessment functions used in the above hybrid fuzzy optimization system. In this system, GA(Genetic Algorithm) is adopted so that an optimal and evolutionary design of active control systems can be performed.

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FUNDAMENTAL THEORY OF EVOLUTIONARY HYBRID ACTIVE CONTROL SYSTEM

Fundamental assumption

An objective structure is assumed to be a five-degree-of-freedom system. The objective structure has an active mass driver (AMD) at the top of it as shown in Figure 1. Control force is inclined by the reaction against inertia which appears by the mass of AMD. The intelligent fuzzy control is performed by means of equivalent damping method. The equations of motion are shown as follows.

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

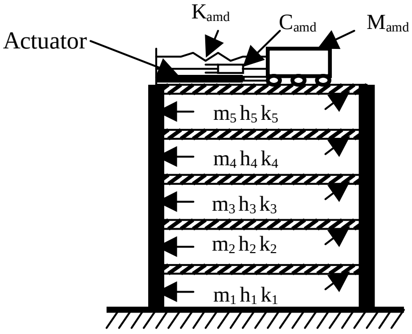
$$m_i\ddot{y}_i + c_i(\dot{y}_i - \dot{y}_{i-1}) - c_{i+1}(\dot{y}_{i+1} - \dot{y}_i) + k_i(y_i - y_{i-1}) - k_{i+1}(y_{i+1} - y_i) + = -m_i\ddot{z} \text{ @ (@} = 2,.., 4) \tag{2}$$

$$m_5\ddot{y}_5 + c_5(\dot{y}_5 - \dot{y}_4) - c_{amd}(\dot{y}_{amd} - \dot{y}_5) + k_5(y_5 - y_4) - k_d(y_{amd} - y_5) + f = -m_5\ddot{z} \tag{3}$$

$$m_{amd}\ddot{y}_{amd} + c_{amd}(\dot{y}_{amd} - \dot{y}_5) + k_{amd}(y_{amd} - y_5) - f = -m_{amd}\ddot{z} \tag{4}$$

$$f = u_c = \alpha \cdot \dot{y}_5 \quad \text{(in case of the intelligent fuzzy control)} \tag{5}$$

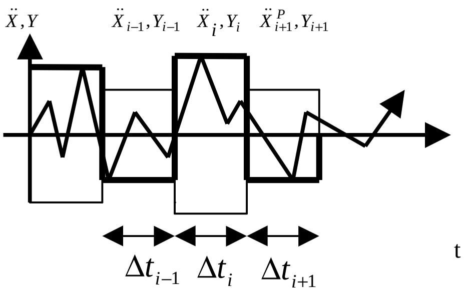
In this paper, $\ddot{y}, \dot{y}, y$ means relative response acceleration, velocity and displacement and $\ddot{x}$ means input acceleration of earthquake ground motion. In Eq (4), $\ddot{y}_{amd}$, $\dot{y}_{amd}$ and y_{amd} means relative response acceleration, velocity and displacement of AMD. If hybrid control chooses intelligent fuzzy control, u_c means control force and α means control variable in case of equivalent damping method. In case of hybrid control, active control force is determined by whether intelligent fuzzy control or reflective fuzzy control mentioned after.



m: mass
k: stiffness
c: coefficient of viscous damping
m_{amd}: mass of AMD
k_{amd}: stiffness of AMD
c_{amd}: coefficient of viscous damping of AMD

Figure 1: Assumed five-degree-of-freedom structure

Furthermore, control interval time Δt as shown in Figure 2 is also introduced to make it more practical [Kawamura, H. and Yao, J. T. P., 1990]. In Figure 2, x, y and t mean earthquake input, response of structure and time. Moreover, earthquake input and response of structure are predicted using $\ddot{X}_i, Y_i$ which express maximum of absolute value in Δt_i. Control variable (α_I) is assumed to be constant in each Δt.



Δt : control interval
$\ddot{X}$: maximal absolute value of earthquake input in Δt
Y : maximal of absolute value of response of structure in Δt

Figure 2: Assumption to input and responses

A flow of hybrid active control system

In this paper, intelligent fuzzy control system and reflective fuzzy control system are combined. Intelligent fuzzy control consists of three systems which are already proposed: (1)prediction of earthquake input (2)structural identifucation (3)fuzzy maximizing decision [Bellman,R.E. and Zadeh,L.A., 1970]. On the other hand, conditioned fuzzy set rules are employed in fuzzy control system.

Figure 3 shows a flow chart of hybrid control system used in this research. This hybrid active control system has the following special and intelligent features,: 1) Objective and constraint conditions of active control are described with membership functions of fuzzy theory, 2) Prediction of earthquake input and the structural identification are performed in real time, 3) An optimal control variable is determined by means of fuzzy maximizing decision, and 4) Fuzzy control system is employed as the reflective fuzzy control system against unexpected large disturbance.

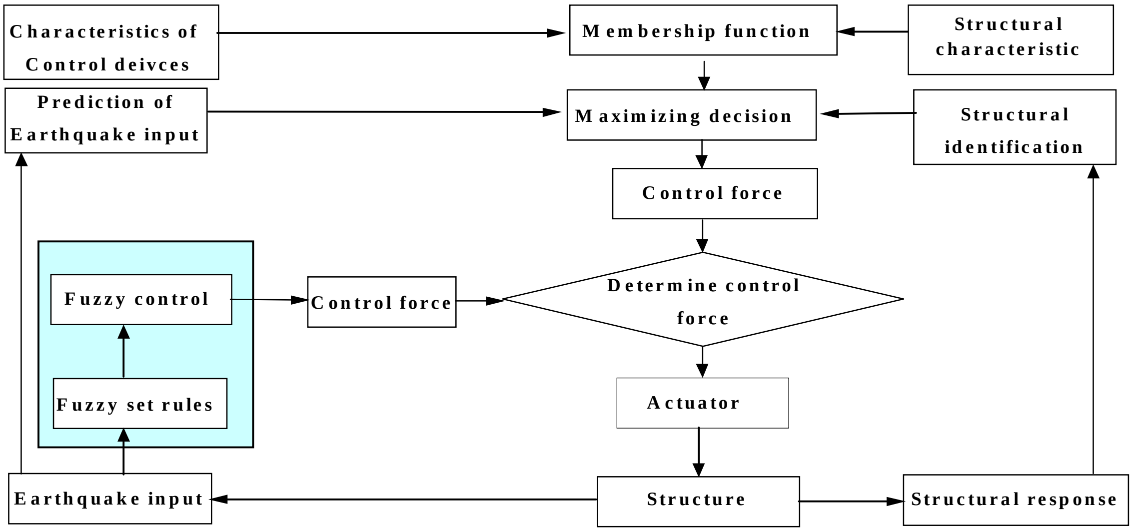


Figure 3: A flow chart of hybrid active control system

INTELLIGENT FUZZY CONTROL SYSTEM

Prediction of earthquake input

As for the prediction method of earthquake input, conditioned fuzzy set rules [Kawamura, H., Tani, A., Yamada, M and Tsunoda, K., 1990][Kawamura, H., Tani, A. and Yamada, M., 1992] proposed by authors are employed. In this method, the next predicted increment of $\ddot{X}^{P}_{i+1}$ is determined by using the first and the second order differences $\Delta\ddot{X}_{i}$ and $\Delta\ddot{X}^{2}_{i+1}$.

Structural identification

In intelligent system, the next optimal control variable α_{i+1} is defined by maximizing decision considering the membership functions of the next relative story displacement $Y^{P}{}_{i+1}$, the next control force $U^{P}{}_{i+1}$ and the next stroke of actuator S^{P}_{i+1}. So, it is necessary to identify the relations among $Y^{P}{}_{i+1}$, S^{P}_{i+1}, $U^{P}{}_{i+1}$ and α_{i+1} at the next control interval Δt_{i+1}. To identify these relations, following simple piece-wise linear response equations [Kawamura, H., Tani, A., Yamada, M and Tsunoda, K., 1990][Kawamura, H., Tani, A. and Yamada, M., 1992] are assumed for $Y^{P}{}_{i+1}$, S^{P}_{i+1} and $U^{P}{}_{i+1}$:

$$Y_{i+1}^{P} = a_{i+1} \cdot X_{i+1}^{P} / \alpha_{i+1} \qquad (6)$$

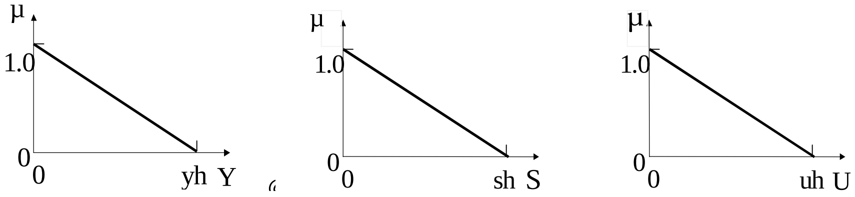
$$S_{i+1}^{P} = b_{i+1} \cdot \ddot{X}_{i+1}^{P} \qquad (7)$$

$$U_{i+1}^{P} = c_{i+1} \cdot \alpha_{i+1} \cdot \dot{y} \qquad (8)$$

where a_{i+1}, b_{i+1} and c_{i+1} are constant. These values are defined by using preceding response results at the i-1-th and i-th control intervals

Fuzzy maximizing decision

To perform maximizing decision [Bellman,R.E. and Zadeh,L.A., 1970], it is necessary to define membership functions of relative story displacement Y, stroke of actuator S and control force U. The desirable membership functions of Y, S and U are assumed as shown in Figure 4 to take into account of comfort, structural safety of buildings, economy and the limitation of control devices. By using Eqs. (6), (7) and (8), $Y^{P}{}_{i+1}$, S_{i+1}^{P} and $U^{P}{}_{i+1}$ are transformed into the μ -α_{i+1} plane. Values of μ^{*} and α^{*} are determined as the optimal membership degree and the optimal control variable.



(a) Relative story response of displacement Y (b) Stroke of actuator S (c) Control force U

Figure 4: Membership functions

REFLECTIVE FUZZY ACTIVE CONTROL SYSTEM

Fuzzy control rules

In reflective fuzzy control, conditioned fuzzy set rules consist of IF (former = displacement and velocity) and THEN (latter = control force) as shown in Figure 5. Former means response of displacement and velocity. Latter means control force in each control interval Δt. Fuzzy control rules are made empirically. Min-max method is employed to unite fuzzy assumption. Gravity method is employed as defuzzification method. 7 triangles of fuzzy variable are used to determine the fuzzy control rules as shown in Figure 6.

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

Control

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

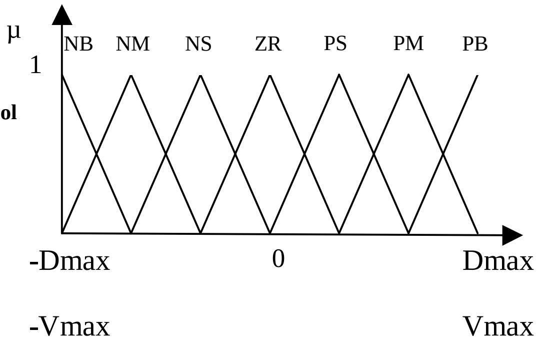


Figure 5: Conditioned fuzzy control rules **Figure 6: Fuzzy membership functions**

Optimization by using GA (Genetic Algorithm)

According to 4.1, maximal of absolute values of displacement (Dmax), velocity (Vmax) and control force (Umax) are employed in fuzzy control. So it is necessary to determine these three parameters to perform relative fuzzy control. For example, in order to aim for 50% reduction of response displacement compared with uncontrolled, optimal parameters have to be determined. To search the optimal parameters, GA (Genetic Algorithm) is employed, because GA is effective to search optimal parameters.

Method of GA (Genetic Algorithm)

From 4.2, the following equations are obtained:

$$V_R = V_{\max} / D_{\max} \qquad (9)$$

$$U_R = U_{\max} / D_{\max} \qquad (10)$$

Here, $D_{\max}$, $V_{\max}$ and $U_{\max}$ mean the maximal absolute values of displacement, velocity and control force mentioned in the section of 4.1. In order to aim 50% reduction of response displacement, $D_{\max}$ has to be half value of uncontrolled response displacement. Therefore, $D_{\max}$ is a constant in Eqs. (9) and (10). By using GA, optimal(such as 50% reduction) ratio V_R and U_R are determined.

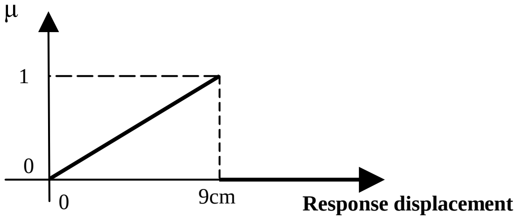
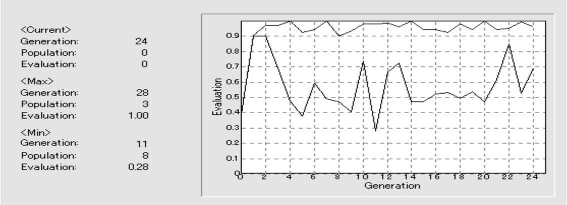


Figure 7: Evaluation function (in case of 50% reduction)

GA needs the evaluation function to evaluate each parameter. Here, each response displacement is evaluated. As the evaluation function, the membership function as shown in Figure 7 is assumed. In this case, earthquake wave of El Centro is employed. The maximal acceleration value is regulated into 350gal. 9cm is assumed to be the maximal value of the response displacement (▪ =1) because uncontrolled maximal response displacement indicates about 18cm.



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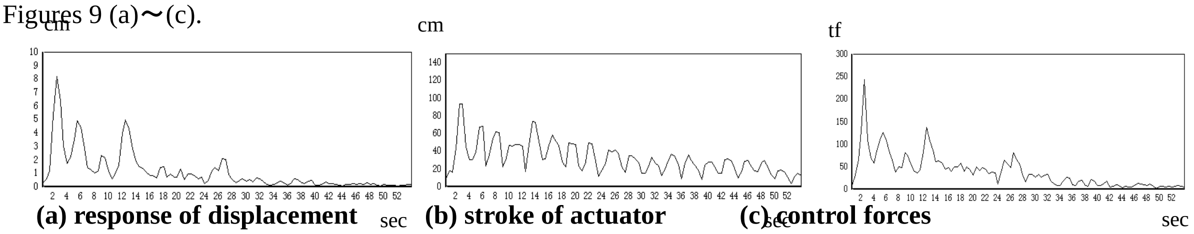
Population:         0
Evaluation:         0
<Max>
Generation:        28
Population:         3
Evaluation:      1.00
<Min>
Generation:        11
Population:         8
Evaluation:      0.28
```

Figure 8: The result of GA (Genetic Algorithm)

The convergence processes of evaluation are shown in Figure 8. It is shown that the ratio V_R and U_R tend to be almost constant whether earthquake input is large or small. In this case, the values of V_R become 21 and U_R become 59 respectively.

Result of reflective fuzzy control to aim for 50% reduction of response displacement

Thus the result of fuzzy control to aim for 50% reduction of response displacement is obtained as shown in Figures 9 (a)～(c).



(a) response of displacement **(b) stroke of actuator** **(c) control forces**

Fig.9 Results of operation GA

METHOD OF COMBINING INTELLIGENT AND REFLECTIVE FUZZY CONTROL SYSTEM

In hybrid control system, control forces of intelligent fuzzy system and reflective fuzzy system are determined simultaneously in each calculating interval. In this paper, activation methods of active control forces are changed in accordance with preceding response displacements y_5 at the top floor, i.e.; in case of y_5 larger than 4cm, the reflective fuzzy control is employed and in case of y_5 less equal 4cm, the intelligent fuzzy control is employed. The reason is that fuzzy control is more effective to the large displacement than the intelligent one.

RESULT OF DIGITAL SIMULATIONS

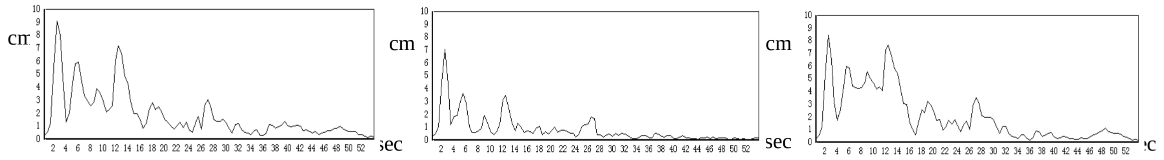
As earthquake input wave, El Centro as far-field earthquake, and Kobe (Hyogoken-Nanbu Earthquake) as near source earthquake are employed. These maximal absolute values of acceleration are regulated into 350gal. Assumed structural characteristics are as follows:

Mass of structure : $m = 510$ kg・sec^2/cm,
Spring constant of structure : $k = 500$ tf/cm,
Damping factor of Structure : $h = 0.01$,
Mass of AMD : $m_{amd} = 76.5$ kg・sec^2/cm,
Spring constant of AMD : $k_{amd} = 0.1$ tf/cm,
Damping factor of AMD : $h_{amd} = 0.5$,
Natural period of structure : $T = 0.703$ sec.

The linear acceleration method is employed as a numerical integration method and integration interval times are assumed to be 0.02 sec. In the intelligent fuzzy control, assumed membership functions are shown in Figure 4. Here, yh=15(cm), sh=200(cm) and uh=180(tf) are assumed. The control interval Δt is assumed to be 1.0sec. In the reflective fuzzy control, Dmax=7(cm), Vmax=357(cm) and Umax=1477(tf) are also used. These parameters are determined by GA. In this case, these parameters are set to aim for about 60% reduction of response displacement in case of El Centro.
Using the assumption mentioned above, the following digital simulations are carried out:

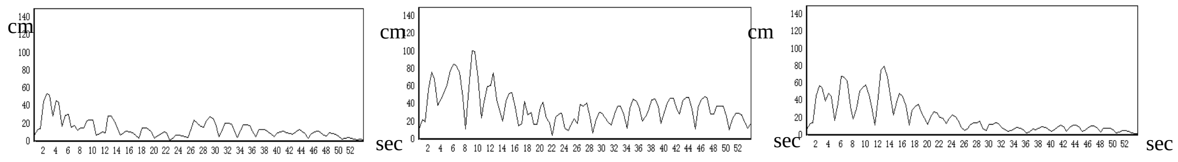
①To compare the reduction of response displacement among intelligent control, fuzzy control and hybrid control.
②To compare the restrict of stroke of actuator among intelligent control, fuzzy control and hybrid control.
③To compare the differences between El Centro Earthquake and Kobe (Hyougaken-Nanbu) Earthquake.
④To check the transit of control force in hybrid control. This means whether fuzzy control supplements the effect of intelligent control of reduction or not.

Figures 10, 11 and 12 shows the results of digital simulations of maximal response displacements at the top floor, maximal strokes of the actuator, and maximal control forces respectively in case of El Centro Earthquake. In each figure, the results of three control systems, i.e.; (a) intelligent fuzzy control, (b) reflective fuzzy control, (c) hybrid control are compared. In Figures 13, 14 and 15, the results of digital simulations in case of Kobe Earthquake are shown in the same manner.



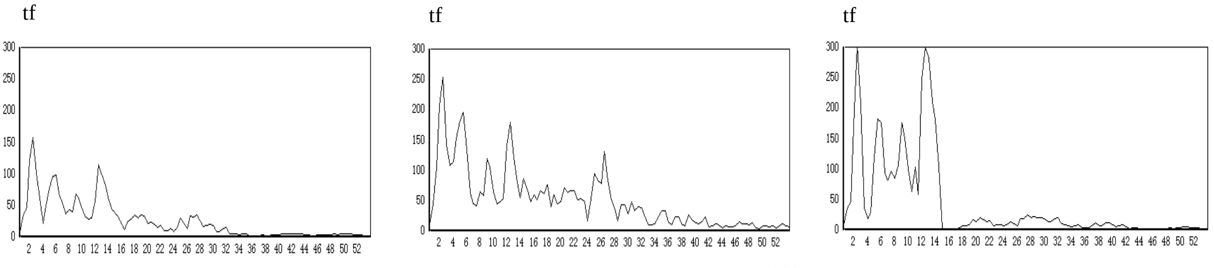
(a)intelligent fuzzy control **(b)reflective fuzzy control** **(c)hybrid control**

Figure 10: Response of displacements in each control method in case of El Centro earthquake



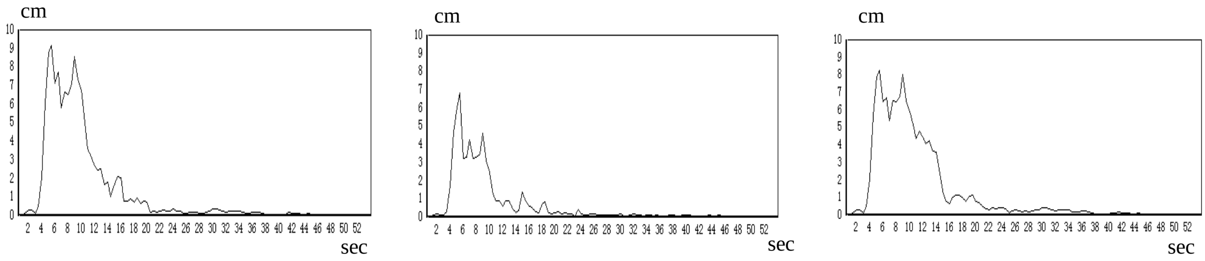
(a)intelligent fuzzy control **(b)reflective fuzzy control** **(c)hybrid control**

Figure 11: Strokes of actuator in each control method in case of El Centro earthquake



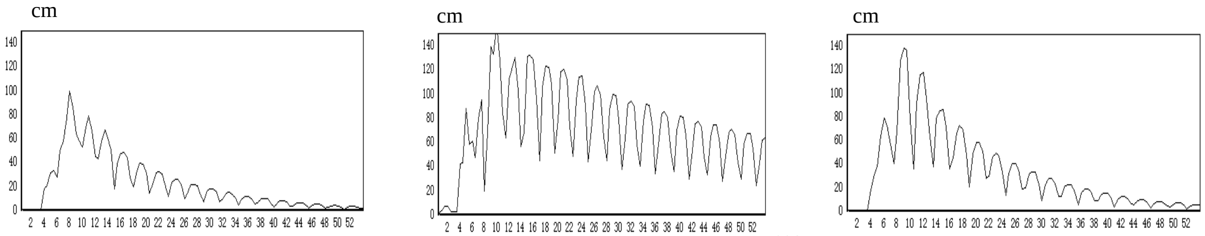
(a)intelligent fuzzy control (b)reflective fuzzy control (c)hybrid control

Figure 12: Control forces in each control method in case of El Centro earthquake



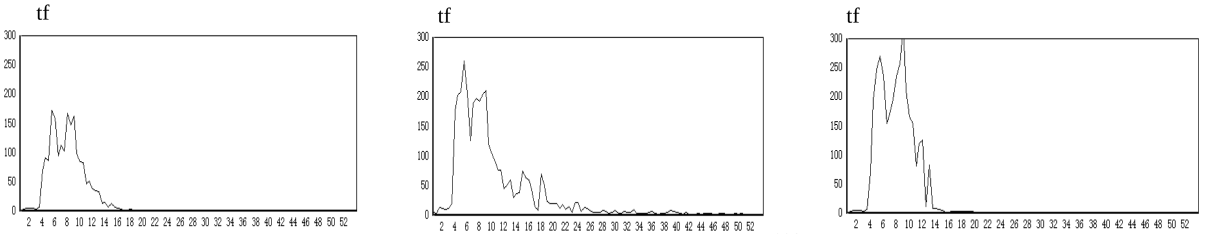
(a)intelligent fuzzy control (b)reflective fuzzy control (c)hybrid control

Figure 13: Response of displacements in each control method in case of Kobe earthquake



(a)intelligent fuzzy control (b)reflective fuzzy control (c)hybrid control

Figure 14: Strokes of actuator in each control method in case of Kobe earthquake



(a)intelligent fuzzy control (b)reflective fuzzy control (c)hybrid control

Figure 15: Control forces in each control method in case of Kobe earthquake

DISCUSSION

As for the maximal values of displacements as shown in Figures 10 (a)～(c) and Figures 13 (a)～(c), the reflective fuzzy control (b) indicates the smallest value and the intelligent fuzzy control (a) indicates the largest value among three methods. The hybrid control indicates almost the same values as the reflective fuzzy control. This means that hybrid control is suitable for large earthquake inputs as the reflective fuzzy control is.

As for the strokes of actuators as shown in Figures 11 (a) ～(c) and Figures 14 (a) ～(c), the strokes of reflective fuzzy control tends to remain large (b). The reason is that control forces are decided so reflectively that the origin of strokes can not necessarily be fixed. On the other hand, the values of the strokes in the intelligent fuzzy control (a) remain small. The reason is that membership functions (shown in Fig.4) restrict the strokes of actuators. The values of strokes in hybrid control are about half of the reflective fuzzy control.

It is proved that the control forces as shown in Figures 12 (a) ～(c) and Figures 15 (a) ～(c) in the hybrid control need more than the intelligent fuzzy control forces.

Judging from Figure 8, GA is proved to be effective to search the optimal fuzzy control rules. Here, V_R and U_R shown in Eqs. (9) and (10) seem to be constant when the reduction ratios of response displacements are determined.

CONCLUSION

In this paper, an evolutionary hybrid control system is proposed. Digital simulations are carried out to compare the results of the intelligent, reflective fuzzy and hybrid control systems. The following conclusions are obtained:

(1) By combining intelligent and reflective fuzzy control methods, the effectiveness of both the control methods is obtained in the hybrid control. This means the hybrid control can restrict the strokes of actuators and can reduce extremely and instantaneously large response displacements.
(2) By adding the reflective fuzzy control to the intelligent fuzzy control, this proposed hybrid control system becomes suitable for near-source earthquake motions with impulsive and large velocities, too and so for all types of earthquake motions.
(3) The parameters and characteristic values employed in this proposed evolutionary hybrid active control system, GA implies the possibility to optimize and to make system more evolutionary.

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