13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 0762

Shaking Table Tests on Intelligent Fuzzy Optimal Active Control System of Building Structures Adapting to Vibration Mode

Kentaro Yano[1], Akinori Tani[2], Hiroshi Kawamura[3] and Atushi Takizawa[4]

SUMMARY

In this paper, experimental researches on an intelligent fuzzy optimal active control system proposed by the authors are performed by shaking table tests and digital simulations. In order to clarify an applicability of the intelligent fuzzy optimal control system to multi-degree-of-freedom system, a two-degree-of freedom system with active mass driver (AMD) system is employed. As for an activation method of control forces, an input reduction method is employed. Results of shaking table tests and digital simulations show that response displacements can be reduced in accordance with assumed membership functions and the applicability of proposed system to multi-degree-of-freedom system is verified.

INTRODUCTION

In development of an active control system of architectural buildings, it is necessary to take account of uncertain loadings such as earthquakes and strong winds [1]. Generally, buildings are large-scale and complex, so it is difficult to perform predictions of external loadings and structural responses and these predictions are performed by observed and estimated data which include inevitable errors. Furthermore, it is necessary to take account of not only objective data but also subjective judgments of users, owners and/or experts of structural engineers. To develop an effective active control system of architectural buildings, it is necessary to consider these special features appropriately. Kawamura and Yao [2] have already proposed a basic idea of an active control system considered these features. A purpose of the research is to examine the effectiveness of fuzzy optimal [3]-[6] active control system [7]-[9] on multi-degree-of-freedom system because effectiveness of proposed system is clarified only in case of single-degree-of-freedom system. In the case of applying the system on two-degree-of-freedom system, it is necessary to consider the cases that higher mode such the secondary mode are predominant depending on the characteristic of structures. Then, in this paper, two patterns of shaking table test are performed, i.e.; 1) In case that the first mode is predominant and 2) the secondary mode is predominant. From now on, the former is named pattern 1, and the latter is named pattern 2. In this paper, different observation values are employed in Pattern 1 and Pattern 2, and shaking table tests are carried out. By using the

[1] Graduate Student, Graduate School of Science and Tech., Kobe Univ., Japan, y-ken0925@mail.goo.ne.jp
[2] Assoc. Prof., Graduate School of Science and Tech., Kobe Univ., Japan, E-mail:tani@arch.kobe-u.ac.jp
[3] Professor, Department of Architecture and Civil Eng., Faculty of Eng., Kobe University, Japan
[4] Research Assoc., Graduate School of Engineering, Department of Architecture, Kyoto University, Japan

results of shaking table tests and digital simulations, the effectiveness of proposed control methods are discussed and clarified.

BASIC THEORY OF INTELLIGENT FUZZY OPTIMAL ACTIVE CONTROL SYSTEM

Flow of intelligent active control system

Fig.1 shows a flow chart of an intelligent fuzzy optimal active control system employed in this paper. This system has following three features. The objective function and the constraint condition concerning the control are described with membership function of fuzzy theory [10]. The prediction of earthquake inputs and structural responses are performed in real time. An optimal control variable is determined by fuzzy maximizing decision [11] which is suitable for multi-objective optimization including both objective and subjective evaluations. The earthquake motion is measured by a sensor, and prediction of earthquake inputs is performed. On the other hand structural identification is also performed. A fuzzy maximizing decision is carried out by using the result of prediction of earthquake input and structural identification, and optimal control variable is determined in real time.

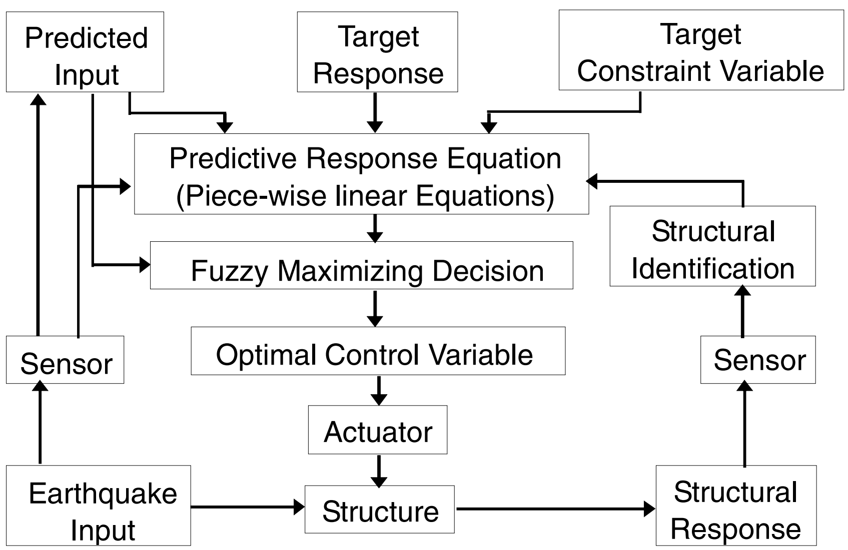


Fig.1 Flow Chart of Intelligent Fuzzy Optimal Active Control System

Basic assumption

In this paper, a two-degree-of-freedom system is employed as a specimen as shown in Fig.2. An active mass driver (AMD) system is introduced at the top of it. In fig.2, m_i, c_i, and k_i denote mass, damping factor and rigidity of the i-th floor (i=1, 2). Coefficients of m_d, c_d and k_d denote those of AMD. In this paper, active control forces are activated as inertia force m_d, then c_d and k_d is assumed to be zero. $\ddot{x}$, y and t also denote the earthquake input acceleration, the structure response displacement and time, respectively. Equations of motion are shown in Eqs.(1)-(3). As for an activation method of control forces, an input reduction method is employed.

Active control forces are calculated by Eq.(3) in case of activation method of an input reduction method and are activated to the structure in real time. In Eqs.(1) and (2), $\ddot{y}_j$, $\dot{y}_j$ and y_j denote the relative response accelerations, velocities and displacements of the structure from the foundation of it in j-th floor (j=1,2), respectively. $\ddot{x}$, U_m and α_I show the input accelerations, active control forces and control variables in case of the equivalent input reduction method. Subscript i in Eqs.(1)-(3) denotes a sampling number of earthquake input. In proposed system, a certain interval Δt is introduced as a control interval as shown in Fig.3. In Fig.3, X_i and Y_i denote maximal absolute value of input accelerations and structural responses in each Δt and predictions of input accelerations, structural responses, and fuzzy maximizing decision are performed by using these values in each Δt. The control variable is assumed to be constant in each Δt.

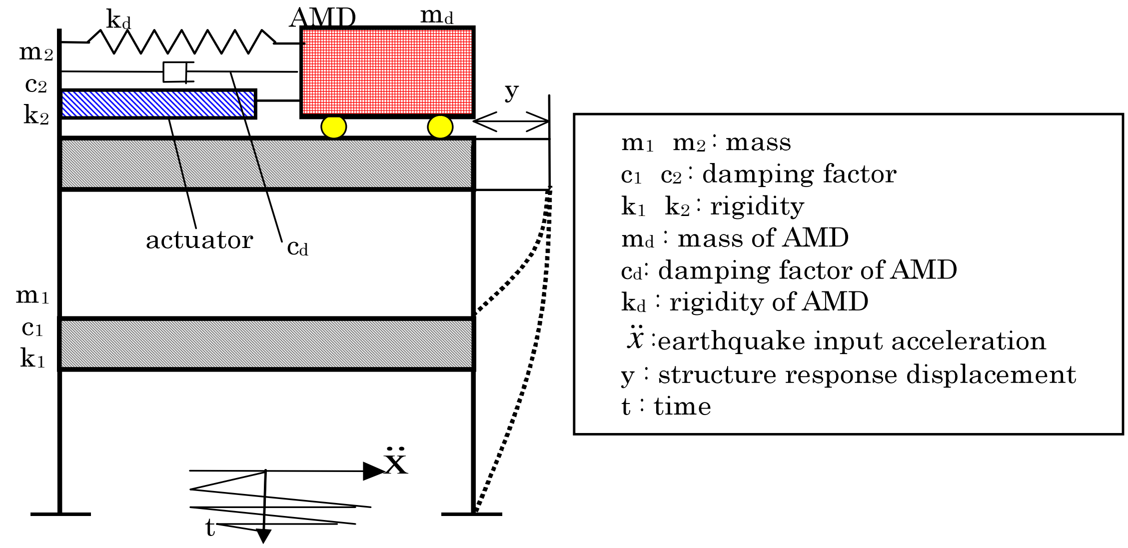


Fig.2 Objective Structure

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

$$m_2\ddot{y}_2 + c_2(\dot{y}_2 - \dot{y}_1) + k_2(y_2 - y_1) + u_m = -m_2\ddot{x}_i \quad (2)$$

$$u_m = -\alpha_i m_2 \ddot{x}_{i-1} \quad (3)$$

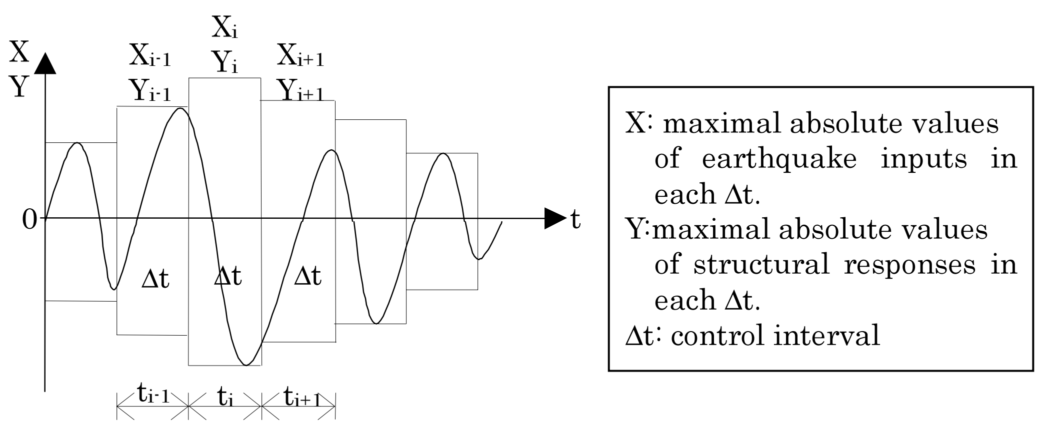


Fig.3 Assumption of input and response

Prediction of Earthquake Inputs

As for a prediction method of earthquake inputs, conditioned fuzzy set rules proposed by the authors are employed [2][3]. This conditional fuzzy set rule is obtained by statistical processing of observed seismic waves (Nos.1-4 in Table1). At first, the maximal absolute values of each earthquake wave in every Δt are calculated. In the next, the first and second differences value are calculated by Eqs.(4) and (5).

$$\Delta\ddot{X}_i = \ddot{X}_i - \ddot{X}_{i-1} \quad (4)$$

$$\Delta^2\ddot{X}_i = \ddot{X}_i - 2\cdot\ddot{X}_{i-1} + \ddot{X}_{i-2} \quad (5)$$

$$\ddot{X}^P_{i+1} = \ddot{X}_i + \Delta\ddot{X}_{i+1} \quad \text{(Superscript P is predictive value here.)} \quad (6)$$

Here, $\ddot{x}_i$ is the maximal absolute value of the input acceleration in each Δt. The frequency distributions of next increments are obtained statistically subject to representative first and second differences value. Maximal values of each frequency distribution are normalized 1, and membership functions of the conditioned fuzzy set rules are obtained subject to representative first and second difference value. An example of a part of conditioned fuzzy set rules is shown in Fig.4. In the prediction stage of earthquake inputs, first and second difference value are calculated by using observed data and apply to the conditioned fuzzy set rules. The membership functions of the conditional fuzzy set rules are interpolated in accordance with input data such as $\Delta\ddot{x}_i$ and $\Delta^2\ddot{x}_i$. Next increment is determined as a center of gravity of the interpolated membership function. The predicted value of the earthquake input in the next control interval is obtained by Eq.(6) as the maximal absolute value.

Table 1 Observed Earthquake Waves

No.	Place of Observation	Direction	Date of Occurrence	Duration (sec.)	Max.Acc. (gal)
1	Shin'ishikari Br.	TR	1968.5.16	50	186.9
2	Itajima Br.	TR	1968.4.1	40	198.1
3	Itajima Br.	LG	1968.8.6	11	199
4	Yihei Br.	TR	1968.10.16	16	175.9

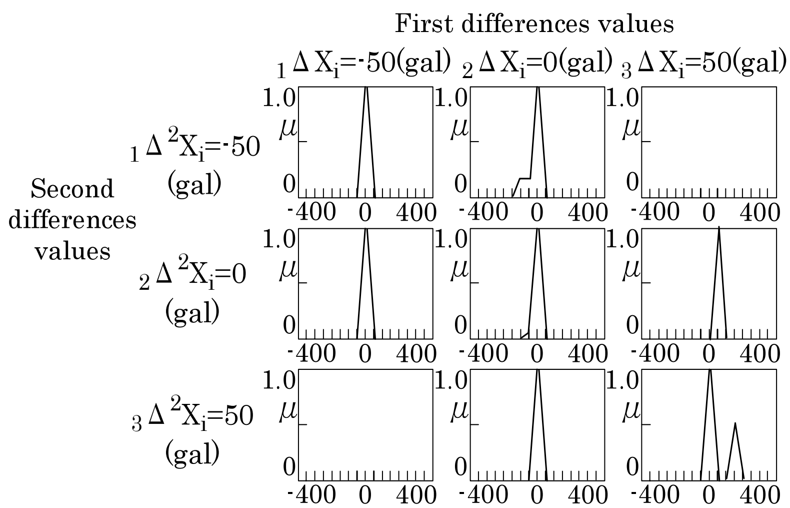


Fig.4 A part of conditioned fuzzy set rules

Prediction of Structural Responses

In this system, a next optimal control variable such as α_{Ii} in Eq.(3) is determined by fuzzy maximizing decision described in the next chapter. So, it is necessary to perform the structural identification and the prediction of structural responses in the next control interval. As for a prediction method of structural responses, piece-wise linear response equations also proposed by the authors [2][3] are employed. These equations are assumed based on qualitative characteristics of structural responses. In this paper, two equations as shown in Eqs.(7) and (8) are assumed. Eqs.(7) and (8) correspond to maximal response displacements Y and maximal control forces U in each control interval, respectively. In these equations, the relations among Y, U and α_I in the next control interval are identified.

$$Y^P_{i+1} = a_{i+1} \cdot (1 - \alpha_{Ii+1}) \cdot \ddot{X}^P_{i+1} \tag{7}$$

$$U^P_{i+1} = b_{i+1} \cdot \alpha_{Ii+1} \cdot \ddot{X}^P_{i+1} \tag{8}$$

p: prediction   i: number of Δt

Here, coefficients ‘a’ and ‘b’ are constant and these values are determined by using observed data in preceding i-1-th and i-th control intervals as follows:

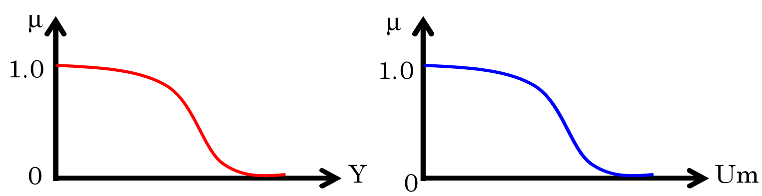
$$a_{i+1} = \max\{a_{i-1}, a_i\} \tag{9}$$

$$b_{i+1} = \max\{b_{i-1}, b_i\} \tag{10}$$

In Eqs.(9) and (10), maximal coefficients are employed in the engineering point of view.

Fuzzy maximizing decision

To perform fuzzy maximizing decision, it is necessary to define membership functions in accordance with objective and constraint conditions of the active control. Maximal relative displacements of the structure and maximal control forces are employed as objective and constraint conditions. A membership function of response displacement Y can be assumed as shown Fig.5(a) in consideration of comfort, structural safety and so on. Control force U can be also assumed as shown Fig.5(b) in consideration of economy and limitations of control devices, and so on. Predicted values of Y^{p}_{i+1} and U^{p}_{i+1} are obtained in accordance with assumed control variable α_{Ii+1} in the next control interval by Eqs.(7) and (8). By using these predicted values, assumed membership functions as shown in Fig.5 are transformed into those in μ-α_I plane as shown in Fig.6. Values of μ^* and α_I^* are determined as the optimal membership degree and the optimal control variable in the next Δt is determined by fuzzy maximizing decision.



(a) Response displacement Y (b) Control force U

Fig.5 Assumed membership functions

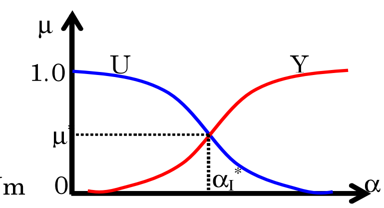


Fig.6 Fuzzy maximize decision

Specimen

In this paper, Specimen is assumed to be a two-degree-of-freedom system as shown in Fig.7, which is composed of steel plates. The composition component of specimen is shown in Table2. The nominal weight of specimens is 39kgf.

Table2 Member Lists of Specimen

Column	PL100.5×3.0
Beam	C-75×40×4×7
Floor	PL1.5

The outline of experimental system

The outline of the experimental system is shown in Fig.8. In this experimental system, two personal computers are used and are named as CPU1 and CPU2, respectively. These computers are connected each other. In CPU1 and CPU2, following operations are performed:

1) CPU1: a) DA translation to the shaking table, b) AD translation of observed responses of the specimen and the shaking table, c) Calculation of maximal absolute values of inputs and responses in each control interval, d) Output of the data as data files, e) Calculation of the optimal control variable in each control

interval. a)-d) is carried out in sampling time interval. e) and f) is carried out at the starting point of each control interval.

2) CPU2: a) Calculation of activation data to an actuator by using observed data in each 0.5 msec., b) Output of the data as the data files with respect to the activation of the actuator.

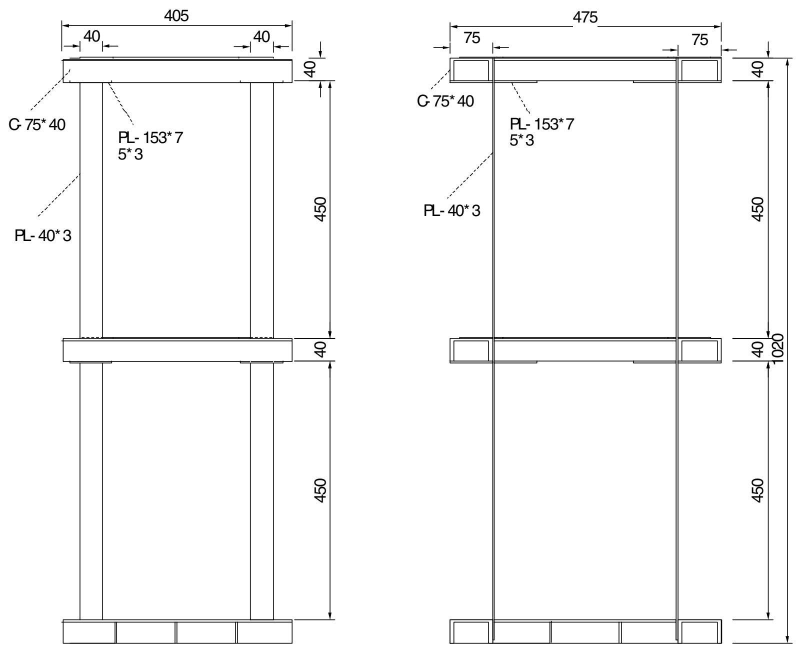


Fig.7 Specimen

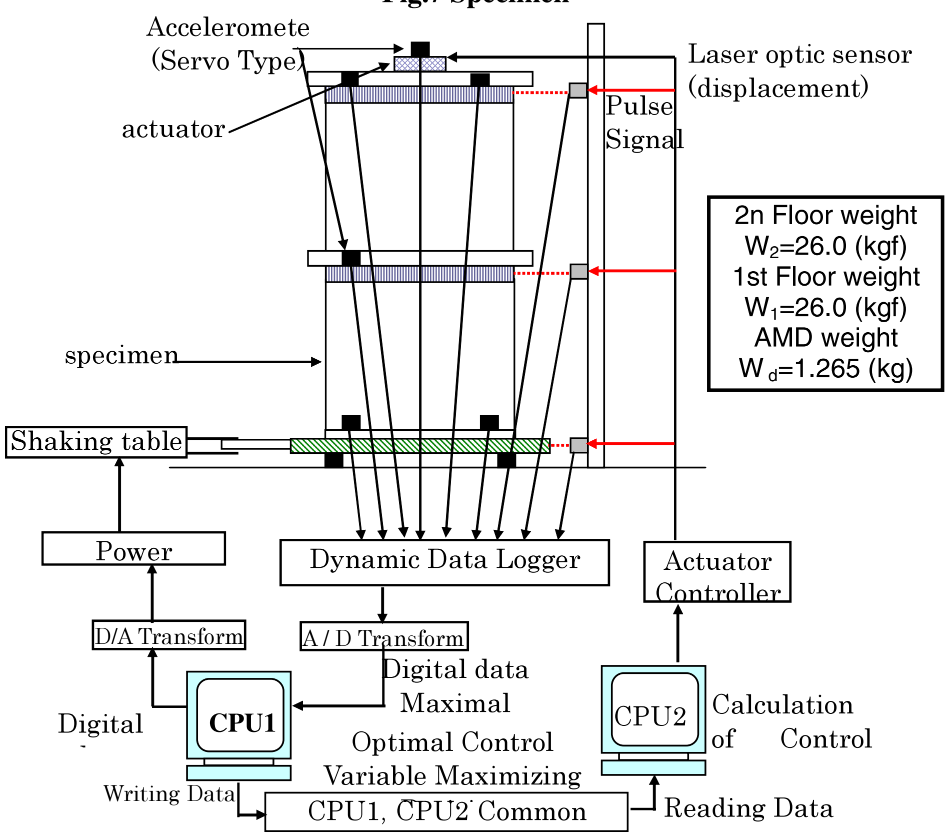


Fig.8 Configuration of Experimental System

Free vibration tests

To determine dynamical characteristics of the structure such as natural period and damping ratio of the specimen, free vibration tests are carried out. In the free vibration test, the shaking table is fixed and some displacements are forced to the top of the specimen. As the results of free vibration tests, the first natural period becomes 0.499 sec. and the damping factor becomes 0.00284 in the case of the Patern1 and the first natural period becomes 0.49 sec. and the damping factor became 0.002385 in the case of the Pattern2.

STRUCTURAL IDENTIFICATION

Structural identification of specimen

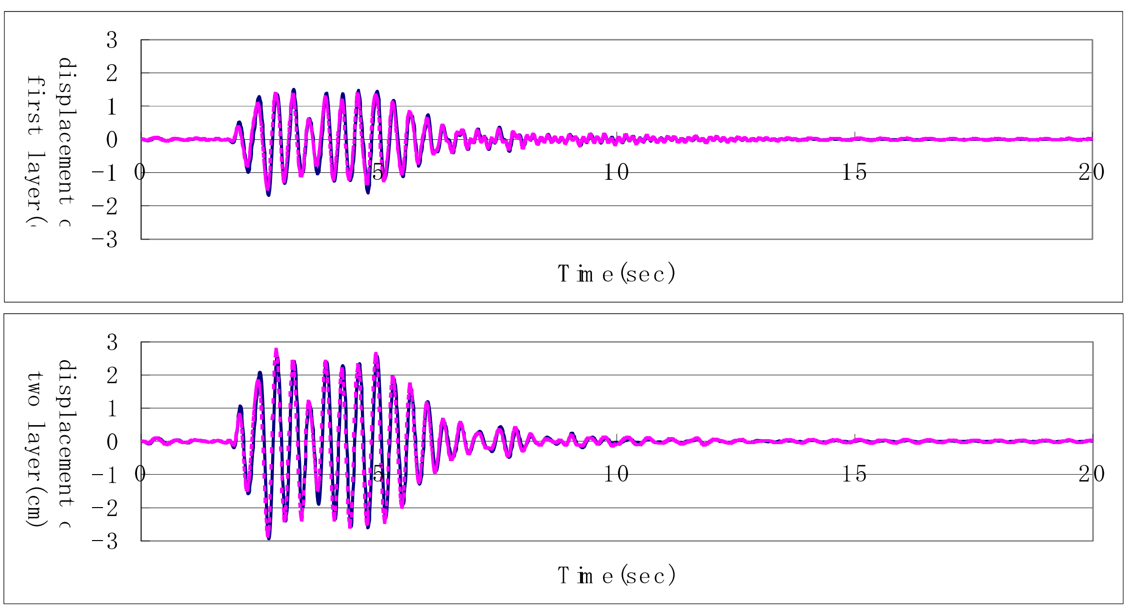
Shaking table test is carried out by using three earthquake wave data of El Centro(1940 NS), Kobe(1995 NS) and Taft(1952 NS). Earthquake response analyses are carried out by using observed values of the input acceleration and relative response displacement of first and second floor from the foundation of the specimen. Weight, damping factor and rigidity of each floor are identified by results of shaking table tests and those of earthquake response analysis. Fig.9 shows results of shaking table test and those of earthquake response analysis. Two patterns of structure identification are performed. Results of structural identification are shown in Tables 3.

Structural identification of added mass

The added weight of the movable part on an actuator is identified in the following procedures.

1) The movable part of the actuator is locked at the in order not to move.
2) The sine waves with several kinds of frequencies are given as driving signals of the actuator.
3) The displacements of movable part of the actuator and the displacements of specimen are observed.
4) The weight of the movable part on an actuator is identified by using observed values of relative acceleration and relative displacement of second floor.

As the result of identification, the weight of the movable part w_d becomes 1.265 kgf.



Results of shaking table test Results of response analysis El Centro(1940 NS)

Fig.9 results of shaking table test with those of response analysis

Table 3 Identification Results in case of Pattern1 and 2

	Pattern 1	Pattern 2
weight of first layer	w1=26.0 (kgf)	w1=14.5 (kgf)
weight of second layer	w2=26.0(kgf)	w2=29.0(kgf)
rigidity of first layer	k1=11.0 (kgf/cm)	k1=11.0 (kgf/cm)
rigidity of second layer	k2=11.0 (kgf/cm)	k2=11.0 (kgf/cm)
damping factor of first layer	c1=0.004954 (kgf・sec/cm)	c1=0.004085 (kgf・sec/cm)
damping factor of second layer	c2=0.004954 (kgf・sec/cm)	c2=0.004085 (kgf・sec/cm)
predominante period of first layer	T1=0.499 (s)	T1=0.49 (s)
predominante period of second layer	T2=0.19 (s)	T2=0.15 (s)
participation factor for mode of first layer	1β=0.723	1β=0.621
participation factor for mode of second layer	2β=0.276	2β=0.378

ACTIVE CONTROL TESTS

Non-control Test

In non-control tests, a sampling interval of DA and AD translation for the activation of shaking table and sensing structural responses is assumed to be 0.01 second. The number of sampling data is assumed to be 2000, so whole duration of the shaking table test becomes 20 seconds. As for input earthquake waves, Hachinohe NS (1968) and El Centro NS (1940) are employed. In non-control tests, the movable part of the actuator is locked at the origin. Results of non-control tests are shown in Table 4.

Table4 Results of Non-control tests in the case of Pattern1

	input acceleration (cm/s/s)	relative response displacement of first layer from foundation of the	relative response displacement of second layer from foundation of the
Hachinohe (1968 NS)	453	1.94	3.23
El Centro (1940 NS)	445	1.04	1.55

Active Control Test

Active control tests are carried out under the same condition in case of non-control tests. Here, different observation values are employed in Pattern 1 and Pattern2. In case of Pattern1, the first mode is considered to be predominant, so relative displacement of the second floor form the foundation of the specimen is employed as the response displacement for the active control. In case of Pattern 2, the second mode is considered to be predominant, so relative displacement of the second floor form the first floor is employed as the response displacement for the active control. As for another observation values, same ones are used in each pattern. The activation method of the active control force is assumed to be the equivalent input reduction method. As for parameters of active control tests, maximal values of membership functions such as Y_{max} and U_{max} in Fig.10 and the maximal control variable α_{max} are employed. Here, Y_{max} is the maximal value of assumed membership function on the response displacement and U_{max} is that on the active control force. The maximal values of input accelerations are adjusted almost the same values in case of non-control tests. The control interval Δt is assumed be 1.0 second. Experimental conditions are shown in Table 5.

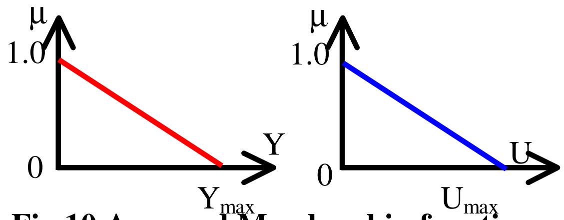


Fig.10 Assumed Membership function

Table 5 Experimental Conditions of Active Control

Case1	Case2
Y_{max}=0.5cm U_{max}=1kgf	Y_{max}=0.5cm U_{max}=2kgf
α_{max}=0.3	α_{max}=0.3
α_{max}=0.5	α_{max}=0.5
α_{max}=0.7	α_{max}=0.7

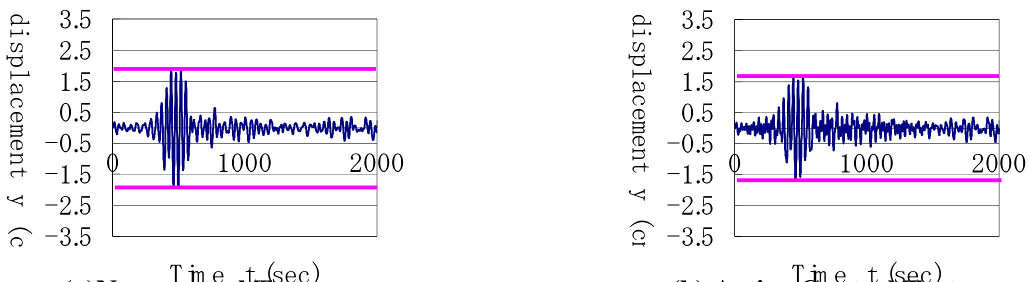
α_{maz}: Maximal control Variable

DIGITAL SIMULATION

Digital simulations are carried out under the same condition in case of non-control and active control tests. As for the input accelerations of digital simulations, accelerations observed on the shaking table in case of active control tests are employed. In digital simulations, predictions of earthquake inputs and structural responses, and fuzzy maximizing decision are performed in each control interval. As for a numerical integration method, a linier acceleration method is employed. Delay of signals is also taken into account as the same condition as the active control test.

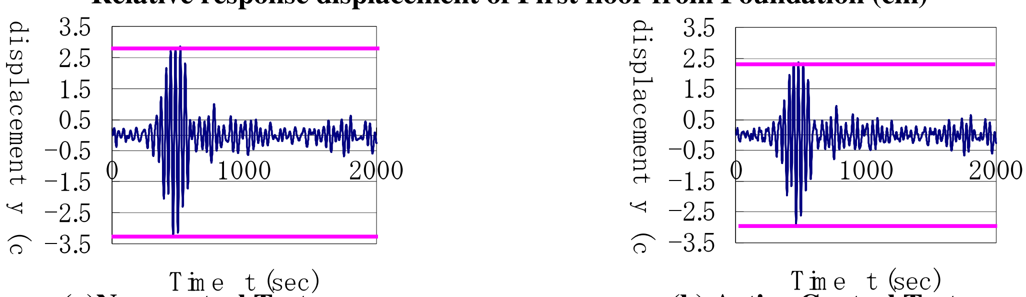
RESULTS OF ACTIVE CONTROL TEST AND DIGITAL SIMULATION

Fig.11 shows a comparison of the results between non-control test and active control test in case of Hachinohe NS (1968). Fig.12 shows the comparison of displacements in Case1 and Case2. In this case, displacement means to be the average value of the maximum displacement and absolute of minimum displacement. Fig.13 shows comparison of reduction ratio in Case1-2 of Pattern2. Figs.14 and 15 shows comparisons of the results between an active control test and a digital simulation in case of Hachinohe NS (1968), where maximal displacements and optimal control variables in each Δt and response results in planes of membership functions are shown. In Table 6, comparisons among reduction ratios are shown in Cases 1 and 2 and Pattern2.



(a)Non-control Test **(b) Active Control Test**

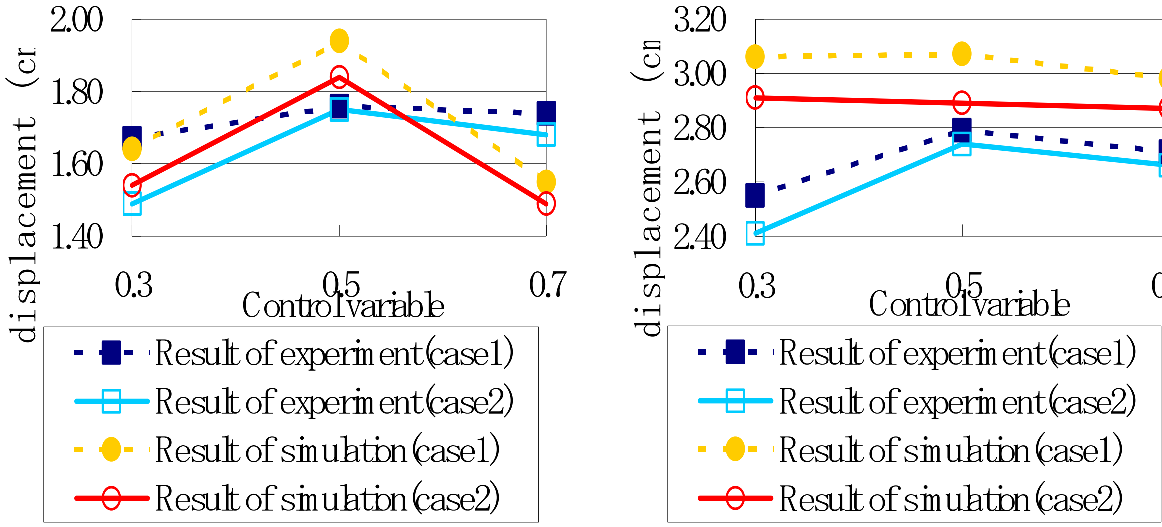
Relative response displacement of First floor from Foundation (cm)



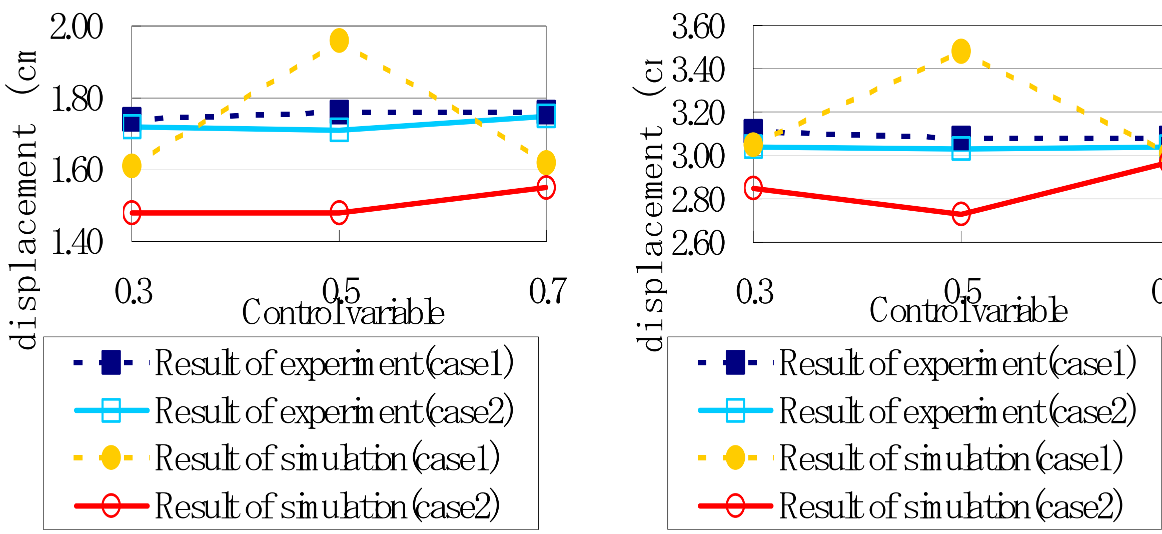
(a)Non-control Test **(b) Active Control Test**

Relative response displacement of Second floor from Foundation (cm)

Fig.11 Relative response displacement (Case1, Hachinohe, Pattern1)



(Hachinohe in case of the Pattern1)



(Hachinohe in case of the Pattern2)

Fig.12 Comparison of displacement (cm)

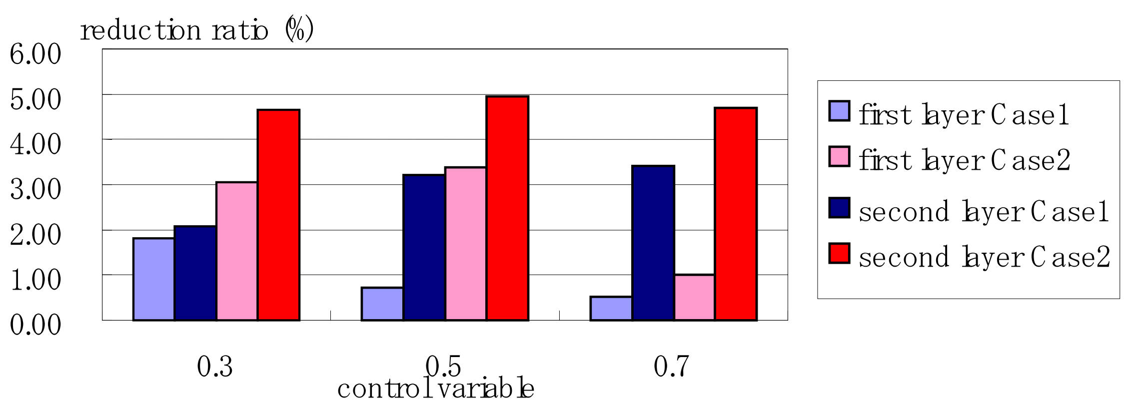
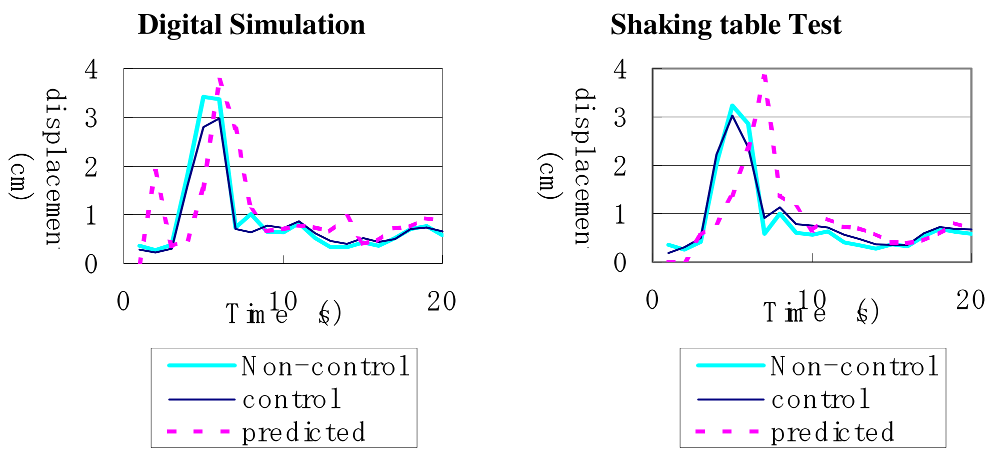
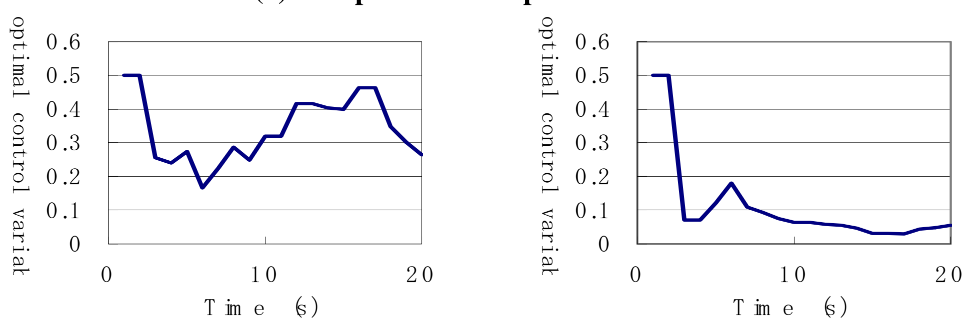


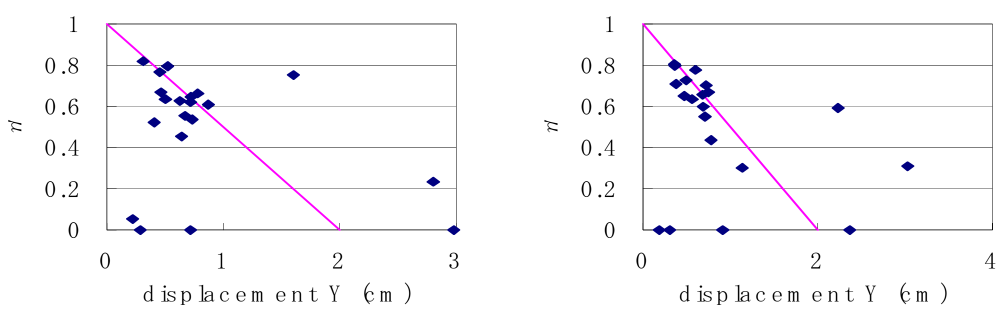
Fig.13 Comparison of reduction ratio in case of Active control Test in Pattern2 (%)



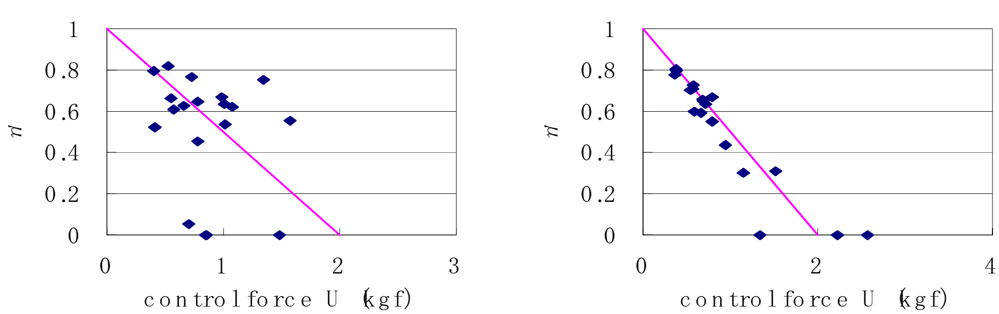
(a) Comparison of displacement



(b) Time historical changes of control variable



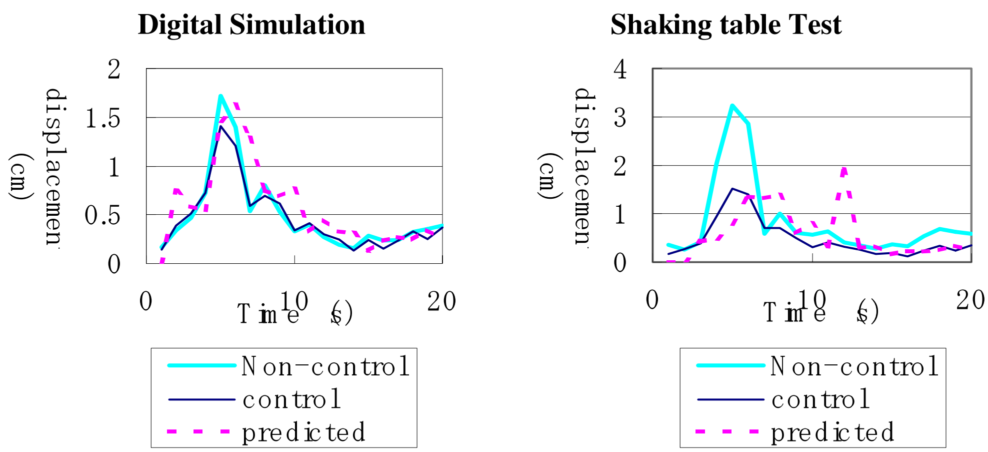
(c) Membership function of displacement Y



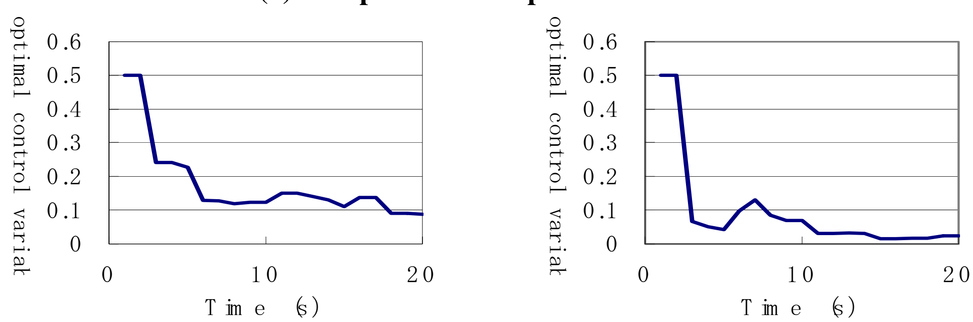
(d) Membership function of control force U

(Hachinohe, Case2 A=0.5 Pattern1)

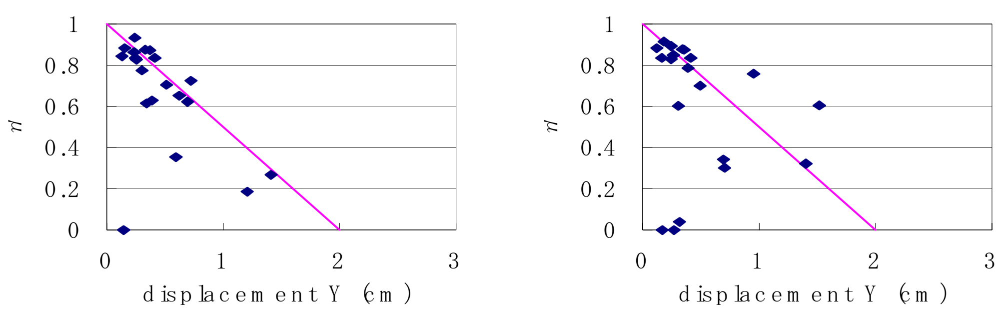
Fig.14 Comparison of Shaking table Test and Digital Simulation



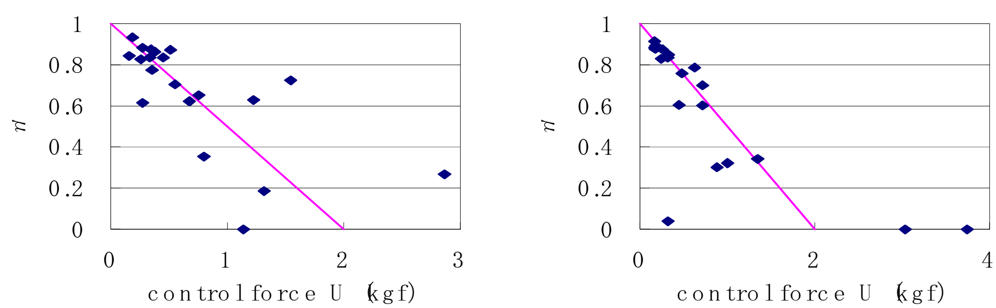
(a) Comparison of displacement



(b) Time historical changes of control variable



(c) Membership function of displacement Y



(d) Membership function of control force U

(Hachinohe, Case2 α=0.5 Pattern2)

Fig.15 Comparison of Shaking table Test and Digital Simulation

Table6 comparisons of reduction ratios

Digital Simulation

Hachinohe (1968 NS)	Maximal input acceleration (cm/s/s)	relative response displacement of first layer (cm)	relative response displacement of second layer from first layer (cm)	reduction ratio of first layer(%)	reduction ratio of second layer(%)
input reduction method(Y=0.5cm U=1kgf)					
α_{max}=0.3	410.03	1.74	3.29	8.16	8.29
	410.03	1.84	3.46		
α_{max}=0.5	422.74	2.17	3.84	-1.15	-0.31
	422.74	2.08	3.74		
α_{max}=0.7	420.35	1.71	3.13	12.3	12.5
	420.35	1.88	3.56		
input reduction method(Y=2cm U=2kgf)					
α_{max}=0.3	411.82	1.48	2.91	13.18	11.65
	411.82	1.72	3.29		
α_{max}=0.5	424.98	1.62	2.96	20.76	19.51
	424.98	2.01	3.68		
α_{max}=0.7	423.94	1.55	3.04	25.26	24.07
	423.94	2.1	3.95		

Shaking table Test

Hachinohe (1968 NS)	Maximal input acceleration (cm/s/s)	relative response displacement of first layer (cm)	relative response displacement of second layer from first layer (cm)	reduction ratio of first layer(%)	reduction ratio of second layer(%)
Non-control	418.25	1.83	3.29		
input reduction method(Y=0.5cm U=1kgf)					
α_{max}=0.3	410.03	1.8	3.17	1.81	2.07
α_{max}=0.5	422.74	1.85	3.16	0.71	3.21
α_{max}=0.7	420.35	1.84	3.14	0.52	3.41
input reduction method(Y=2cm U=2kgf)					
α_{max}=0.3	411.82	1.77	3.11	3.05	4.66
α_{max}=0.5	424.98	1.79	3.11	3.38	4.94
α_{max}=0.7	423.94	1.83	3.11	1	4.7

DISCUSSION

It is clearly to reduce the response displacement in the case of active control than non-control in Fig.11. Fig.12 shows that maximal response displacement becomes small when the assumed maximal values of membership functions, i.e., Y_{max} and U_{max} become larger in each pattern. So, it is necessary to clarify the relationship between assumptions of membership functions and obtained control effects by shaking table tests and digital simulations. Fig.13 shows reduction ratio of second floor is larger than those of first floor in every case. It is proved that proposed control method for Pattern 2 can reduce response displacement well in case that the second mode is predominant. However, in this case, the control effect to the response displacement of the first floor is small. So, it is necessary to improve the control system to obtain higher control effect to the first floor. As for the response results in planes of membership functions, response results of maximal displacements Y and maximal control forces U are distributed around assumed membership functions and in the range of higher membership values. These results show that effective active control is carry out in range of assumed membership values. Therefore, the applicability of proposed system to multi-degree-of freedom system is verified and clarified.

CONCLUSION

In this paper, in order to examine the effectiveness of the intelligent fuzzy optimal active control system on multi-degree-of-freedom system, new control criteria are proposed. The effectiveness of proposed system is discussed and verified by shaking table tests and digital simulations. In case that the first mode is considered to be predominant (the Pattern1), results of shaking table tests and digital simulations show that the proposed system can reduce the response displacements well and the effectiveness of the proposed system is clarified. On the other hand, in case that the second mode is considered to be predominant (the Pattern2), the reduction ratio of shaking table tests is lower than digital simulations. Therefore, it is necessary to perform further improvements. It is also necessary to clarify the effectiveness of the proposed system in case of another activation methods of active control forces by shaking table tests and digital simulations.

ACKNOWLEDGMENT

This study was supported by the Japan Society for the Promotion of Science (2004 Grants-in-Aid for Scientific Research, Scientific Research (A)(1), No.14205087: System Design for Architecture, Urban and Social Systems Adapting to Human and Environment by Complexity Science), and supported in part by the Twenty-First Century Center of Excellence (COE) Program "Design Strategy towards Safety and Symbiosis of Urban Space" awarded to Graduate School of Science and Technology, Kobe University. The Ministry of Education, Culture, Sports, Science and Technology of Japan sponsors the Program.

REFERENCES

[1] Yao J. T. P.”Concept of structural control.” J. Struct. Div., ASCE, 98, (ST7), 1972: pp.1567-1574.

[2] Kawamura, H., Yao, J. T, P.”Application of fuzzy Logic to Structural Control Motion of Civil Engineering Structure.” Proc. of NAFIPS’90 Quarter Century of Fuzzyness, Tronto, June 1990; Vol.I: pp.67-70.

[3] Kawamura H., Tani A and Yamada M.”Real Time Prediction of Earthquake Ground Motions and Structural Response by Statistics and Fuzzy Logic.” Analysis and Management of Uncertainty: Theory and Application Elsevier Science Publishers, 1992: pp.263-275.

[4] Ryu S., Tani A. and Kawamura H. “Simulation System on Fuzzy Optimal Active Control of Buildings by Intelligent Systems.” Proc. of the 7th International Conference on Computing in Civil and Building Engineering (ICCCBE-VII), 1997; Vol.2: pp.1353-1358.

[5]Mitsui T., Tani A., Kawamura H. and Takizawa A.”Intelligent Fuzzy Optimal Active Control System in case of Combinatorial Activation Methods of Active Control Forces” Proc. of the 8th International Conference on Computing in Civil and Building Engineering (ICCCBE-VIII), 2000; Vol2: pp.1317-1324.

[6] Mitsui T., Tani A., Kawamura H. and Takizawa A.”Intelligent Fuzzy Optimal Active Control System in case of Combinatorial Activation Methods of Active Control Forces” Proc. of the 9th International Conference on Computing in Civil and Building Engineering (ICCCBE-IX), 2002; Vol.I: pp. 513-518.

[7] Tani A., Nishimura K., Ryu S., Nishihata M. and Kawamura H.”Research on intelligent Fuzzy Optimal Active Control System of Buildings” Proc. of the 12th World Conference on Earthquake Engineering, CD-ROM, 2000; Paper No.755, pp.1-8.

[8] Hiroyuki Fujita., Tani A., Kawamura H. and Takizawa A.”Experimental Research on Intelligent Fuzzy Optimal Active Control System of Buildings” Proc. of the 25th Symposium on Computer Technology of Information, Systems and Applications, Architectural Institute of Japan, 2002.12; pp.229-232.(in Japanese)

[9] Hiroyuki Fujita., Tani A., Kawamura H. and Takizawa A.”Experimental Research on Intelligent Fuzzy Optimal Active Control System of Buildings” Annual meeting of Architectural Institute of Japan, Kinki Branch, Struct, Div., pp.433-436. (in Japanese)

[10] Bellman R. E. and Zadeh L. A.”Decision Making in a Fuzzy Environment” Management Science, Vol. 17: No.4, Dec. 1970; pp. B-141-B-164.

[11] Zadeh L. A.”Fuzzy Sets”Information and Control, 1965.8; pp.338-353.

[12] Kawamura H., Yao J. T, P.”Application of fuzzy Logic to Structural Control Motion of Civil Engineering Structure” Proc. of NAFIPS’90 Quarter Century of Fuzzyness, Tronto, Vol.I: June 1990; pp.67-70.