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EXPERIMENTAL RESEARCH ON INTELLIGENT ACTIVE CONTROL OF BUILDING STRUCTURES BY FUZZY OPTIMAL LOGIC

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SUMMARY

In this paper, a fundamental research on shaking table tests of active control system is performed. An intelligent active control method proposed by the authors is employed. As an active control method, an input reduction method is employed. Test specimen is a single-degree-of-freedom system with AMD at the top of it. In the experiment, the authors use two types of sine waves which change amplitudes and frequencies, and an observed earthquake wave as input waves. In parallel with experiments, digital simulations are also carried out and are compared with experimental results. Test results show that in case of harmonised waves such as sine waves and random waves such as earthquake inputs, this testing system can reduce the responses of the specimen. Finally, it is considered that the fundamental experimental system of the intelligent active control can be developed and the effectiveness of proposed system is also verified by the results of shaking table tests and digital simulations.

INTRODUCTION

In resent years, many researches on the active control system based on modern control theory have been performed actively. To develop active control systems of building structures, it is necessary to take account of their special features such as complexity, uncertainty and large scale [Yao, 1972]. Kawamura, one of the authors and Yao [Kawamura and Yao, 1990] already proposed a new idea of the application method of fuzzy logic [Zadeh, 1965] [Bellman and Zadeh, 1970] to civil engineering structures subjected to earthquake loading. According to this paradigm, the authors already presented fuzzy optimal adaptive and predictive control systems with those digital simulations as intelligent active control systems [Kawamura, Tani, Watari, and Yamada, 1990][Tani, Kawamura, 1992][Tani, Kawamura and Ryu, 1998]. The purpose of this paper is to develop and verify the effectiveness of proposed testing system [Nishimura, Tani, Ryu, Nishihata and Kawamura, 1998] [Tani, Furuichi, Ryu, Nishihata and Kawamura, 1998] [Kawamura, 1998] by shaking table tests and digital simulations.

FUNDAMENTAL THEORY OF INTELLIGENT ACTIVE CONTROL

A flow of intelligent active control system

Figure 1 shows a flow chart of the intelligent active control system using in this research [Kawamura and Yao, 1990]. This intelligent active control system has the following special and intelligent features, i.e.; 1) objective and constraint conditions of active control are described with membership functions of fuzzy theory, 2) the 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. In this paper, 'intelligent control' means that it imitates human's intelligent function and activity such as prediction, consideration and judgement which exist in human brains.

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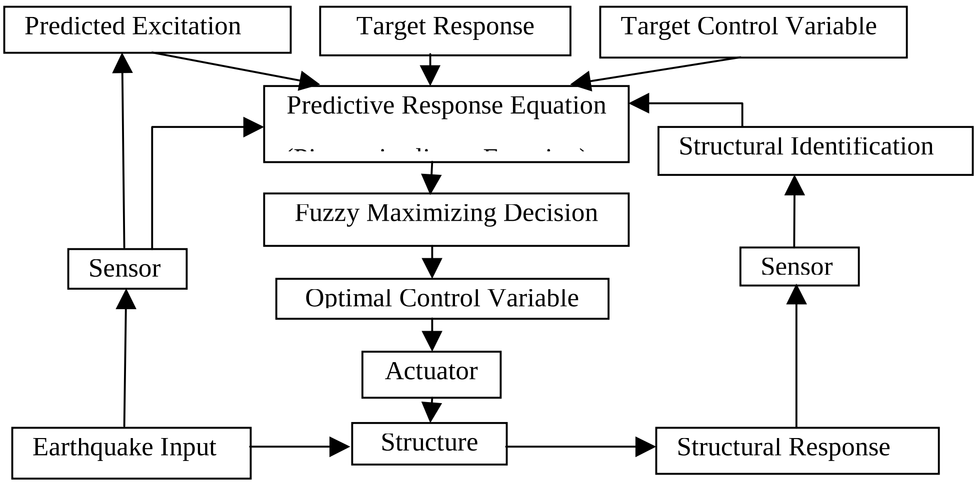


Figure 1: A flow chart of the intelligent active control system[Kawamura and Yao, 1990]

Fundamental assumption

An objective structure is assumed to be a single-degree-of-freedom system. The objective structure has an active mass driver (AMD) at the top of it. Figure 2 shows a model of the objective structure. Coefficients of mass, viscous damping ratio and stiffness are assumed to be constant. Control force is activated by inertia force, which appears by the movement of mass of AMD. As for a control method, an input reduction method is employed. Equations of motion are shown as follows:

$$m\ddot{y} + c\dot{y} + ky + u = -m\ddot{x} \qquad (1)$$

$$u = -\alpha_I m\ddot{x} = m_d \cdot (\ \ddot{y}_{amd} - \ddot{y}\ ) \qquad (2)$$

In this paper, $\ddot{y}, \dot{y}$ and y mean relative response acceleration, velocity and displacement of structure, respectively. $\ddot{x}$ means input acceleration of earthquake ground motion. In equation (2), $\ddot{y}_{amd}$ means relative response acceleration of AMD, u means active control force and α_I means control variable in case of the input reduction method. Control force is calculated by equation (2) and activated to the structure in real time.

m: mass

k: stiffness

c: coefficient of viscous damping

m_d: mass of AMD

k_d: stiffness of AMD

c_d: coefficient of viscous damping of AMD

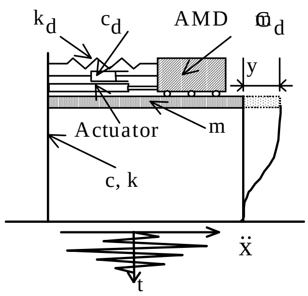
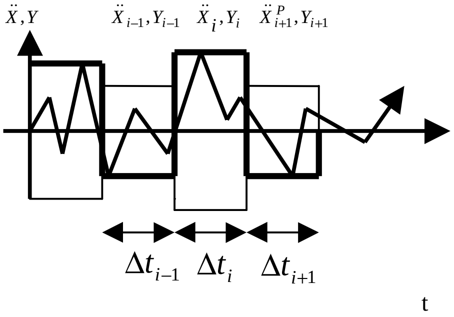


Figure 2: A model of objective structure

Further, a certain interval Δt (shown in figure 3) is introduced as a control interval. In Figure 3, x, y and t mean earthquake input, response of structure and time, respectively. Moreover, earthquake input and response of structure are predicted by using $\ddot{X}_i, Y_i$ which express maximal absolute values of x and y in Δt_i. Control variable(α_I) is assumed to be constant in each Δt.



Δt : control interval

$\ddot{X}$: maximum of absolute value of earthquake input in Δt

Figure 3: Assumption to input and response

Prediction of earthquake input

As for the method of prediction of earthquake input, the conditioned fuzzy set rules proposed by the authors [Kawamura, Tani, Yamada and Tsunoda, 1990][Kawamura, Tani and Yamada, 1992] are employed. In this method, the next increment of $\Delta\ddot{X}_{i+1}$ is predicted by using the first and the second order differences $\Delta\ddot{X}_i$ and $\Delta^2\ddot{X}_i$ given by equations(3) and (4). The next predicted excitation $\ddot{X}^P{}_{i+1}$ is calculated by equation (5).

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

$$\Delta^2\ddot{X}_i = \ddot{X}_i - 2\cdot\ddot{X}_{i-1} + \ddot{X}_{i-2} \tag{4}$$

$$\ddot{X}^P_{i+1} = \ddot{X}_i + \Delta\ddot{X}_{i+1} \tag{5}$$

Structural identification

In this system, the next optimal control variable $\alpha_{I\,i+1}$ is defined by maximizing decision considering the membership functions of the next relative story displacement $Y^P{}_{i+1}$ and the next control force $U^P{}_{i+1}$. So, it is necessary to identify the relations among $Y^P{}_{i+1}$, $U^P{}_{i+1}$ and $\alpha_{I\,i+1}$ at the next control interval Δt_{i+1}. To identify these relations, following simple piece-wise linear response equations proposed by the authors [Kawamura, Tani, Yamada and Tsunoda, 1990][Kawamura, Tani and Yamada, 1992] are assumed for $Y^P{}_{i+1}$ and $U^P{}_{i+1}$ as follows:

$$Y^P_{i+1} = a_{i+1}\cdot(1-\alpha_{I\,i+1})\cdot\ddot{X}^P_{i+1} \tag{6}$$

$$U^P_{i+1} = b_{i+1}\cdot\alpha_{I\,i+1}\cdot\ddot{X}^P_{i+1} \tag{7}$$

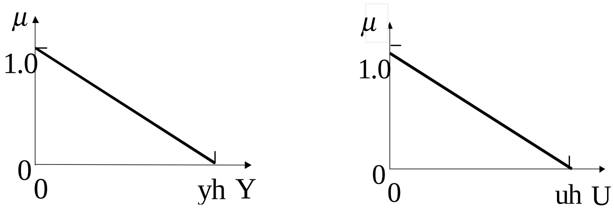
where a_{i+1} and b_{i+1} are constant. These values are determined by using preceding response results at i-1-th and i-th control intervals as follows:

$$a_{i+1} = max\{\, a_{i-1}, a_i \,\} \tag{8}$$

$$b_{i+1} = max\{\, b_{i-1}, b_i \,\} \tag{9}$$

Maximizing decision

To perform fuzzy maximizing decision [Bellman and Zadeh, 1970], it is necessary to define membership functions of relative story displacement Y and control force U. The desirable membership functions of Y and U are assumed as shown in Figure 4 to take account of comfort, structural safety of buildings, economy and the limitation of control devices, and so on. By using equations(6) and(7), $Y^P{}_{i+1}$ and $U^P{}_{i+1}$ are transformed into the μ - α_{i+1} plane as shown in Figure 5. Values of μ^* and α^* are determined as the optimal membership degree and the optimal control variable by fuzzy maximizing decision.



(a) Relative story response displacement Y (b) Control force U

Figure 4: Membership functions

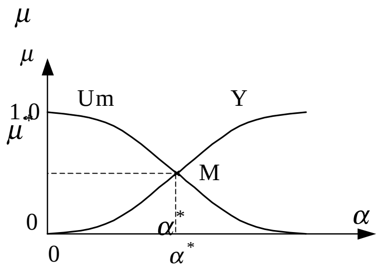


Figure 5 :Optimal α by maximizing decision

EXPERIMENTAL SYSTEM

Specimen

An objective specimen as shown in Figure 6 and table 1 is assumed to be a single-degree-of-freedom system, which is composed of steel plates. Natural period and damping ratio of this specimen are 0.678sec and 0.00152, respectively. These values are determined by free vibration tests.

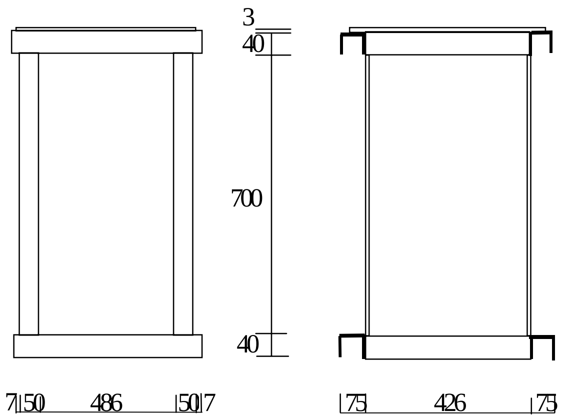


Figure 6: Specimen

Table 1: Compornent parts of specimen

Column	PL50× 3.2 (mm)
Beam	C-75× 40× 5× 7 (mm)
Floor (1F)	PL3.2 (mm)

Outline of experimental system

The active mass driver system is employed as an active control system. Here, active control forces are activated by an actuator which is activated by DC servomotor. Proposed experimental system shown in Figure 7 is composed of three personal computers (CPU1, CPU2 and CPU3) connected each other. In the first computer

(CPU1), DA translation to the control of the shaking table, and AD translation of observed responses of the specimen are performed. Observed results and the optimal control variable are sent to CPU3 simultaneously. In the second one (CPU2), the fuzzy maximizing decision is performed and the optimal control variable is calculated in each control interval. This optimal control variable is sent to CPU1 by RS-232-C interface (9600 baud). In the third one, the DC servomotor of the actuator is controlled in accordance with observed results and the optimal control variable sent from CPU1.

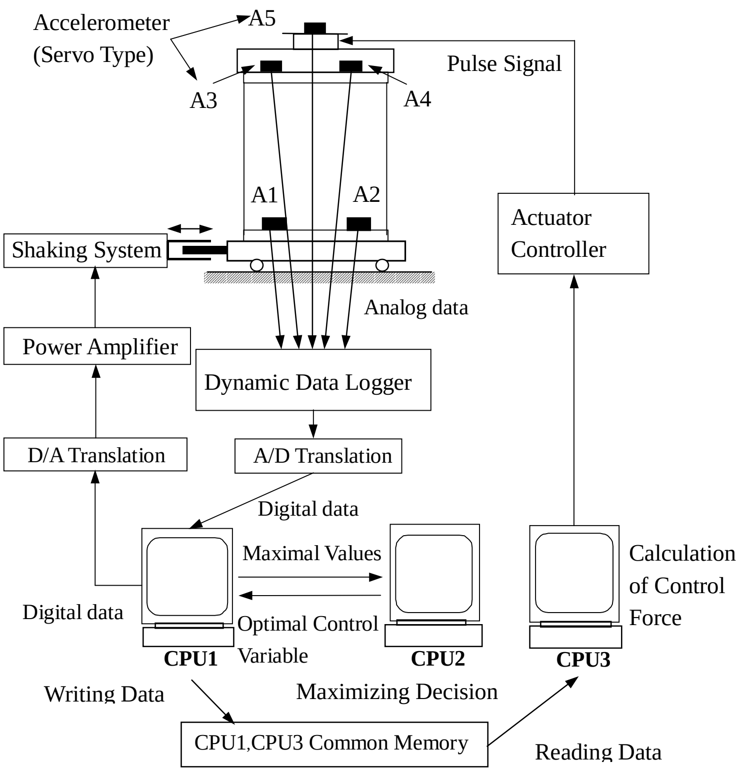


Figure 7: Composition of experimental system

ACTIVE CONTROL EXPERIMENT

Here, intelligent active control tests are carried out by using the experimental system mentioned in chapter 3. A sampling time to the movement of shaking table (DA translation) and the observation of response values (AD translation) is assumed to be 0.01sec. Control interval Δt is assumed to be 1.0sec considering the natural period of the specimen. The optimal control variable is decided in each Δt . Membership functions set up to response displacement Y and control force U are assumed as shown in Figure 4. Input reduction factor α_I is assumed to be between 0 and 0.5,and 0.5 is given at the first and second control interval, because in these two cases, proposed system cannot decide the optimal control variable. As input waves, an observed earthquake wave and two sine waves are employed. In case of the earthquake wave, the data observed at El Centro (NS component) is employed. A sampling interval of these data is 0.02 sec. In this paper, the sampling interval is assumed to be 0.01 sec. In case of sine waves, amplitudes and frequency are changed. A frequency of one sine wave is assumed to be 4Hz and the other is assumed to be 4Hz and 5Hz which are changed by the authors. Amplitudes of them are also changed by the authors. In this paper, former sine wave is denoted as ‘Sin 4Hz’ and latter one ‘Sine 45Hz’.

Table 2 shows the active control experimental data and results. As the parameters of the intelligent active control tests, here are employed maximal values of assumed membership functions yh and uh in Figure 4, and output ranges which shows the volume of output adjustment to DA translation instructions to the shaking table. In table 2, the values of yh, uh and output range are shown in each experimental case. In these tests, the results of non-control and control are compared in the same acceleration on shaking table, because the shaking table employed in this system is affected the reaction force of specimen. In Table 2, maximal absolute values of accelerations observed on the shaking table are also shown as ‘Amax’. Figure 8 shows a test results in case of E6 in Table 2. Figure 8 (a) shows an input wave. In Figure 8 (b), response displacements in case of non-control and control are compared. Figures 9 (a) and (b) show assumed membership functions of response displacements and control forces and the response results of them. The abscissa and ordinate in each figure show real responses of the specimen and the optimal membership values obtained by fuzzy maximizing decision in each Δt , respectively. Figure 9 (c) shows the changes of optimal control variables in each Δt .

SIMULATION

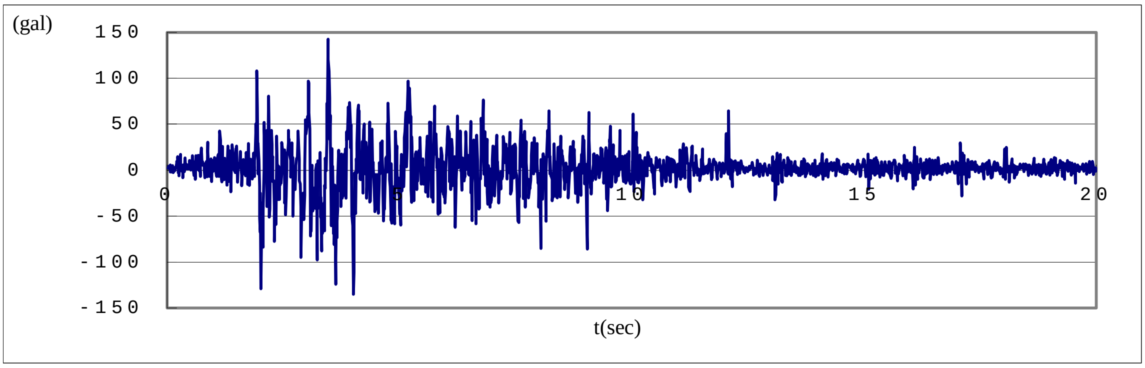
In this paper, digital simulations adjusted to the condition of each experiment are also performed. In these simulations, acceleration data on the shaking table tests in case of non-control is used as input waves. In experiments, the optimal control variable in each control interval is calculated CPU2 and sent to CPU1 with delay between about 0.05sec to 0.1sec. However, in these simulations, optimal control variable is renewed in each control interval with no delay. The results of a digital simulation in case of E6 are also shown in Figure 8 (c) and Figure 10.

Table 2: Parameters and control effects in experiments and digital simulations

Case	Input wave	Membership function	Control effect T : experiment S : simulation
E1	Sin 4Hz Non-control Amax=106G Control Amax=104G	yh =0.3 (cm) uh =3 (kgf) Output Range 2	T : 0.579 S : 0.686
E2	Sin 4Hz Non-control Amax=148G Control Amax=155G	yh =0.2 (cm) uh =3 (kgf) Output Range 3	T : 0.535 S : 0.597
E3	Sin 45Hz Non-control Amax=148G Control Amax=143G	yh =0.3 (cm) uh =3 (kgf) Output Range 3	T : 0.534 S : 0.741
E4	El Centro Non-control Amax=146G Control Amax=154G	yh =0.3 (cm) uh =3 (kgf) Output Range 3	T : 0.623 S : 0.633
E5	El Centro Non-control Amax=146G Control Amax=143G	yh =0.3 (cm) uh =4 (kgf) Output Range 3	T : 0.618 S : 0.548
E6	El Centro Non-control Amax=146G Control Amax=143G	yh =0.5 (cm) uh =3 (kgf) Output Range 3	T : 0.672 S : 0.772
E7	El Centro Non-control Amax=146G Control Amax=156G	yh =0.5 (cm) uh =4 (kgf) Output Range 3	T : 0.672 S : 0.696
E8	El Centro Non-control Amax=196G Control Amax=195G	yh =0.5 (cm) uh =4 (kgf) Output Range 4	T : 0.684 S : 0.605

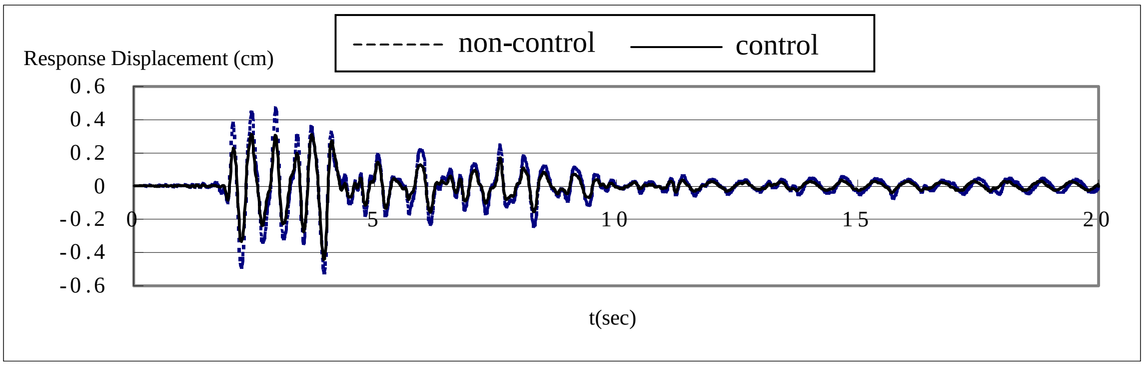
DISCUSSION

Figure 8 (b) shows that an experimental system of the intelligent active control constructed in this paper can reduce response displacements of specimen. In Table 2, a value of the control effect means the ratio of maximal response displacement in case of control to maximal response displacement in case of non-control. In Table 2, T and S mean the control effects estimated by test and simulation results, respectively. These values of the control effects in experimental results show that about 30 to 50 % reduction of response displacements are obtained. However, these experimental results in case of experiments cannot be compared simply because maximal input accelerations are a little different. The control effects of experiments and simulations cannot be also compared simply, because assumptions of them are rather different mentioned in chapter 5. As for the results of digital simulations in Table 2, almost similar control effects are obtained in case of the results of shaking table tests. However, there remain a little differences between tests and simulation results, because of a little differences of the assumption. In Figures 9 (a), (b) and 10 (a), (b), results of response displacements and control forces are distributed around the assumed membership functions in the same manner. However, in Figure 10 (c), the optimal control variables are not changed dynamically in comparison with those in Figure 9 (c). In these experiments, some parameters on the intelligent active control, i.e.; yh ,uh and output range are changed parametrically, and the observed control effects are varied in accordance with setting values. However, in some cases, when output ranges, input waves, and/or settings of membership functions are changed, the control effects become small in some cases. So, further improvements and case studies are necessary to discuss and prove the effectiveness of this system; i.e.; control and activation method of actuator and so on.

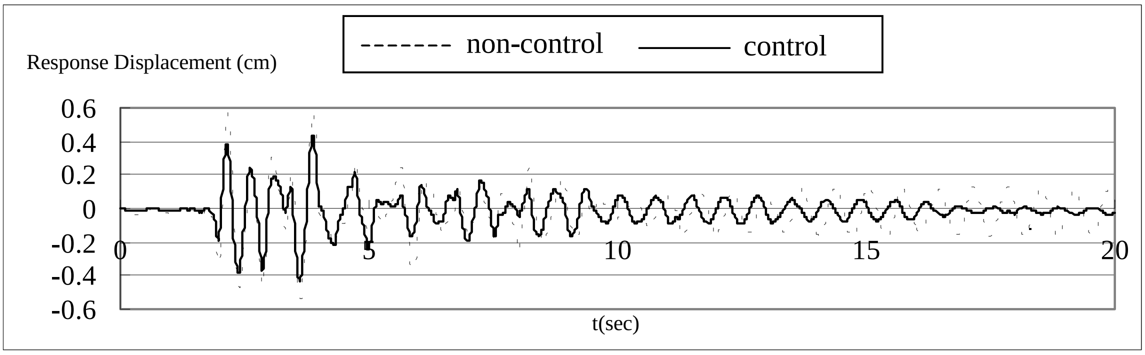


(a)

Input wave (E6)

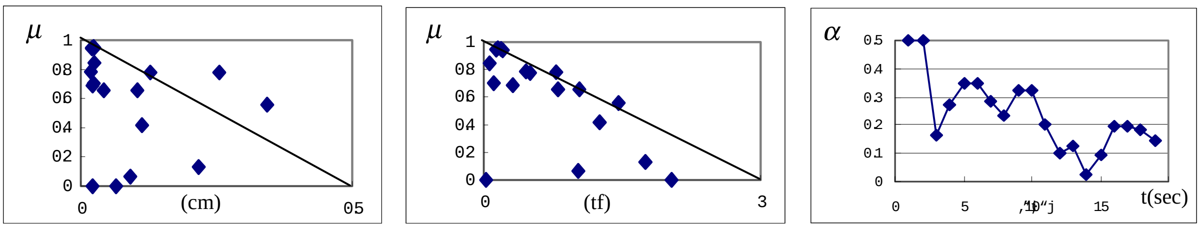


(b) Response displacement (experiment) (E6)



(c) Response displacement (simulation)

Figure 8: Results of experiment and simulation (E6)

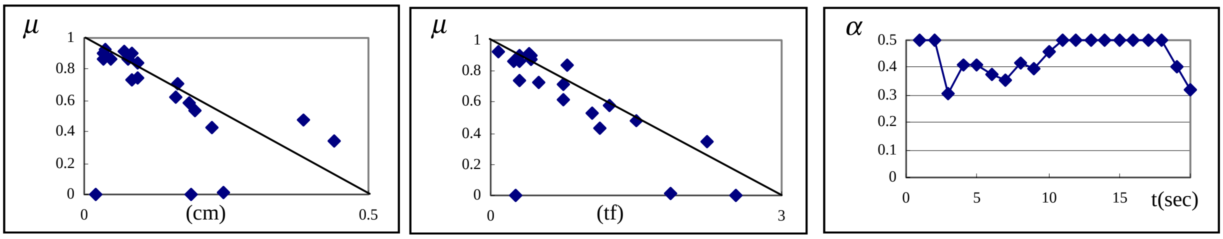


(a) Membership function for response displacement

(b) Membership function for control force

(c) Changes of optimal control variables

Figure 9: Membership function and optimal control variable (experiment) (E6)



(a) Membership function for response displacement (b) Membership function for control force (c) Changes of optimal control variables

Figure 10: Membership function and optimal control variable (simulation) (E6)

CONCLUSION

In this paper, the intelligent active control experimental system is developed, and shaking table tests and those digital simulations are carried out. The response displacements of the specimen can be reduced 30%-50% in shaking table tests. Almost the same control effects are obtained by digital simulations. It is proved that proposed experimental system on the intelligent active control is developed fundamentally. The effectiveness of proposed intelligent active control system is also verified by shaking table tests and digital simulations. There remain some problems in proposed experimental system that proposed system cannot reduce response displacements of the specimen well in some cases when the output ranges, input waves and/or settings of membership functions are changed.

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