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Optimal adaptive and predictive control of seismic structures by fuzzy logic

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ABSTRACT: This paper describes a fuzzy optimal adaptive and predictive control system and its digital simulations for a two-degree-of-freedom system subjected to earthquake loading. Prediction of earthquake input is performed by using conditioned fuzzy sets. Optimization is performed by means of maximizing decision, and structural identification is performed assuming piece-wise linear relations between maximal absolute earthquake input accelerations and output structural responses. In the maximizing decision, membership functions of target responses (displacements) and target control variables (input reduction factors and additional damping factors) are assumed. In this system, a certain interval of time is introduced as control interval. Prediction of earthquake input, structural identification and maximizing decision is performed in every control interval. Digital simulations show the effectiveness of the proposed system for seismic structural control comparing to normalized probability mass functions with assumed membership functions.

1. INTRODUCTION

In the dynamic control of civil engineering and building structures, their special features such as complexity, uncertainty and large scale should be taken into account (Yao 1972). Recent advances in dynamic structural control are summarized by Yang and Soong (Yang and Soong 1988). On the other hand, in recent years, fuzzy theory originated by Zadeh (Zadeh 1965) has been tried to realize engineering control systems (Tong 1977). The most modern subject in the dynamic control is how to constitute an intelligent, i.e., optimal, adaptive and predictive control system (Chong, Liu and Li 1990). To realize such an intelligent control system, Yao and one of the authors (Kawamura and Yao 1990) proposed a new idea of the application method of fuzzy logic to civil engineering structures subjected to earthquake loading. According to this paradigm, the authors (Kawamura, Tani, Yamada and Tsunoda 1990) presented digital simulations regarding real time prediction of earthquake ground motions by using conditioned fuzzy set (Bellman and Zadeh 1970). The authors (Kawamura, Tani, Watari and Yamada 1991) also presented an optimal and adaptive seismic control system based on fuzzy maximizing decision (Bellman and Zadeh 1970).

The purpose of this paper is to integrate the authors' above mentioned preceding studies and to show digital simulations regarding an intelligent, i.e., optimal, adaptive and predictive seismic control system by fuzzy logic for buildings idealized as a lumped mass model with hybrid equivalent variable mass and damper systems (Kawamura, Tani, Watari, Yasui and Yamada 1992).

2. FUNDAMENTAL SYSTEM

2.1. Flow Chart

Fig.1 shows a flow chart of fuzzy optimal feedforward control system (Kawamura and Yao 1990) employed in this system. The special features of this system are given as follows:

(1) Target responses and control variables described with membership functions,

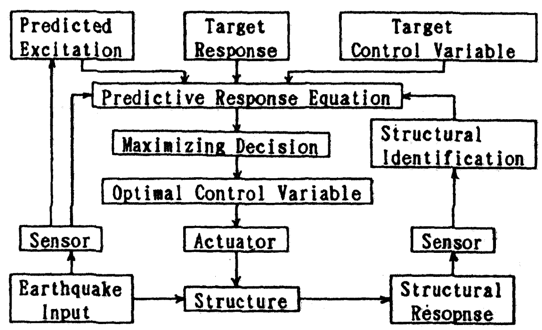
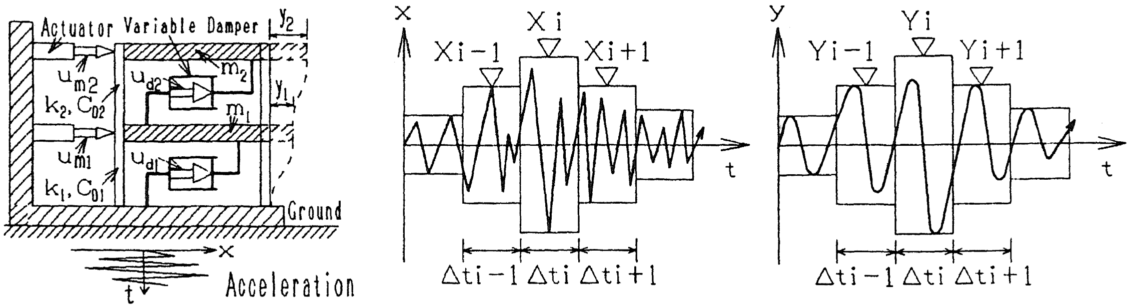


Fig.1 Flow Chart of Fuzzy Optimal Control System (Kawamura, Tani, Yamada and Tsunoda 1990)



(a) Structure (b) Excitation (c) Response

Fig.2 Structure, Excitation and Response (Kawamura and Yao 1990)

(2) Real time structural identification,
(3) Fuzzy maximizing decision (Bellman and Zadeh 1970).

2.2. Preliminary Definitions and Assumptions

Fig.2(a) shows the controlled structure employed in this paper. This structure is assumed to be shear-type structure which has two-degree-of-freedom. In Fig.2(a), x denotes input excitation, y_1 and y_2 output responses, and t time. It is assumed that mass (m_1,m_2), spring constants (k_1,k_2), and damping factors (c_{01},c_{02}) are constants. u_{m1}, u_{m2}, u_{d1}, and u_{d2} denote control forces. As control methods, hybrid equivalent variable mass and visco-elastic damper system are employed. The former reduces the effect of earthquake input and the latter raises the efficiency of the brakes. Equations of motion are as follows:

$$m_2\ddot{y}_2+c_{02}(\dot{y}_2-\dot{y}_2)+k_2(y_2-y_1)-u_{m2}+u_{d2}=-m_2x \quad (1)$$

$$m_1\ddot{y}_1+c_{01}\dot{y}_1-c_{02}(\dot{y}_2-\dot{y}_1)+k_1y_1-k_2(y_2-y_1) -u_{m1}+u_{d1}-u_{d2}=-m_1x \quad (2)$$

$$u_{d1}=\Delta c_1\dot{y}_1 \quad (3), \quad u_{d2}=\Delta c_2(\dot{y}_2-\dot{y}_1) \quad (4)$$

$$u_{m1}=\alpha_1 m_1 x \quad (5), \quad u_{m2}=\alpha_2 m_2 x \quad (6)$$

where

y_j, $\dot{y}_j$, $\ddot{y}_j$ (j=1,2) : relative displacement, velocity and acceleration with respect to the foundation,
m_1,m_2 : mass,
k_1,k_2 : spring constants,
c_{01},c_{02} : damping factors,
Δc_1,Δc_2 : additional damping factors,
α_1,α_2 : input reduction factors,
u_{dj}, u_{mj} (j=1,2) : control forces,
x :earthquake input acceleration.

After this, index j is assumed to denote j-th story of structure. u_{mj}(j=1,2) are activated for each floor in the opposite direction of earthquake input as foundation reaction forces(Eqs.5,6). u_{dj}(j=1,2) are estimated as additional damping forces by eqs.3, 4. In this system, α_1, α_2, Δc_1 and Δc_2 are assumed to be control variables.

In this control system, a certain interval of time Δt is introduced, and X_i and Y_i are defined as the i-th maximal absolute values of x and y within i-th control interval Δt_i as shown in Fig.2(b) and Fig.2(c) (Kawamura and Yao 1990). Here, maximal absolute values X_i, Y_{2i} and Y_{1i} are assumed to be those of earthquake input acceleration, relative displacement of second floor with respect to the first floor and that of first floor with respect to the foundation, respectively. U_{mji} and U_{dji} (j=1,2) are defined as the i-th maximal absolute values of u_{mj} and u_{dj} as the same way. The i-th input reduction factors α_{1i} and α_{2i}, and additional damping factors Δc_{1i} and Δc_{2i} are assumed to be kept constant during the i-th control interval Δt_i.

2.3. Prediction of Earthquake Input

Fig.3 shows a part of the conditioned fuzzy sets for real time prediction of the next ground earthquake motion (Kawamura, Tani, Yamada and Tsunoda 1990). These rules are described from observed two earthquake waves No.1 (EERL 1976) and No.3 (the Building Center of Japan 1986) as shown in Table 1 in a certain interval time Δt. Based on these observed waves, the first and second order differences ΔX_i, $\Delta^2 X_i$ given by eqs.7 and 8 are calculated and probability mass functions of the next increment ΔX_{i+1} are illustrated. By normalization, membership functions μ's of ΔX_{i+1} are given as shown in Fig.3.

$$\Delta X_i=X_i-X_{i-1} \quad (7), \quad \Delta^2 X=X_i-2X_{i-1}+X_{i-2} \quad (8)$$

The linear interpolation method is introduced to obtain the membership function $\mu(\Delta X_{i+1})$ of the next increment ΔX_{i+1} and by the center of gravity method, the next increment of $\Delta X'$ is determined, and the next predicted excitation X^{P}_{i+1} is calculated as follows (Kawamura, Tani, Yamada and Tsunoda 1990).

$$X^{P}_{i+1}=X_i+\Delta X' \tag{9}$$

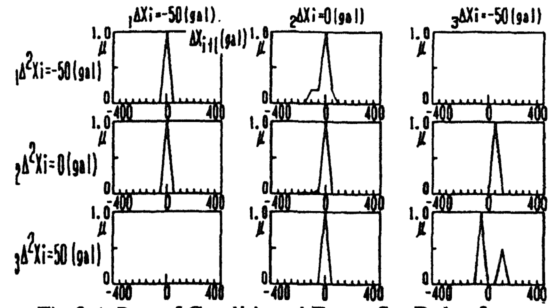


Fig.3 A Part of Conditioned Fuzzy Set Rules for Prediction of Next Earthquake Ground Motions

Table 1 Observed Earthquake Waves

No	Place of Observation	Dirct.	Date of Occurrence	Dur. (sec)	Max. Acc. (gal)
1	El Centro	NS	1940. 5. 18	53. 73	341. 7
2	Taft	EW	1952. 6. 21	54. 38	175. 9
3	Hachinohe	NS	1968. 5. 16	35. 99	225. 0

2.4. Structural Identification

In this control system, i-th optimal control variables α_{ji} and Δc_{ji} are defined by the maximizing decision among relative story displacements Y_{ji} and control forces U_{mji} and U_{dji} (j=1,2). So, it is necessary to identify the relations among Y_{ji+1}, Δc_{ji+1} and α_{ji+1}, and among $\dot{Y}_{ji+1}$, Δc_{ji+1} and α_{ji+1} (j=1,2) at the next control interval Δt_{i+1}. In order to identify these relations, the following simple linear relations are employed.

$$Y_{ji+1}=a_{ji+1}(1-\alpha_{ji+1})X_{i+1}/\Delta c_{ji+1} \quad (j=1,2) \tag{10}$$

$$\dot{Y}_{ji+1}=b_{ji+1}(1-\alpha_{ji+1})X_{i+1}/\Delta c_{ji+1} \quad (j=1,2) \tag{11}$$

where a_{ji+1} and b_{ji+1} are constant and $\dot{Y}_{ji+1}$ is maximal relative story velocity. These values are defined by using preceding response results at the i-th and i-1-th control intervals as follows.

$$a_{ji+1}=\max\{a_{ji-1}, a_{ji}\} \quad (j=1,2) \tag{12}$$

$$b_{ji+1}=\max\{b_{ji-1}, b_{ji}\} \quad (j=1,2) \tag{13}$$

Control forces U_{mji+1} and U_{dji+1} at Δt_{i+1} are also derived as follows.

$$U_{mji+1}=\alpha_{ji+1}m_jX_{i+1} \quad (j=1,2) \tag{14}$$

$$U_{dji+1}=\Delta c_{ji+1}\dot{Y}_{ji+1} =b_{ji+1}(1-\alpha_{ji+1})X_{i+1} \quad (j=1,2) \tag{15}$$

Eq.15 is derived from eqs.3, 4 and 11.

2.5. Maximizing Decision

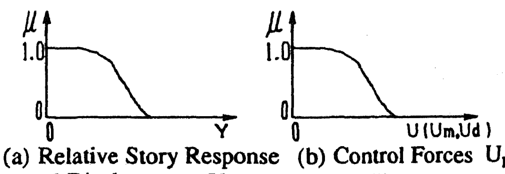
To perform maximizing decision (Bellman and Zadeh 1970), it is necessary to define membership functions of relative story displacement Y and control forces U_m and U_d. The membership function of desirable relative story displacement is assumed as shown in Fig.4(a) to take into account comfort and structural safety of buildings. μ denotes the satisfaction degree of Y and is defined between 0 and 1. Membership functions of desirable control forces U_m and U_d are assumed as shown in Fig.4(b) to take into account economy and the limitation of control devices.

By using eqs.14 and 15, U_{mj} and U_{dj} (j=1,2) in Fig.4(b) are transformed into α_j as shown in Fig.5(a). Values of $\mu*$ and $\alpha*$ at the point M are determined as the optimal satisfaction degree and the optimal reduction factor. When transformed membership functions of U_m and U_d have no crossing point as shown in Fig.5(b) and (c), $\alpha*_j$ is assumed to be defined as follows.

$$\alpha^*_{j1}=[\min\{\alpha j/\mu(Umj)=0\}+\max\{\alpha j/\mu(Udj)=0\}]/2 \quad (j=1,2) \tag{16}$$

$$\alpha^*_{j2}=\max\{\alpha j/\mu(Umj)=1\} \quad (j=1,2) \tag{17}$$

Furthermore, by using eq.10, Y in Fig.4(a) is transformed into Δc as shown in Fig.6. In this step, the obtained optimal value $\alpha*$ is used in eq.10. Using



(a) Relative Story Response of Displacement Y (b) Control Forces U_m and U_d

Fig.4 Membership Functions

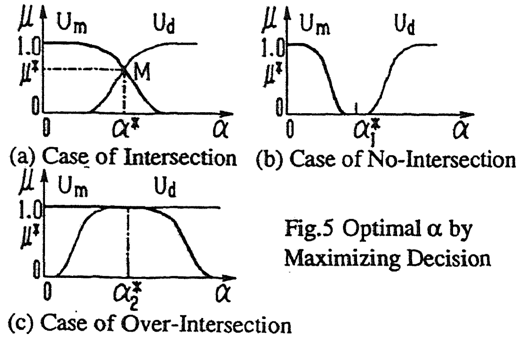


Fig.5 Optimal α by Maximizing Decision

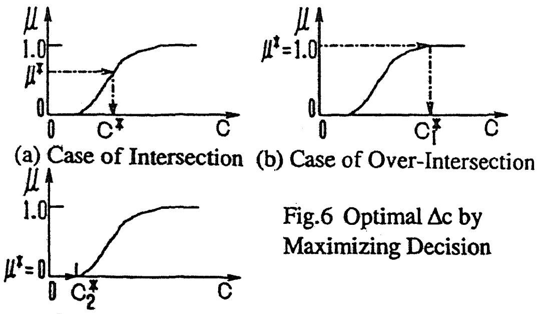


Fig.6 Optimal Δc by Maximizing Decision

the same value of $\mu*$ in Fig.5, an optimal additional damping factor $\Delta c*j$ is determined as shown in Fig.6(a) . When $\mu*$ equals to 1 or 0 as shown in Fig.6(b) and (c), $\Delta c*_j$ is assumed to be defined as follows.

$$\Delta c*_{j1}=\min\{\Delta cj/\mu(Yj)=1\} \quad (j=1,2) \tag{18}$$

$$\Delta c*_{j2}=\max\{\Delta cj/\mu(Yj)=0\} \quad (j=1,2) \tag{19}$$

3. DIGITAL SIMULATION

3.1. Input Earthquake Waves and Dynamic Structural Characteristics

As earthquake input, two earthquake waves, i.e., No.2 (EERL 1976) and No.3 (the Building Center of Japan 1986) in Table 1, are used. The control interval Δt is assumed to be 1.2 sec.. Assumed structural characteristics are as follows:

Mass of each story: $m_1=m_2=2000$ (kg),
Spring constants : $k_1=k_2=390$ (kN/m),
Damping factors : $c_{01}=c_{02}=0.271$ (kN sec/m),
1st Natural Period : $T_1=0.728$ (sec),
2nd Natural Period : $T_2=0.278$ (sec).

Linear acceleration method is employed as a response analysis method and integration interval times are 0.02 sec. for No.2, 0.01 sec. for No.3. In this system, at the 1st and 2nd control interval, the prediction of earthquake input and the structural identification are not performed, and the following control variables, i.e., $\alpha_{j1}=\alpha_{j2}=0.7$, $\Delta c_{j1}=4*c_{0j}$, and $\Delta c_{j2}=9*c_{0j}$ (j=1,2), are assumed.

3.2. Membership Function of Target Responses and Control Variables

To perform the maximizing decision, the membership functions μ of target responses, i.e., relative story displacements, and target control variables, i.e., input reduction forces and additional damping forces, are assumed in Fig.7 and Fig.8. Here, regarding target control variables, the same membership function is assumed for the first and second story.

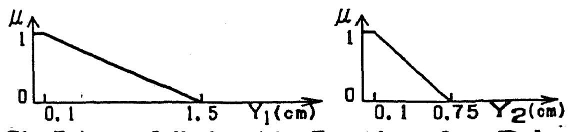


Fig.7 Assumed Membership Functions for Relative Story Responses Y_1 and Y_2

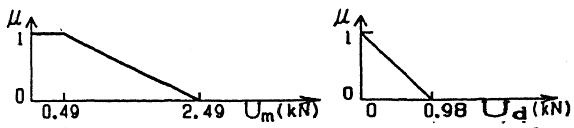


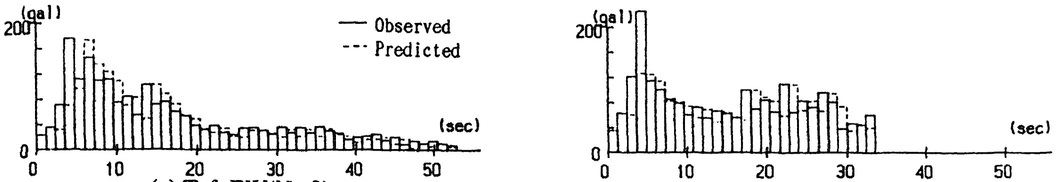
Fig.8 Assumed Membership Functions for Control Forces U_m and U_d

3.3. Numerical Results

Here, numerical results are shown only for the first story. A comparison between maximal observed and predicted earthquake motion is shown in Fig.9. Fig.10 shows a comparison between uncontrolled and controlled structural response displacements in each control interval Δt. Fig.11 shows changes of control forces U_m and U_d in each Δt.

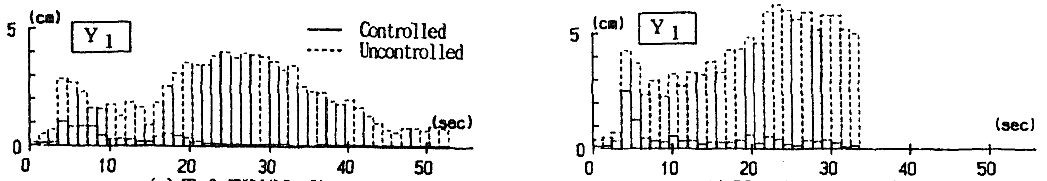
3.4. Evaluation of The Effect of Control

To illustrate the effects of control on response displacements comparing with their assumed membership functions μ of Y, the normalized probability mass functions f of Y are shown in Fig.12 (Kawamura, Tani, Watari and Yamada 1991). Here, "normalized" means "divided by the maximal value in a probability mass function". To compare the frequencies of control forces with their assumed



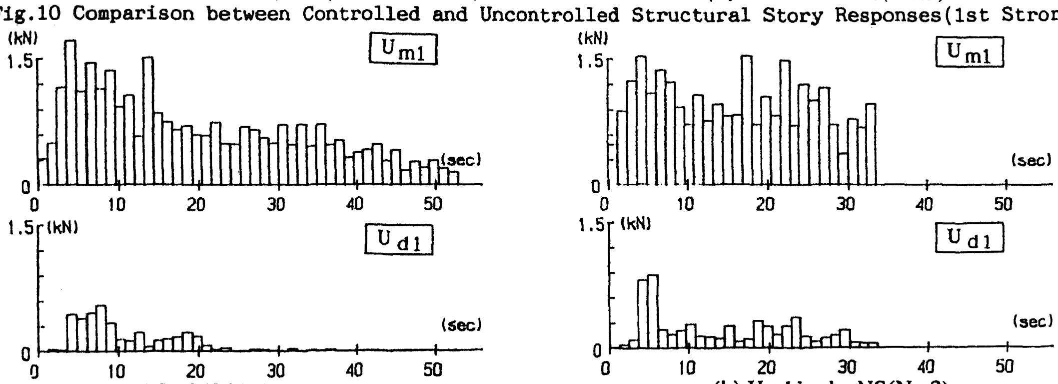
(a) Taft EW(No.2) (b) Hachinohe NS(No.3)

Fig.9 Comparison between Maximum Observed and Predicted Earthquake Waves(Δt=1.2 sec.)



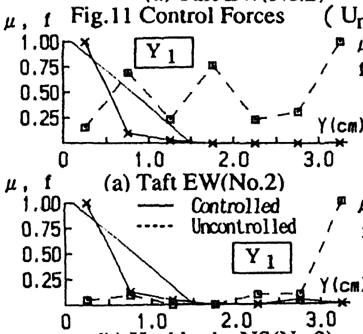
(a) Taft EW(No.2) (b) Hachinohe NS(No.3)

Fig.10 Comparison between Controlled and Uncontrolled Structural Story Responses(1st Strory)



(a) Taft EW(No.2) (b) Hachinohe NS(No.3)

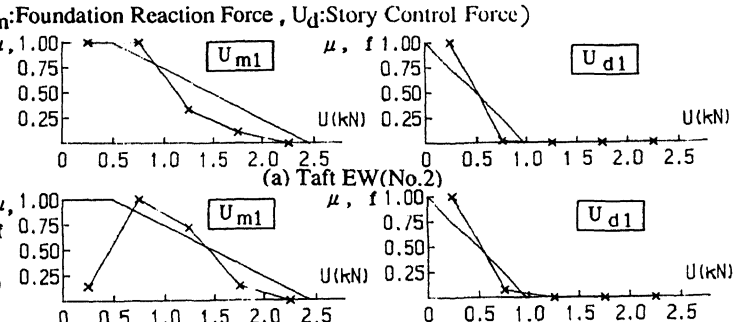
Fig.11 Control Forces (U_m:Foundation Reaction Force , U_d:Story Control Force)



(a) Taft EW(No.2)

(b) Hachinohe NS(No.3)

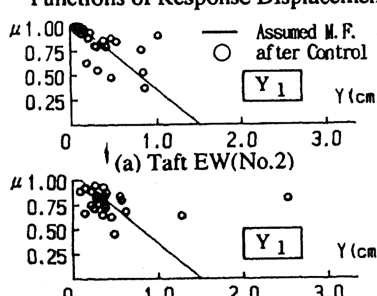
Fig.12 Normalized Probability Mass Functions of Response Displacement(1st Story)



(a) Taft EW(No.2)

(b) Hachinohe NS(No.3)

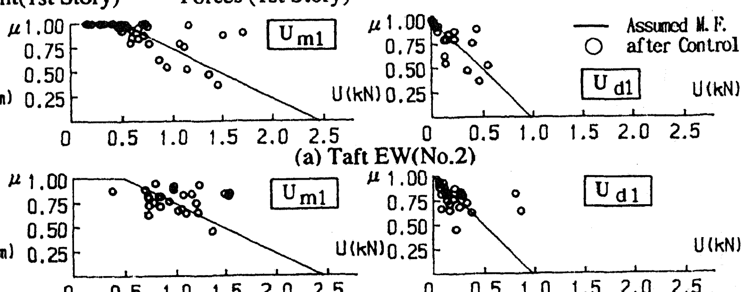
Fig.13 Normalized Probability Mass Function of Control Forces (1st Story)



(a) Taft EW(No.2)

(b) Hachinohe NS(No.3)

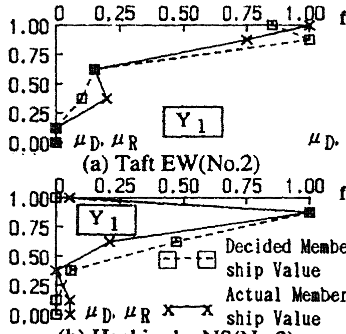
Fig.14 Actual Membership Response after Control (1st Story)



(a) Taft EW(No.2)

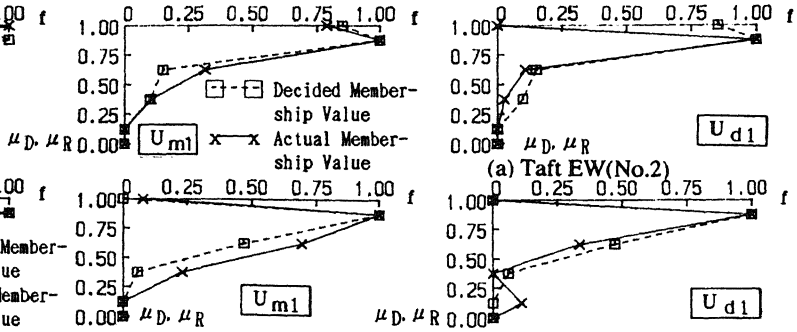
(b) Hachinohe NS(No.3)

Fig.15 Actual Membership Control Forces after Control Forces (1st Story)



(a) Taft EW(No.2)
(b) Hachinohe NS(No.3)

Fig.16 Comparison between Decided and Actual Membership Values Distributions of Response Displacement (1st Story)



(a) Taft EW(No.2)
(b) Hachinohe NS(No.3)

Fig.17 Comparison between Decided and Actual Membership Values Distributions of Control Forces (1st Story)

membership function μ of U_m and μ of U_d, the normalized probability mass functions f of U_m and U_d are shown in Fig.13.

The optimal input reduction factor α^* and additional damping factor Δc^* in the time interval Δt_{i+1} are decided by the maximizing decision and sent to the control devices. However, due to the errors included in the prediction of earthquake input and the predictive response equation, the actual response displacement Y is not necessarily located on its membership function. Fig.14 shows the actual membership plane response distributions after control (Kawamura, Tani, Watari and Yamada 1990). Fig.15 shows the actual membership plane distributions of control forces U_m and U_d. The normalized probability mass functions of f of decided(broken line) and actual (solid line) membership values μ of Y and μ of U_m and U_d are shown in Fig.16 and Fig.17, respectively.

4. CONCLUSION

In this paper, a fuzzy optimal, adaptive and predictive control system of structures subjected to earthquake loading is proposed. Digital simulations of this proposed system are performed and following conclusions are obtained.

(1) In case of the employed earthquake waves, they are predicted well in real time (Fig.9).

(2) Fuzzy maximizing decision is proved to be effective for multi-objective optimization, and its effectiveness can be verified by means of the comparison between assumed membership functions and real response frequency distributions (Figs.12-17).

(3) The fundamental idea of the proposal algorithm is considered to be valid for any other control systems such as active mass driver, active tendon and so on.

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