HEDGE-ALGEBRAS-BASED FUZZY CONTROLLER: APPLICATION TO ACTIVE CONTROL OF A FIFTEEN-STORY BUILDING AGAINST EARTHQUAKE

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ABSTRACT

Active control problem of seism-excited civil structures has attracted considerable attention in recent years. In this paper, conventional, hedge-algebras-based and optimal hedge-algebras-based fuzzy controllers, respectively denoted by FC, HAFC and OHAFC, are designed to suppress vibrations of a structure with active tuned mass damper (ATMD) against earthquake. The interested structure is a high-rise building modeled as a fifteen-degree-of-freedom structure system with two type of actuators installed on the first storey and fifteenth storey which has ATMD. The structural system is simulated against the ground accelerations, acting on the base, of the El Centro earthquake in USA on May 18th. The control effects of FC, HAFC and OHAFC are compared via the time history of the storey displacements of the structure.

Keywords. Fuzzy control; active control; hedge algebras; high-rise building; earthquake.

1. INTRODUCTION

Vibration occurs in most structures, machines, and dynamic systems. Vibration can be found in daily life as well as in engineering structures. Undesired-vibration results in structural fatigue, lowering the strength and safety of the structure, and reducing the accuracy and reliability of the equipment in the system. The problem of undesired-vibration reduction is known for many years and it has become more attractive nowadays in order to ensure the safety of the structure, and increase the reliability and durability of the equipment [1, 2].

A critical aspect in the design of civil engineering structures is the reduction of response quantities such as velocities, deflections and forces induced by environmental dynamic loadings (i.e., wind and earthquake). In recent years, the reduction of structural response, caused by dynamic effects, has become a subject of research, and many structural control concepts have been implemented in practice [3 - 7].

Depending on the control methods, vibration control in the structure can be divided into two categories, namely, passive control and active control. The idea of passive structural control is energy absorption, so as to reduce displacement in the structure. Passive vibration control devices have traditionally been used, because they do not require an energy feed and therefore do not run the risk of generating unstable states. However, passive vibration control devices have no sensors and cannot respond to variations in the parameters of the object being controlled or the controlling device. Recent development of control theory and technique has brought vibration control from passive to active and the active control method has become more effective in use. An active vibration controller is equipped with sensors, actuators, and it requires power [2, 8].

Fuzzy set theory introduced by Zadeh in 1965 has provided a mathematical tool useful for modelling uncertain (imprecise) and vague data and been presented in many real situations. Recently, many researches on active fuzzy control of vibrating structures have been done [2, 4, 5, 7, 9 - 11].

Although a FC is flexible and easy in use, but its semantic order of linguistic values is not closely guaranteed and its fuzzification and defuzzification methods are quite complicated.

Hedge algebras (HAs) was introduced and investigated since 1990 [12 - 19]. The authors of HAs discovered that: linguistic values can formulate an algebraic structure [12, 13] and it is a Complete Hedge Algebras Structure [17, 18] with a main property is that the semantic order of linguistic values is always guaranteed. It is even a rich enough algebraic structure [15] and, therefore, it can describe completely reasoning processes. HAs can be considered as a mathematical order-based structure of terms-domains, the ordering relation of which is induced by the meaning of linguistic terms in these domains. It is shown that each terms-domain has its own order relation induced by the meaning of terms, called semantically ordering relation. Many interesting semantic properties of terms can be formulated in terms of this relation and some of these can be taken to form an axioms system of hedge algebras. These algebras form an algebraic foundation to study a kind of fuzzy logic, called linguistic-valued logic and provide a good mathematical tool to define and investigate the concept of fuzziness of vague terms and the quantification problem and some approximate reasoning methods. In [19], HAs theory was begun applying to fuzzy control and it provided very much better results than FC, but studied objects in [19] were too simple to evaluate completely its control effect.

That reason suggests us, in this paper, applying HAs in active fuzzy control of a structure, which is a high-rise building modeled as a fifteen-degree-of-freedom structure system against earthquake with two controllers (FC and HAFC) in order to compare their control effect.

2. DYNAMIC MODEL OF THE STRUCTURAL SYSTEM

In this paper, the structure model in [7] is used in order to investigate the control effects of FC, HAFC and OHAFC. The high-rise building modeled as a structure, which has fifteen degrees of freedom with ATMD all in a horizontal direction as shown in figure 1.

The system is modeled including the dynamics of two active isolators installed on the first and fifteenth storeys to suppress earthquake-induced vibrations. The system and ATMD parameters are given in table 1.

Here m_1 is movable mass of the ground storey, these mass of others are $m_2, m_3, \ldots, m_{14}, m_{15}$, and m_{16} is the mass of the ATMD. $x_1, x_2, x_3, \ldots, x_{14}, x_{15}$ are the horizontal displacements and x_{16} is the displacement of ATMD. The masses cover both the ones of storeys and walls over them. All springs and dampers are acting in horizontal direction.

The equations of motion of the system subjected to the ground acceleration $\ddot{x}_0$ (see Figure 2), with control force vector $\{F\}$, can be written as:

$$[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\}=\{F\}-[M]\{r\}\ddot{x}_0 \tag{1}$$

where, $\{x\} = [x_1\ x_2\ x_3 \ldots\ x_{14}\ x_{15}\ x_{16}]^T$, $\{F\} = [-u_2\ u_2\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ u_{15}\ -u_{15}]^T$, the 16×1 vector $\{r\}$ is the influence vector representing the displacement of each degree of freedom resulting from static application of a unit ground displacement. u_2 and u_{15} are the control forces produced by linear motors; the 16×16 matrices $[M]$, $[C]$ and $[K]$ represent the structural mass, damping and stiffness matrices, respectively.

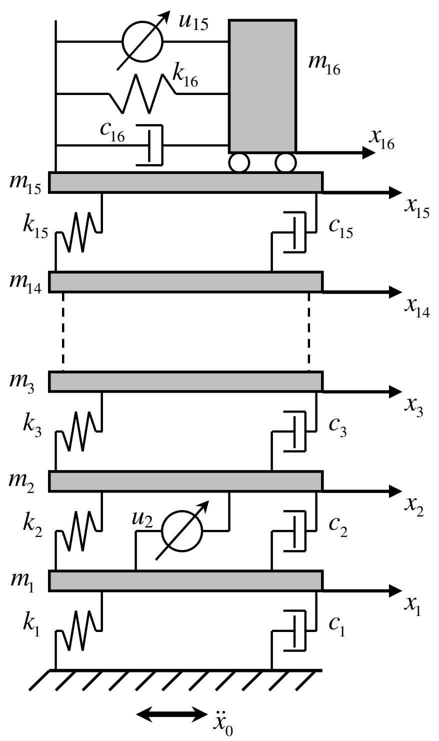

Figure 1. The structural system

Table 1. The system parameters with ATMD

Storey i	Mass m_i (10^3 kg)	Damping c_i (10^2 Ns/m)	Stiffness k_i (10^5 N/m)
1	450	261.7	180.5
2-15	345.6	2937	3404
16 (ATMD)	104.918	5970	280

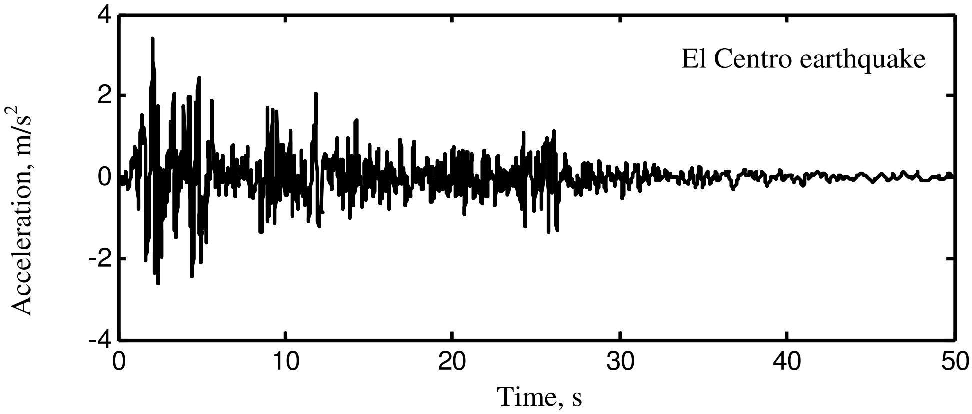

Figure 2. The ground acceleration $\ddot{x}_0$, m/s^2

The mass matrix for a high-rise building structure, with the assumption of masses lumped at floor levels, is a diagonal matrix in which the mass of each story is sorted on its diagonal, as given in the following (where m_i is the ith storey mass):

$$[M]=\begin{bmatrix} m_1 & 0 & ... & 0 & 0 \\ 0 & m_2 & ... & 0 & 0 \\ ... & ... & ... & ... & ... \\ 0 & 0 & ... & m_{15} & 0 \\ 0 & 0 & ... & 0 & m_{16} \end{bmatrix}. \tag{2}$$

The structural stiffness matrix [K] is developed based on the individual stiffness, k_i, of each storey is given in Eq. (3).

$$K_{ij}=\begin{cases} k_i+k_{i+1} & i=j\neq 16 \\ k_{16} & i=j=16 \\ -k_i & i-j=1 \\ -k_{i+1} & j-i=1 \\ 0 & \text{Else.} \end{cases} \tag{3}$$

The structural damping matrix [C] is given as

$$C_{ij}=\begin{cases} c_i+c_{i+1} & i=j\neq 16 \\ c_{16} & i=j=16 \\ -c_i & i-j=1 \\ -c_{i+1} & j-i=1 \\ 0 & \text{Else.} \end{cases} \tag{4}$$

3. HEDGE ALGEBRAS

In this section, the idea and basic formulas of HAs are summarized based on definitions, theorems, propositions in [12 - 19].

By the term meaning we can observe that *extremely small* < *very small* < *small* < *approximately small* < *little small* < *big* < *very big* < *extremely big* ... So, we have a new viewpoint: term-domains can be modelled by a *poset* (partially ordered set), a semantics-based order structure. Next, we explain how we can find out this structure.

Consider TRUTH as a linguistic variable and let X be its term-set. Assume that its linguistic hedges used to express the TRUTH are *Extremely*, *Very*, *Approximately*, *Little*, which for short are denoted correspondingly by E, V, A and L, and its primary terms are *false* and *true*. Then, $X = \{$*true*, *V true*, *E true*, *EA true*, *A true*, *LA true*, *L true*, *L false*, *false*, *A false*, *V false*, *E false* ...$\} \cup \{\boldsymbol{0}, \boldsymbol{W}, \boldsymbol{1}\}$ is a term-domain of TRUTH, where $\boldsymbol{0}$, $\boldsymbol{W}$ and $\boldsymbol{1}$ are specific constants called *absolutely false*, *neutral* and *absolutely true*, respectively.

A term-domain X can be ordered based on the following observation:

- *Each primary term has a sign which expresses a semantic tendency*. For instance, *true* has a tendency of "going up", called *positive* one, and it is denoted by c^+, while *false* has a tendency of "going down", called *negative* one, denoted by c^-. In general, we always have $c^+ \geq c^-$.

- Each hedge has also a *sign*. It is *positive* if it increases the semantic tendency of the primary terms and *negative*, if it decreases this tendency. For instance, V is *positive* with respect to both primary terms, while L has a reverse effect and hence it is *negative*. Denote by H^- the set of all negative hedges and by H^+ the set of all positive ones of TRUTH.

The term-set X can be considered as an abstract algebra $AX = (X, G, C, H, \leq)$, where $G = \{c^-, c^+\}$, $C = \{\boldsymbol{0}, \boldsymbol{W}, \boldsymbol{1}\}$, $H = H^+ \cup H^-$ and $\leq$ is a partially ordering relation on X. It is assumed that $H^- = \{h_{-1}, ..., h_{-q}\}$, where $h_{-1} < h_{-2} < ... < h_{-q}$, $H^+ = \{h_1, ..., h_p\}$, where $h_1 < h_2 < ... < h_p$.

Fuzziness measure of vague terms and hedges of term-domains is defined as follow (Definition 2 – [19]): a fm: $X \to [0, 1]$ is said to be a fuzziness measure of terms in X if:

- $fm(c^-) + fm(c^+) = 1$ and $\sum_{h\in H} fm(hu) = fm(u)$, for $\forall u \in X$;

- for the constants $\boldsymbol{0}$, $\boldsymbol{W}$ and $\boldsymbol{1}$, $fm(\boldsymbol{0}) = fm(\boldsymbol{W}) = fm(\boldsymbol{1}) = 0$;

- for $\forall x, y \in X$, $\forall h \in H$, $\dfrac{fm(hx)}{fm(x)} = \dfrac{fm(hy)}{fm(y)}$, this proportion does not depend on specific elements, called *fuzziness measure of the hedge h* and denoted by $\mu(h)$.

For each fuzziness measure fm on X, we have (Proposition 1 – [19]):

- $fm(hx) = \mu(h)fm(x)$, *for every* $x \in X$;

- $fm(c^-) + fm(c^+) = 1$;

- $\sum_{-q\leq i\leq p, i\neq 0} fm(h_i c) = fm(c)$, $c \in \{c^-, c^+\}$;

- $\sum_{-q\leq i\leq p, i\neq 0} fm(h_i x) = fm(x)$;

- $\sum_{-q\leq i\leq -1} \mu(h_i) = \alpha$ *and* $\sum_{1\leq i\leq p} \mu(h_i) = \beta$ *where* $\alpha, \beta > 0$ *and* $\alpha + \beta = 1$.

A function Sign: $X \to \{-1, 0, 1\}$ is a mapping which is defined recursively as follows, for $h, h' \in H$ and $c \in \{c^-, c^+\}$ (Definition 3 – [19]):

- $\text{Sign}(c^-) = -1$, $\text{Sign}(c^+) = +1$;

- $\text{Sign}(hc) = -\text{Sign}(c)$, if h is negative w.r.t. c; $\text{Sign}(hc) = +\text{Sign}(c)$, if h is positive w.r.t. c;

- Sign($h'hx$) = − Sign(hx), if $h'hx \neq hx$ and h' is negative w.r.t. h; Sign($h'hx$) = + Sign(hx), if $h'hx \neq hx$ and h' is positive w.r.t. h;

- Sign($h'hx$) = 0 if $h'hx = hx$.

Let fm be a fuzziness measure on X. A semantically quantifying mapping (SQM) φ: $X \to [0,1]$, which is induced by fm on X, is defined as follows (Definition 4 – [19]):

i) $\varphi(\boldsymbol{W}) = \theta = fm(c^-)$, $\varphi(c^-) = \theta - \alpha fm(c^-) = \beta fm(c^-)$, $\varphi(c^+) = \theta + \alpha fm(c^+)$;

ii) $\varphi(h_j x) = \varphi(x) + \mathrm{Sign}(h_j x)\{\sum_{i=Sign(j)}^{j} fm(h_i x) - \omega(h_j x) fm(h_j x)\}$,

where $j \in \{j: -q \le j \le p \;\&\; j \neq 0\} = [-q\text{^}p]$ and $\omega(h_j x) = \dfrac{1}{2}[1 + \mathrm{Sign}(h_j x)\mathrm{Sign}(h_p h_j x)(\beta - \alpha)]$.

It can be seen that the mapping φ is completely defined by $(p+q)$ free parameters: one parameter of the fuzziness measure of a primary term and $(p + q - 1)$ parameters of the fuzziness measure of hedges.

To illustrate the way to compute SQMs, we consider the following example.

Example: Consider a hedge algebra $AX = (X, G, C, H, \le)$, where $G = \{small, large\}$; $C = \{\boldsymbol{0}, \boldsymbol{W}, \boldsymbol{1}\}$; $H^- = \{Little\} = \{h_{-1}\}$; $q = 1$; $H^+ = \{Very\} = \{h_1\}$; $p = 1$; $\theta = 0.5$; $\alpha = 0.5$; $\beta = 0.5$ $(\alpha + \beta = 1)$. Hence,

$\mu(Very) = 0.5$; $\mu(Little) = 0.5$; $fm(small) = 0.5$; $fm(large) = 0.5$;

$\varphi(small) = \theta - \alpha fm(small) = 0.5 - 0.5 \times 0.5 = 0.25$;

$\varphi(Very\ small) = \varphi(small) + \mathrm{Sign}(Very\ small) \times (fm(Very\ small) - 0.5 fm(Very\ small))$

$= 0.25 + (-1) \times 0.5 \times 0.5 \times 0.5 = 0.125$;

$\varphi(Little\ small) = \varphi(small) + \mathrm{Sign}(Little\ small) \times (fm(Little\ small) - 0.5 fm(Little\ small))$

$= 0.25 + (+1) \times 0.5 \times 0.5 \times 0.5 = 0.375$;

$\varphi(large) = \theta + \alpha fm(large) = 0.5 + 0.5 \times 0.5 = 0.75$;

$\varphi(Very\ large) = \varphi(large) + \mathrm{Sign}(Very\ large) \times (fm(Very\ large) - 0.5 fm(Very\ large))$

$= 0.75 + (+1) \times 0.5 \times 0.5 \times 0.5 = 0.875$;

$\varphi(Little\ large) = \varphi(large) + \mathrm{Sign}(Little\ large) \times (fm(Little\ large) - 0.5 fm(Little\ large))$

$= 0.75 + (-1) \times 0.5 \times 0.5 \times 0.5 = 0.625$.

4. FUZZY CONTROLLERS OF THE STRUCTURAL SYSTEM

The fuzzy controllers are based on the closed-loop fuzzy system shown in Figure 3. Where, u_2 and u_{15} are determined by above-mentioned controllers, x_2, $\dot{x}_2$, x_{15} and $\dot{x}_{15}$ are determined by Eqs. (1). The goal of controllers is to reduce displacements in the second and fifteenth storeys, so as to reduce displacements in the structure.

It is assumed that the universes of discourse of four state variables are $-a_2 \le x_2 \le a_2$; $-b_2 \le \dot{x}_2 \le b_2$; $-a_{15} \le x_{15} \le a_{15}$ and $-b_{15} \le \dot{x}_{15} \le b_{15}$ and of the control forces are $-0.1\times10^6 \le u_2 \le 0.1\times10^6$ (N) and $-10\times10^6 \le u_{15} \le 10\times10^6$ (N). Where, $\{a\} = [a_1 \;\; a_2 \;\; \dots \;\; a_{14}$

$a_{15}]^T$ and $\{b\}$ = $[b_1 \;\; b_2 \; \ldots \;\; b_{14} \;\; b_{15}]^T$ are absolute peak displacement and velocity vectors, respectively, of the uncontrolled state of the structure excited by the El Centro earthquake.

In the following parts of this section, establishing steps of the controllers will be presented.

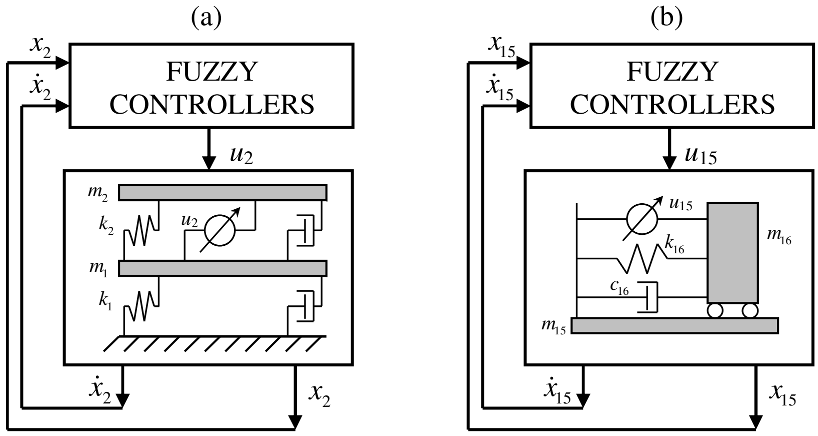

Figure 3. Fuzzy controllers of the structural system, (a) – for the actuator on the first storey, (b) – for the actuator on the fifteenth storey (ATMD)

4.1. Conventional fuzzy controller (FC) of the structure

In this subsection, the FC of the structure could be established based on [7] due to the same form of the problems using Mamdani's inference and centroid defuzzification method with fifteen control rules. The configuration of the FC is shown in figure 4.

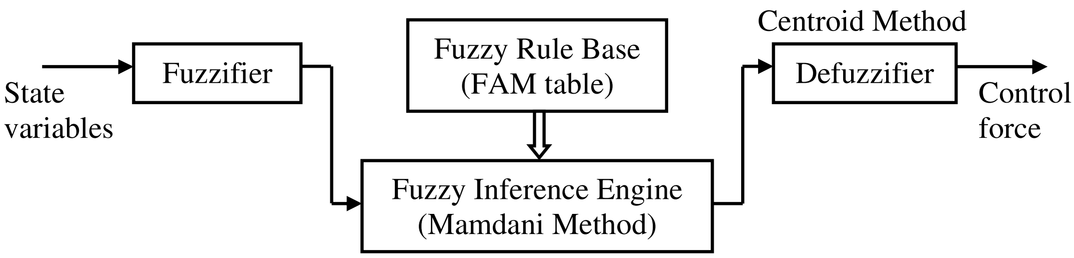

Figure 4. The configuration of the FC

4.1.1. Fuzzifier

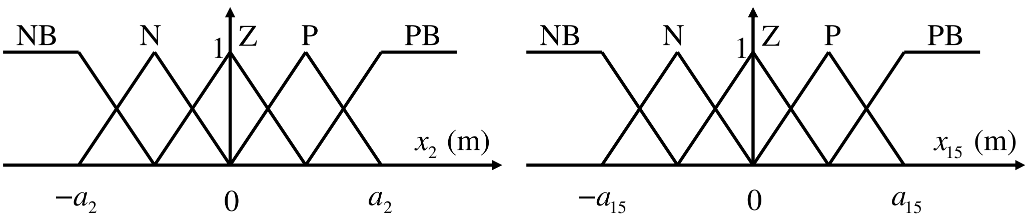

Figure 5. Membership functions for x_2 and x_{15}

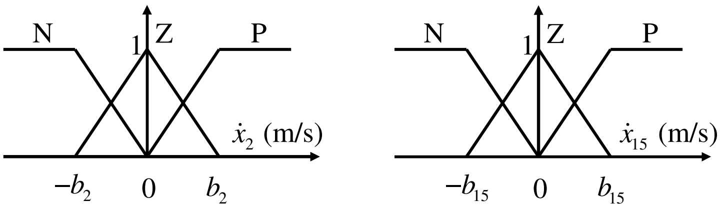

Figure 6. Membership functions for $\dot{x}_2$ and $\dot{x}_{15}$

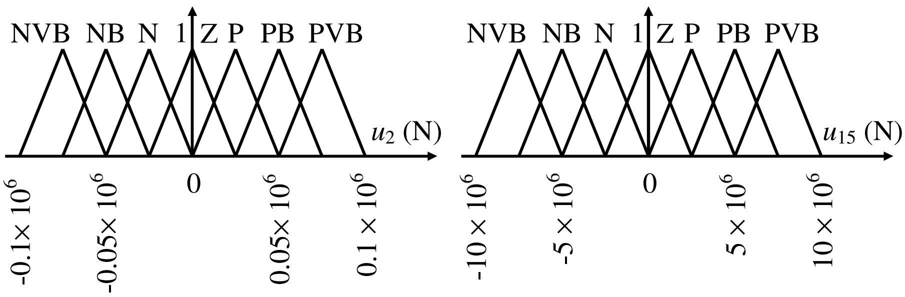

Figure 7. Membership functions for u_2 and u_{15}

Five membership functions for x_2 and x_{15} in their intervals are established with values negative big (NB), negative (N), zero (Z), positive (P) and positive big (PB) as shown in figure 5. Three membership functions for $\dot{x}_2$ and $\dot{x}_{15}$ in their intervals are established with values negative (N), zero (Z) and positive (P) as shown in Figure 6 [7]. Then, seven membership functions for u_2 and u_{15} in their intervals are established with values negative very big (NVB), NB, N, Z, P, PB and positive very big (PVB) as shown in figure 7 [7].

4.1.2. Fuzzy rule base

The fuzzy associative memory tables (FAM table) are established as shown in tables 2 and 3 for the actuators on the first and fifteenth storeys [7], respectively.

Table 2. FAM table for the actuator on the first storey

x_2	$\dot{x}_2$		
	N	Z	P
NB	PVB	PB	P
N	PB	P	Z
Z	P	Z	N
P	Z	N	NB
PB	N	NB	NVB

Table 3. FAM table for the actuator on the fifteenth storey

x_{15}	$\dot{x}_{15}$		
	N	Z	P
NB	PVB	PB	P
N	PB	P	Z
Z	P	Z	N
P	Z	N	NB
PB	N	NB	NVB

4.2. Hedge-algebras-based fuzzy controller (HAFC) of the structure

The linguistic labels in tables 2 and 3 have to be transformed into the new ones given in tables 4 and 5, that are suitable to describe linguistically reference domains of [0, 1] and can be modeled by suitable HAs. The HAs of the state variables x_2, $\dot{x}_2$, x_{15} and $\dot{x}_{15}$ are $AX = (X, G, C, H, \leq)$, where $X = x_2, \dot{x}_2, x_{15}$ or $\dot{x}_{15}$, $G = \{small, large\}$, $C = \{\mathbf{0}, \mathbf{W}, \mathbf{1}\}$, $H = \{H^-, H^+\} = \{Little, Very\}$, and the HAs of the control variables $AU = (U, G, C, H, \leq)$, where $U = u_2$ or u_{15}, with the same sets G, C and H as for x_2, $\dot{x}_2$, x_{15} and $\dot{x}_{15}$, however, their terms describe different quantitative semantics based on different real reference domains. The semantically quantifying mappings (SQMs) φ are determined and shown in tables 6 and 7 (see section 3). The configuration of the HAFC is shown in figure 8.

Table 4. Linguistic transformation for x_2, $\dot{x}_2$, x_{15} and $\dot{x}_{15}$

NB	N	Z	P	PB
small	*Little small*	***W***	*Little large*	*large*

Table 5. Linguistic transformation for u_2 and u_{15}

NVB	NB	N	Z	P	PB	PVB
Very small	*small*	*Little small*	***W***	*Little large*	*large*	*Very large*

Table 6. Parameters of SQMs for x_2, $\dot{x}_2$, x_{15} and $\dot{x}_{15}$

small	*Little small*	***W***	*Little large*	*large*
0.25	0.375	0.5	0.625	0.75

Table 7. Parameters of SQMs for u_2 and u_{15}

Very small	*small*	*Little small*	***W***	*Little large*	*Very large*	*Very large*
0.125	0.25	0.375	0.5	0.625	0.75	0.875

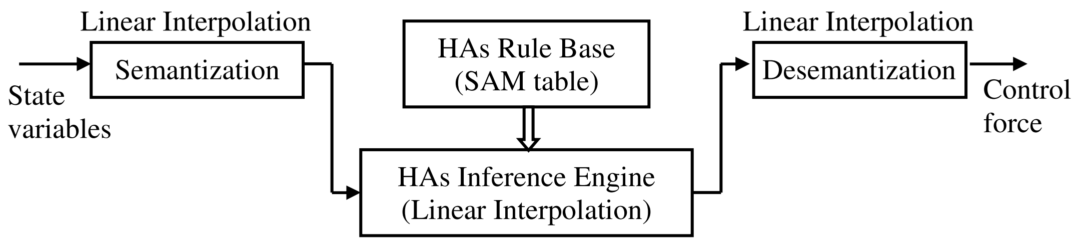

Figure 8. The configuration of the HAFC

4.2.1. Semantization and desemantization

Note that, for convenience in presenting the quantitative semantics formalism in studying the meaning of vague terms, we have assumed that the common reference domain of the linguistic variables is the interval [0,1], called the semantic domain of the linguistic variables. In applications, we need use the values in the reference domains, e.g. the interval [*a*,*b*], of the linguistic variables and, therefore, we have to transform the interval [a,b] into [0,1] and, vice-versa. The transformation of the interval [*a*,*b*] into [0,1] is called a *semantization* and its converse transformation from [0,1] into [*a*,*b*] is called a *desemantization*. The new terminology "semantization" was defined and accepted in Ho et al. [19].

The semantizations for each state variable are defined by the transformations given in Figures 9 and 10. The semantization and desemantization for each control variable are defined by the transformations given in Figure 11 (x_2, $\dot{x}_2$, x_{15}, $\dot{x}_{15}$, u_2 and u_{15} are replaced with x_{2s}, $\dot{x}_{2s}$, x_{15s}, $\dot{x}_{15s}$, u_{2s} and u_{15s} when transforming from real domain to semantic one, respectively).

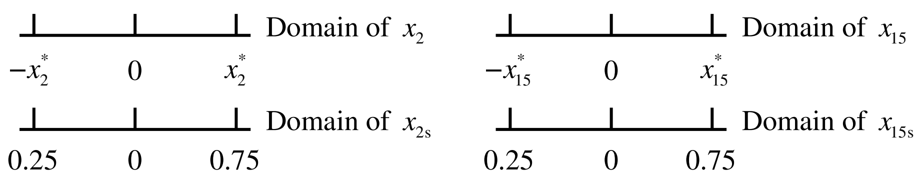

Figure 9. Transformations: x_2 to x_{2s} and x_{15} to x_{15s}

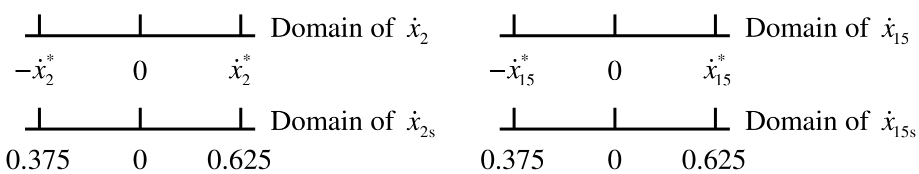

Figure 10. Transformations: $\dot{x}_2$ to $\dot{x}_{2s}$ and $\dot{x}_{15}$ to $\dot{x}_{15s}$

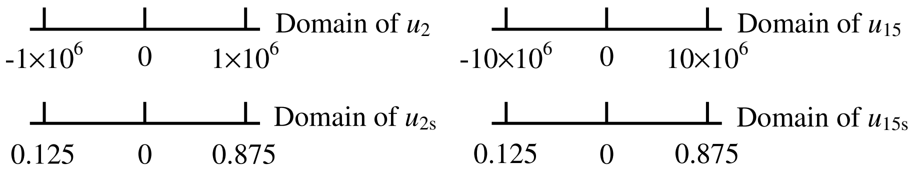

Figure 11. Transformations: u_2 to u_{2s} and u_{15} to u_{15s}

4.2.2. HAs rule base

We have the SAM (semantic associative memory) tables based on FAM ones (Tables 2 and 3) with semantically quantifying mappings as shown in Tables 8 and 9 for the actuators on the first and fifteenth storeys, respectively.

Table 8. SAM table for the actuator on the first storey

x_{2s}	$\dot{x}_{2s}$		
	Little small: 0.375	***W***: 0.5	*Little large*: 0.625
small: 0.25	*Very large*: 0.875	*large*: 0.75	*Little large*: 0.625
Little small: 0.375	*large*: 0.75	*Little large*: 0.625	***W***: 0.5
W: 0.5	*Little large*: 0.625	***W***: 0.5	*Little small*: 0.375
Little large: 0.625	***W***: 0.5	*Little small*: 0.375	*small*: 0.25
large: 0.75	*Little small*: 0.375	*small*: 0.25	*Very small*: 0.125

Table 9. SAM table for the actuator on the fifteenth storey

x_{15s}	$\dot{x}_{15s}$		
	Little small: 0.375	***W***: 0.5	*Little large*: 0.625
small: 0.25	*Very large*: 0.875	*large*: 0.75	*Little large*: 0.625
Little small: 0.375	*large*: 0.75	*Little large*: 0.625	***W***: 0.5
W: 0.5	*Little large*: 0.625	***W***: 0.5	*Little small*: 0.375
Little large: 0.625	***W***: 0.5	*Little small*: 0.375	*small*: 0.25
large: 0.75	*Little small*: 0.375	*small*: 0.25	*Very small*: 0.125

4.2.3. HAs inference engine

HAs inference engine is described by Quantifying Semantic Surfaces established through the points that present the control rules occurring in tables 8 and 9 as shown in figure 12.

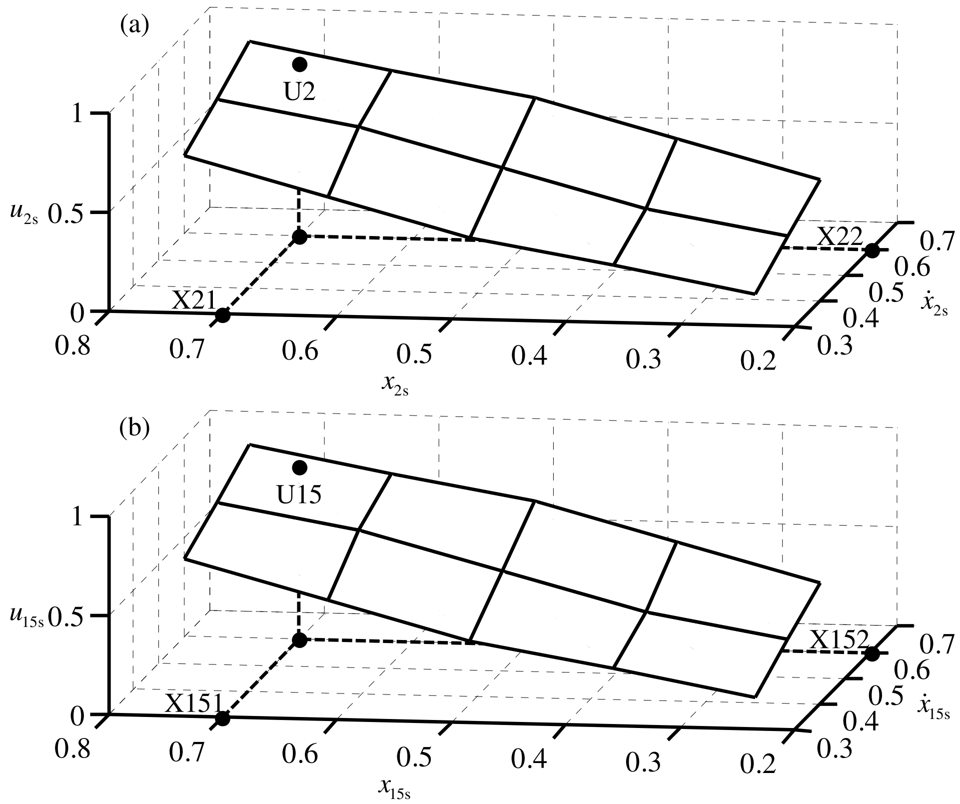

Figure 12. Quantifying Semantic Surfaces, (a) – for the actuator on the first storey, (b) – for the actuator on the fifteenth storey (ATMD)

Hence, u_{2s} and u_{15s} are determined by linear interpolations through x_{2s}, $\dot{x}_{2s}$, x_{15s} and $\dot{x}_{15s}$. For example:

- If $x_{2s} = 0.7$ (point X21) and $\dot{x}_{2s} = 0.6$ (point X22) then $u_{2s} = 0.8643$ (point U2).

- If $x_{15s} = 0.7$ (point X151) and $\dot{x}_{15s} = 0.6$ (point X152) then $u_{15s} = 0.8643$ (point U15).

4.3. Optimal HAFC (OHAFC) of the structure

In this subsection, the OHAFC of the structure is established. Where, a genetic algorithm (GA) is used as the search algorithm and based on the code of Chipperfield et al. [20].

Note that in the fuzzy sets approach, linguistic terms are merely labels of fuzzy sets, i.e. fuzzy sets shape plays an important role, however, in the HAs approach, the algebraic structure is essential and, hence, so are the SQMs. So, the meaning of terms or the fuzziness measure of terms and hedges, which are the parameters of SQMs or parameters of the fuzziness measure of primary terms and hedges, are very important.

In the OHAFC, the parameters of the fuzziness measure of primary terms and hedges of u_2 and u_{15} are now considered as design variables and their intervals are determined as follow:

$$fm(c^{-}) = [0.3 \div 0.7];\ \mu(h^{-}) = [0.3 \div 0.7].$$

The goal function g is defined as follow:

$$g = \sum_{j=0}^{n} \sum_{i=1}^{15} \left(\frac{x_i^2(j)}{a_i^2} \right) = \min \tag{5}$$

where, n is the number of control cycles. The parameters using GA are determined as (Chipperfield et al. [20]): number of individuals per subpopulations: 10; number of generations: 200; recombination probability: 0.8; number of variables: 4 and fidelity of solution: 10.

5. RESULTS AND DISCUSSION

Figures 13-15 show the time responses of the second, eighth and fifteenth storey displacements, respectively. The maximum storey drift is shown in Figure 16. Comparison of the effectiveness of the three controllers used in this study is presented in Table 10.

As shown in above-mentioned figures and tables, vibration amplitudes of the storeys are decreased successfully with FC, HAFC and OHAFC for the structure excited by the El Centro earthquake.

The reduction ratios (ratio of the controlled to uncontrolled response) for maximum displacement of the top floor of the structure are about 50%, 44%, and 37% for the FC, HAFC, and OHAFC, respectively (figure 16 and table 10). Therefore, it is seen that the OHAFC is more effective than the two other controllers in view of reducing the displacement response of the structure.

From tables 4, 5, 6 and 7, it can be conceded that the semantic order of HAFC is always guaranteed.

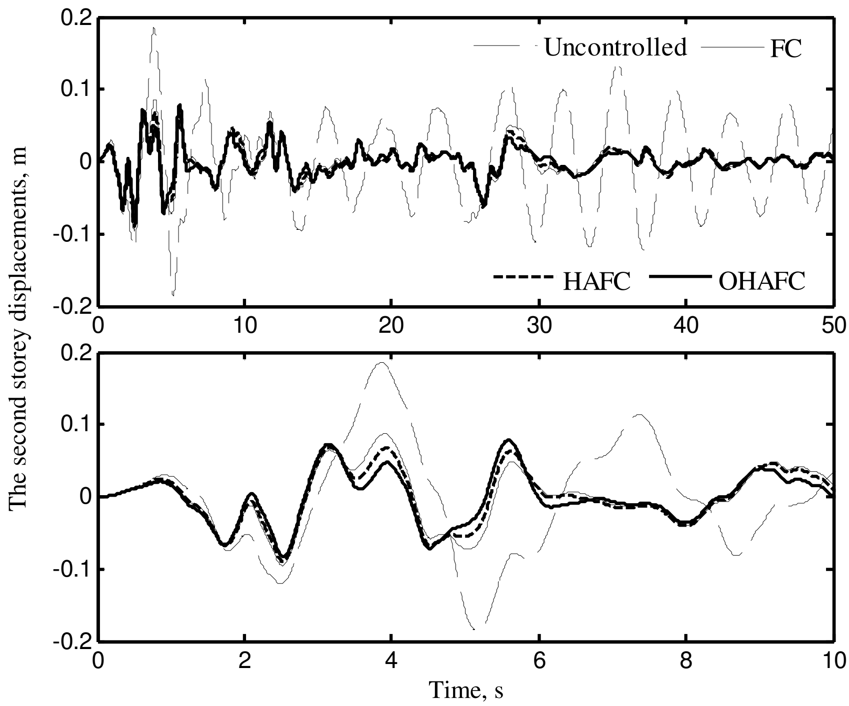

Figure 13. Displacements x_2 (m) versus time (s)

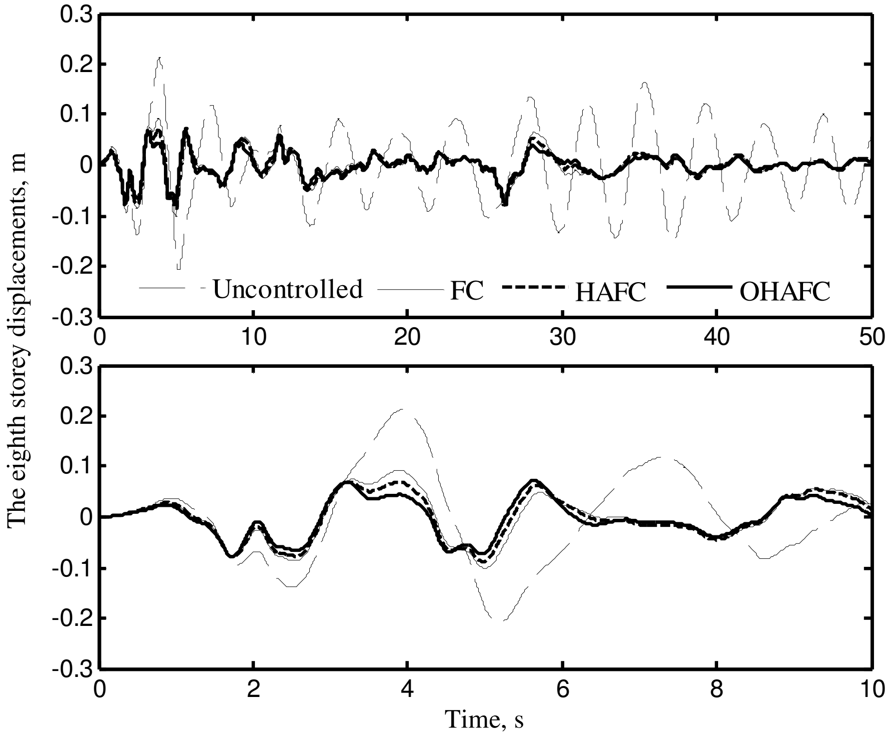

Figure 14. Displacements x_8 (m) versus time (s)

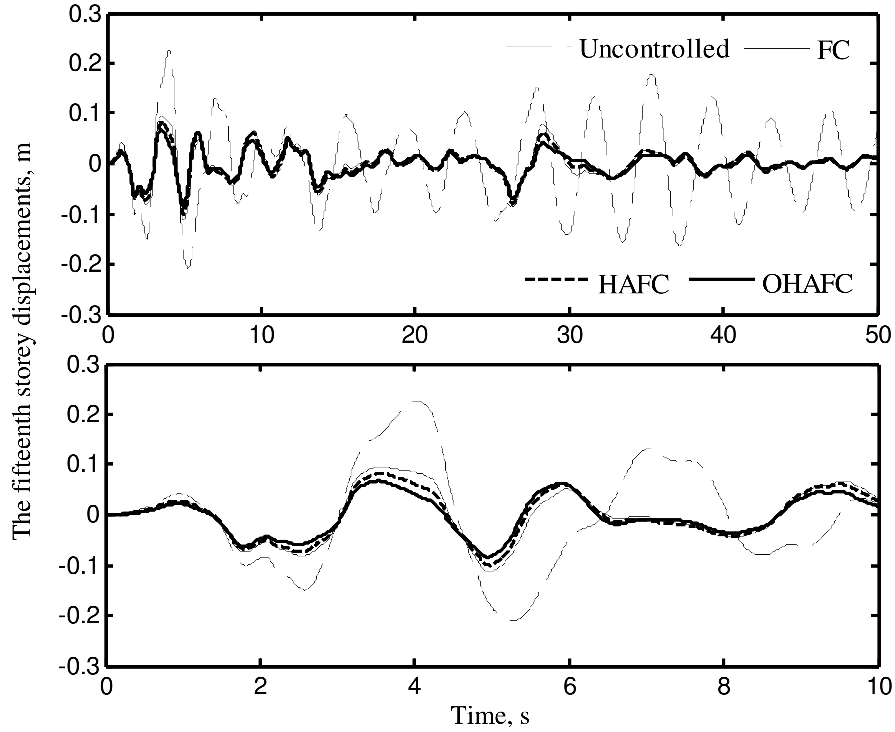

Figure 15. Displacements x_{15} (m) versus time (s)

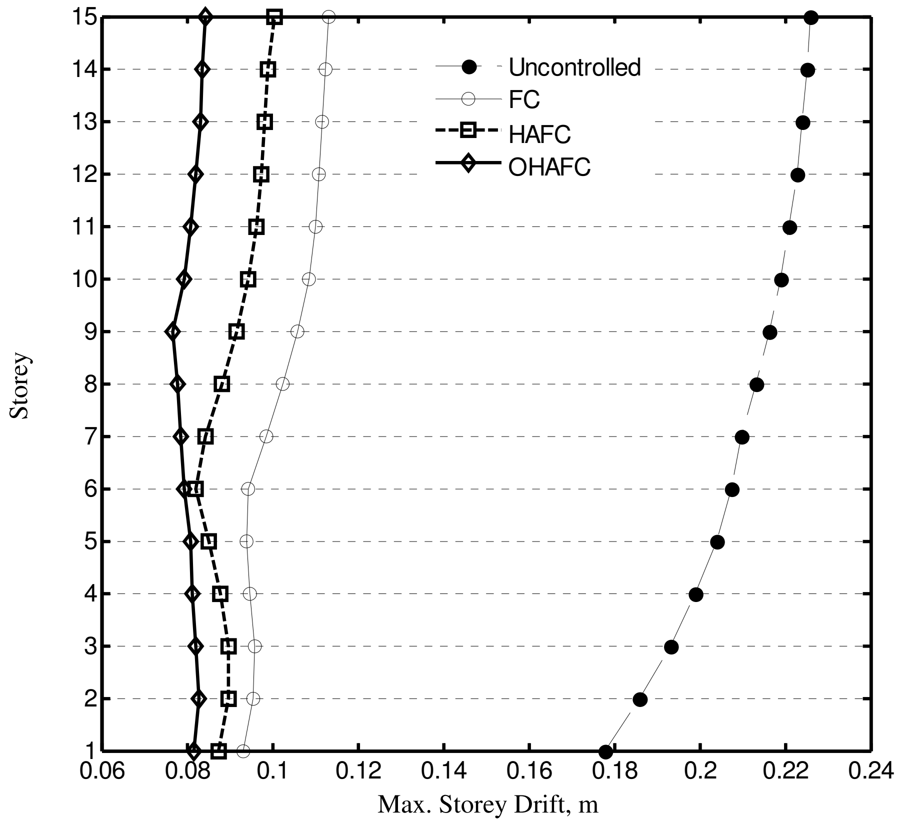

Figure 16. The maximum storey drift

The *semantization* method of HAFC (figures 9 - 11) is simpler than the *fuzzification* method of FC (figures 5 - 7). The *desemantization* method of HAFC, executed by linear interpolations (see figure 11), is simpler than the *defuzzification* method (centroid method – in this paper) of FC very much. The inference method of HAFC, executed by linear interpolations (see figure 12), is simpler than the one of FC (Mamdani method – in this paper) very much.

Hence, HAFC provides better results and very easier way to implementing in comparison with FC.

In order to describe three, five, seven,…, n linguistic labels by HAs, only two independent parameters ($fm(c^-)$ and $\mu(h^-)$, see section 3) are needed. Thus, there are two design variables to establish an optimal HAFC. For an optimal FC based on n linguistic labels, there are ($n \times 3$) design variables (each triangular membership function needs three design variables). Hence, an optimal HAFC is simpler and more efficient than an optimal FC when designing and implementing.

The optimum values of the design variables, the fuzziness measure of primary terms and hedges of u_2 and u_{15}, obtained by a GA provide good results for the structure.

HAFC, a new fuzzy control algorithm, does not require fuzzy sets to provide the semantics of the linguistic terms used in the fuzzy rule system rather the semantics is obtained through the semantically quantifying mappings (SQMs). In the algebraic approach, the design of an HAFC leads to the determination of the parameter of SQMs, which are the fuzziness measure of primary terms and linguistic hedges occurring in the fuzzy model.

Table 10. Comparison of the effectiveness of the three controllers

Building Storey	Maximum uncontrolled displacement, m	Controlled to uncontrolled displacement ratio (reduction ratio)		
		FC	HAFC	OHAFC
1	0.178	0.522	0.491	0.458
2	0.186	0.512	0.480	0.445
3	0.193	0.495	0.463	0.423
4	0.199	0.474	0.441	0.408
5	0.204	0.461	0.417	0.395
6	0.207	0.453	0.395	0.381
7	0.210	0.468	0.400	0.372
8	0.213	0.479	0.413	0.364
9	0.216	0.488	0.423	0.353
10	0.219	0.494	0.430	0.360
11	0.221	0.497	0.434	0.365
12	0.223	0.497	0.436	0.368
13	0.224	0.497	0.437	0.370
14	0.225	0.498	0.439	0.370
15	0.226	0.500	0.443	0.372

6. CONCLUSIONS

In the present work, new fuzzy controllers based on HAs are applied for active control of a structure against earthquake. The main results are summarized as follows:

The algebraic approach to term-domains of linguistic variables is quite different from the fuzzy sets one in the representation of the meaning of linguistic terms and the methodology of solving the fuzzy multiple conditional reasoning problems.

It is clear that HAFC is simpler, more effective and more understandable in comparison with FC for actively controlling the above-mentioned seism-excited civil structure.

In fuzzy logic, many important concepts like fuzzy set, T-norm, S-norm, intersection, union, complement, composition… are used in approximate reasoning. This is an advantage for the process of flexible reasoning, but there are too many factors such as shape and number of membership functions, defuzzification method,… influencing the precision of the reasoning process and it is difficult to optimize. Those are subjective factors that cause error in determining the values of control process. Meanwhile, approximate reasoning based on hedge algebras, from the beginning, does not use fuzzy set concept and its precision is obviously not influenced by this concept. Therefore, the method based on hedge algebras does not need to determine shape and number of membership function, neither does it need to solve defuzzification problem. Besides, in calculation, while there is a large number of membership functions, the volume of calculation based on fuzzy control increases quickly, meanwhile the volume of calculation based on hedge algebras does not increase much with very simple calculation. With these above advantages, it is definitely possible to use hedge algebras theory for many different controlling problems.

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TÓM TẮT

BỘ ĐIỀU KHIỂN MỜ DỰA TRÊN ĐẠI SỐ GIA TỬ: ỨNG DỤNG ĐỂ ĐIỀU KHIỂN CHỦ ĐỘNG KẾT CẤU NHÀ 15 TẦNG CHỊU TẢI ĐỘNG ĐẤT

Bài toán điều khiển chủ động các kết cấu chịu tải động đất đã được quan tâm nhiều trong những năm gần đây. Trong bài báo này, các bộ điều khiển mờ thông thường (FC), dựa trên đại số gia tử (HAFC) và tối ưu dựa trên đại số gia tử (OHAFC) được thiết kế để giảm dao động của một kết cấu nhà 15 tầng chịu tải động đất. Kết cấu được mô phỏng với tải động đất El Centro ở Mỹ ngày 18 tháng 5 năm 1940. Hiệu quả điều khiển của FC, HAFC và OHAFC được so sánh thông qua đáp ứng chuyển vị của các tầng theo thời gian của kết cấu.