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ACTIVE CONTROL OF A THREE - STORY BUILDING USING HEDGE - ALGEBRAS - BASED FUZZY CONTROLLER

Bui Hai Le
Hanoi University of Science and Technology

Abstract. In this paper, conventional and hedge - algebras - based fuzzy controllers, respectively denoted by FC and HAFC, are designed to suppress vibrations of a three - story building against earthquake. The structural system is simulated against the ground accelerations of the El Centro earthquake in USA on May 18th, 1940; the Northridge earthquake in USA on January 17th, 1994 and the Kobe earthquake in Japan on January 16th, 1995. The control effects of FC and HAFC are compared via the time history of the story displacements of the structure.

Keywords: Active control, fuzzy control, hedge algebras, earthquake.

1. INTRODUCTION

Undesired vibrations result in structural fatigue, lowering the strength and safety of the structure, and reducing the accuracy and reliability of equipments. The problem of undesired vibration reduction is known for many years and it has become more attractive nowadays to ensure the safety of structure, and increase the reliability and durability of 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. 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 [2,7,9-11].

Hedge algebras (HAs) has been 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. In [19], HAs theory was begun applying to fuzzy control and it provided better results than FC, but studied objects in [19] are too simple to evaluate completely its control effect.

That reason suggests us, in this paper, applying HAs in active fuzzy control of a three - story building against earthquake.

2. DYNAMIC MODEL OF THE STRUCTURAL SYSTEM

In this paper, the simple structure model in [6] is used to study the control effect of HAFC in comparison with FC. The structure, which has three degrees of freedom all in a horizontal direction, is shown in Fig. 1.

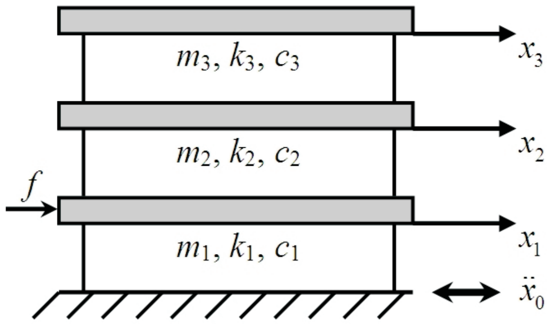

Fig. 1. The structural system

The equations of motion of the system subjected to the ground acceleration $\ddot{x}_0$ (see Fig. 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, $\{x\} = [x_1 \quad x_2 \quad x_3]^T$, $\{F\} = [-f \quad 0 \quad 0]^T$, $\{r\} = [1 \quad 1 \quad 1]^T$. f is the control force, the matrices $[M]$, $[C]$ and $[K]$, respectively representing the structural mass, damping and stiffness ones, are given as follow:

$$[M] = \begin{bmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{bmatrix}, [K] = \begin{bmatrix} k_1 + k_2 & -k_2 & 0 \\ -k_2 & k_2 + k_3 & -k_3 \\ 0 & -k_3 & k_3 \end{bmatrix}, \tag{2}$$

$$[C] = 0.1 \times [M] + 0.003 \times [K].$$

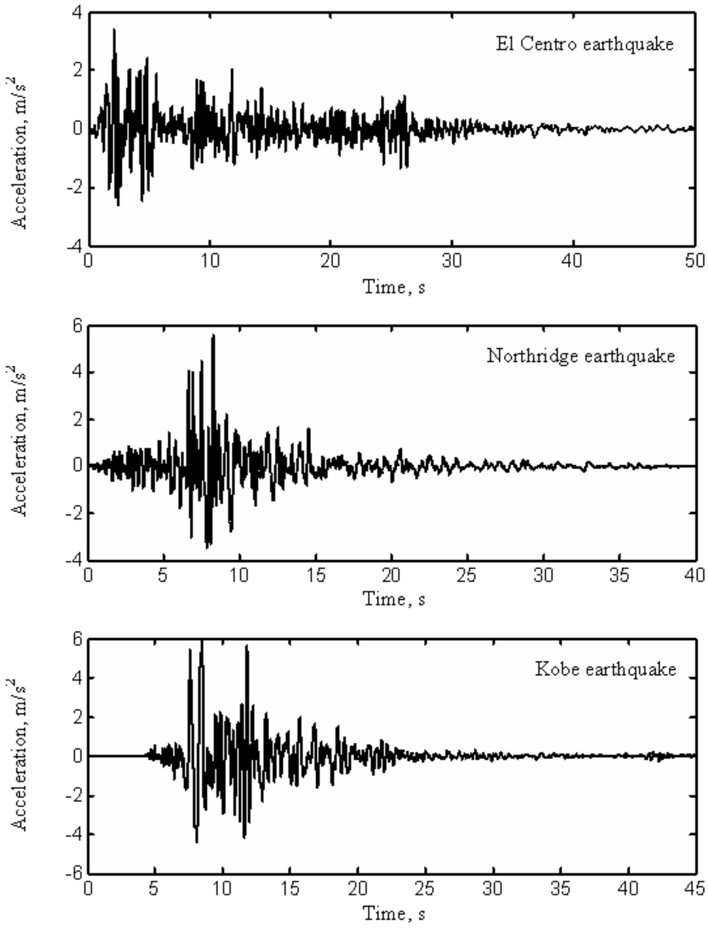

Fig. 2. The ground acceleration $\ddot{x}_0$, m/s^2

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 ***0***, ***W*** and ***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 $c^+ \geq c^-$, semantically.

- *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:

$$fm(c^-) + fm(c^+) = 1 \text{ and } \sum_{h \in H} fm(hu) = fm(u), \text{ for } \forall u \in X. \tag{3}$$

For the constants ***0***, ***W*** and ***1***

$$fm(\boldsymbol{0}) = fm(\boldsymbol{W}) = fm(\boldsymbol{1}) = 0. \tag{4}$$

For $\forall x, y \in X, \forall h \in H$,

$$\frac{fm(hx)}{fm(x)} = \frac{fm(hx)}{fm(y)} \tag{5}$$

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]):

$$fm(hx) = \mu(h) fm(x), \text{ for every } x \in X, \tag{6}$$

$$fm(c^-) + fm(c^+) = 1, \tag{7}$$

$$\sum_{i=-q, i\neq 0}^{p} fm(h_i c) = fm(c), c \in \{c^-, c^+\}, \tag{8}$$

$$\sum_{i=-q, i\neq 0}^{p} fm(h_i c) = fm(x), \tag{9}$$

$$\sum_{i=-q}^{-1} \mu(h_i) = \alpha \text{ and } \sum_{i=1}^{p} \mu(h_i) = \beta \text{ where } \alpha, \beta > 0 \text{ and } \alpha + \beta = 1. \tag{10}$$

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]):

$$\text{Sign}(c^-) = -1,\ \text{Sign}\ (c^+) = +1, \tag{11}$$

$$\text{Sign}\ (hc) = -\ \text{Sign}\ (c),\ \text{if } h \text{ is negative w.r.t. } c, \tag{12}$$

$$\text{Sign}\ (hc) = +\ \text{Sign}\ (c),\ \text{if } h \text{ is positive w.r.t. } c, \tag{13}$$

$$\text{Sign}\ (h'hx) = -\ \text{Sign}\ (hx),\ \text{if } h'hx \neq hx \text{ and } h' \text{ is negative w.r.t. } h, \tag{14}$$

$$\text{Sign}\ (h'hx) = +\ \text{Sign}\ (hx),\ \text{if } h'hx \neq hx \text{ and } h' is \text{ positive w.r.t. } h, \tag{15}$$

$$\text{Sign}\ (h'hx) = 0 \text{ if } h'hx = hx. \tag{16}$$

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

$$\varphi(\boldsymbol{W}) = \theta = fm(c^-), \varphi(c^-) = \theta - \alpha fm(c^-) = \beta fm(c^-), \varphi(c^+) = \theta + \alpha fm(c^+), \tag{17}$$

$$\begin{aligned} &\varphi(h_j x) = \varphi(x) + \text{Sign}(h_j x)\{\sum_{i=\text{Sign}(j)}^{j} fm(h_i x) - \omega(h_j x) fm(h_j x)\}, \\ &\text{where } j \in \{j : -q \leq j \leq p \text{ and } j \neq 0\} = [-q^p] \\ &\text{and } \omega(h_j x) = \frac{1}{2}[1 + \text{ Sign } (h_j x) \text{ Sign } (h_p h_j x)(\beta - \alpha)] \end{aligned} \tag{18}$$

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 a close relationship between the meaning of terms and their fuzziness measure and the way to compute semantically quantifying mappings, we consider the following example.

Example: Consider a hedge algebra $AX = (X, G, C, H, \leq)$, where $G = \{small, large\}$, $C = \{\boldsymbol{0}, \boldsymbol{W}, \boldsymbol{1}\}$, $H^- = \{Little\} = \{h_{-1}\}, q = 1, H^+ = \{Very\} = \{h_1\}, p = 1$. We assume:

$$\theta = 0.5, \alpha = 0.5. \tag{19}$$

It means that the semantically quantifying mapping of the neutral element and the sum of the fuzziness measure of the negative hedges are 0.5. Hence,

- Using Equation (10) with $q = 1$, we have fuzziness measures of the hedges:

$$\mu(Little) = \alpha = 0.5, \mu(Very) = \beta = 1 - \alpha = 0.5.$$

- Next, using Equations (17) and (7), we have fuzziness measures of the terms:

$$fm(small) = \theta = 0.5, fm(large) = 1 - fm(small) = 0.5.$$

- Then, semantically quantifying mappings of the linguistic values are computed by using Equations (17) and (18) as follow:

$\varphi(\boldsymbol{W}) = \theta = 0.5, \varphi(small) = \theta - \alpha fm(small) = 0.5 - 0.5 \times 0.5 = 0.25,$

$\varphi(Very\ small) = \varphi(small) +$ Sign $(Very\ small) \times (fm(Very\ small) - 0.5fm(Very\ small))$
$= 0.25 + (-1) \times 0.5 \times 0.5 \times 0.5 = 0.125,$

$\varphi(Little\ small) = \varphi(small) +$ Sign $(Little\ small) \times (fm(Little\ small) - 0.5fm(Little\ small))$
$= 0.25 + (+1) \times 0.5 \times 0.5 \times 0.5 = 0.375$

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

$\varphi(Very\ large) = \varphi(large) +$ Sign $(Very\ large) \times (fm(Very\ large) - 0.5fm(Very\ large))$
$= 0.75 + (+1) \times 0.5 \times 0.5 \times 0.5 = 0.875,$

$\varphi(Little\ \ large) = \varphi(large) +$ Sign $(Little\ large) \times (fm(Little\ large) - 0.5fm(Little\ large))$
$= 0.75 + (-1) \times 0.5 \times 0.5 \times 0.5 = 0.625,$

$\varphi(Very\ Very\ small) = \varphi(Very\ small) +$ Sign $(Very\ Very\ small) \times (fm(Very\ Very\ small) -$
$- 0.5fm(Very\ Very\ small)) = 0.125 + (-1) \times 0.5 \times 0.5 \times 0.5 \times 0.5 = 0.0625,$

$\varphi(Little\ Very\ small) = \varphi(Very\ small) +$ Sign $(Little\ Very\ small) \times (fm(Little\ Very\ small) -$
$- 0.5fm(Little\ Very\ small)) = 0.125 + (+1) \times 0.5 \times 0.5 \times 0.5 \times 0.5 = 0.1875,$

$\varphi(Very\ Little\ small) = \varphi(Little\ small) +$ Sign $(Very\ Little\ small) \times (fm(Very\ Little\ small) -$
$- 0.5fm(Very\ Little\ small)) = 0.375 + (-1) \times 0.5 \times 0.5 \times 0.5 \times 0.5 = 0.3125,$

$\varphi(Little\ \ Little\ \ small) = \varphi(Little\ small) +$ Sign $(Little\ Little\ small) \times (fm(Little\ Little\ small) -$
$- 0.5fm(Little\ Little\ small)) = 0.375 + (+1) \times 0.5 \times 0.5 \times 0.5 \times 0.5 = 0.4375,$

$\varphi(Little\ Little\ large) = \varphi(Little\ large) +$ Sign $(Little\ Little\ large) \times (fm(Little\ Little\ large) -$
$- 0.5fm(Little\ Little\ large)) = 0.625 + (-1) \times 0.5 \times 0.5 \times 0.5 \times 0.5 = 0.5625,$

$\varphi(Very\ Little\ large) = \varphi(Little\ large) +$ Sign $(Very\ Little\ large) \times (fm(Very\ Little\ large) -$
$- 0.5fm(Very\ Little\ large)) = 0.625 + (+1) \times 0.5 \times 0.5 \times 0.5 \times 0.5 = 0.6875,$

$\varphi(Little\ Very\ large)\varphi(Very\ large) +$ Sign $(Little\ Very\ large) \times (fm(Little\ Very\ large) -$
$- 0.5fm(Little\ Very\ large)) = 0.875 + (-1) \times 0.5 \times 0.5 \times 0.5 \times 0.5 = 0.8125,$

$\varphi(Very\ Very\ large) = \varphi(Very\ large) +$ Sign $(Very\ Very\ large) \times (fm(Very\ Very\ large) -$
$- 0.5fm(Very\ Very\ large)) = 0.875 + (+1) \times 0.5 \times 0.5 \times 0.5 \times 0.5 = 0.9375.$

The results obtained from above example will be used in the following section (see subsection 4.2).

4. FUZZY CONTROLLERS OF THE STRUCTURAL SYSTEM

The fuzzy controllers are based on the closed-loop fuzzy system shown in Fig. 3. where, f is determined by above controllers, x_1 and $\dot{x}_1$ are determined by Eqs. (1). The goal of controllers is to reduce displacement in the first storey, so as to reduce displacements in the structure. It is assumed that the universes of discourse of two state variables are

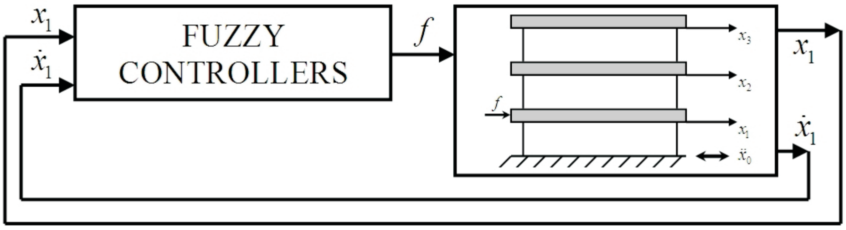

Fig. 3. Fuzzy controllers of the structural system

$-0.03 \leq x_1 \leq 0.03(\mathrm{m}), -0.3 \leq \dot{x}_1 \leq 0.3(\mathrm{m/s})$ and of the control force is $-2 \times 10^7 \leq f \leq 2 \times 10^7$ (N). In the following parts of this section, establishing steps of the controllers will be presented.

4.1. Conventional fuzzy controller (FC) of the structure

In this subsection, FC of the structure is established (establishing steps of a FC could refer in Mandal [20]) using Mamdani's inference and centroid defuzzification method with fifteen control rules. The configuration of the FC is shown in Fig. 4.

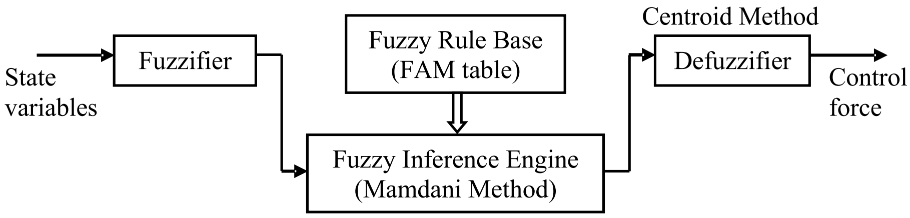

Fig. 4. The configuration of the FC

4.1.1. *Fuzzifier*

Five membership functions for x_1, three membership functions for $\dot{x}_1$ and seven membership functions for f in their intervals are established with values negative very big (NVB), negative big (NB), negative (N), zero (Z), positive (P), positive big (PB) and positive very big (PVB) as shown in Figs. 5 - 7, respectively [7].

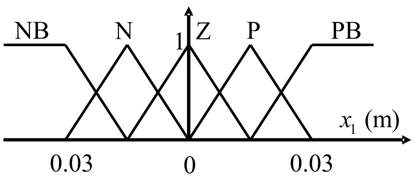

Fig. 5. Membership functions for x_1

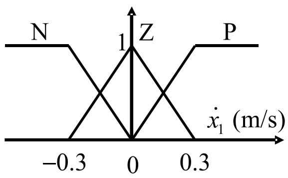

Fig. 6. Membership functions for $\dot{x}_1$

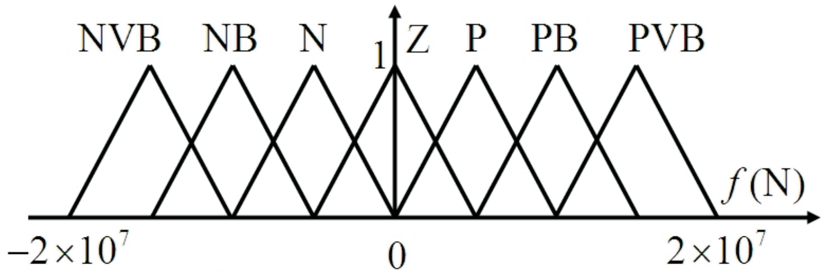

Fig. 7. Membership functions for f

4.1.2. *Fuzzy rule base*

The fuzzy associative memory table (FAM table) is established as shown in Table 1 [7].

Table 1. FAM table

x_1	$\dot{x}_1$		
	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 Table 1 have to be transformed into the new ones given in Tables 2 and 3, that are suitable to describe linguistically reference domains of [0, 1] and can be modeled by suitable HAs. The HAs of x_1 and $\dot{x}_1$ are $AX = (X, G, C, H, \leq)$, where $X = x_1$ or $\dot{x}_1$, $G = \{small, large\}$, $C = \{\boldsymbol{0}, \boldsymbol{W}, \boldsymbol{1}\}$, $H = \{H^-, H^+\} = \{Little(L),\ Very(V)\}$, and the HAs of f is $AF = (f, G, C, H, \leq)$ with the same sets G, C and H as for x_1 and $\dot{x}_1$, however, their terms describe different quantitative semantics based on different real reference domains.

Table 2. Linguistic transformation for x_1 and $\dot{x}_1$

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

Table 3. Linguistic transformation for f

NVB	NB	N	Z	P	PB	PVB
V V small	*L V small*	*V L small*	***W***	*V L Large*	*L V large*	*V V large*

The SQMs φ are determined and shown in Tables 4 and 5 (see section 3).

The configuration of the HAFC is shown in Fig. 8.

Table 4. Parameters of SQMs for x_1 and $\dot{x}_1$

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

Table 5. Parameters of SQMs for f

V V small	*L V small*	*V L small*	***W***	*V L Large*	*L V large*	*V V large*
0.0625	0.1875	0.3125	**0.5**	0.6875	0.8125	0.9375

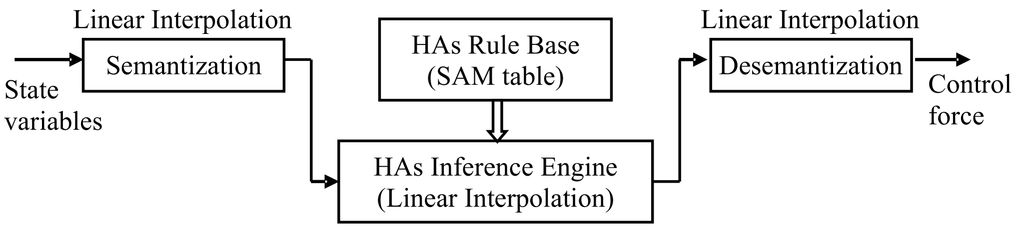

Fig. 8. The configuration of the HAFC

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* [19].

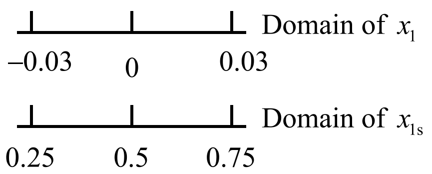

Fig. 9. Transformation: x_1 to x_{1s}

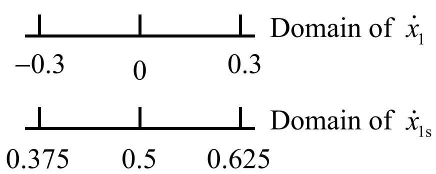

Fig. 10. Transformation: $\dot{x}_1$ to $\dot{x}_{1s}$

The semantizations for each state variable are defined by the transformations given in Figs. 9 and 10. The semantization and desemantization for the control variable are defined by the transformation given in Fig. 11 ($x_1, \dot{x}_1$ and f are replaced with x_{1s}, $\dot{x}_{1s}$ and f_s when transforming from real domain to semantic one, respectively).

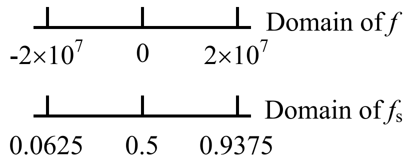

Fig. 11. Transformation: f to f_s

4.2.2. *HAs rule base*

We have the SAM (semantic associative memory) table based on FAM one (Table 1) with semantically quantifying mappings as shown in Table 6.

Table 6. SAM table

x_{1s}	$\dot{x}_{1s}$		
	L small: 0.375	***W***: 0.5	*L large: 0.625*
small: 0.25	*V V large:* 0.9375	*L V large:* 0.8125	*V L large:* 0.6875
L small: 0.375	*L V large:* 0.8125	*V L large:* 0.6875	***W***: 0.5
W: 0.5	*V L large:* 0.6875	***W***: 0.5	*V L small:* 0.3125
L large: 0.625	***W***: 0.5	*V L small:* 0.3125	*L V small:* 0.1875
large: 0.75	*V L small:* 0.3125	*L V small:* 0.1875	*V V small:* 0.0625

4.2.3. *HAs inference engine*

The Quantifying Semantic Curve describing the HAs inference method is established through the points that present the control rules occurring in Table 6 as shown in Fig. 12. Hence, f_s is determined by linear interpolation through x_{1s} and $\dot{x}_{1s}$. For example: if $x_{1s} = 0.7$ and $\dot{x}_{1s} = 0.5$ (point X1s) then $f_s = 0.2375$ (point Fs).

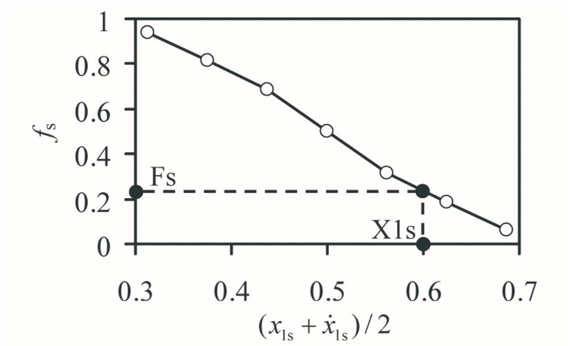

Fig. 12. Quantifying semantic curve

5. RESULTS AND DISCUSSION

The results include: time history of the storey displacements of the structure for both controlled and uncontrolled cases in order to compare control effect of FC and HAFC.

5.1. Results for the structure excited by the El Centro earthquake

In this subsection, the following data will be used: $m_1 = m_2 = m_3 = m_0 = 4 \times 10^5$(kg); $k_1 = k_2 = k_3 = k_0 = 2 \times 10^8$ (N/m).

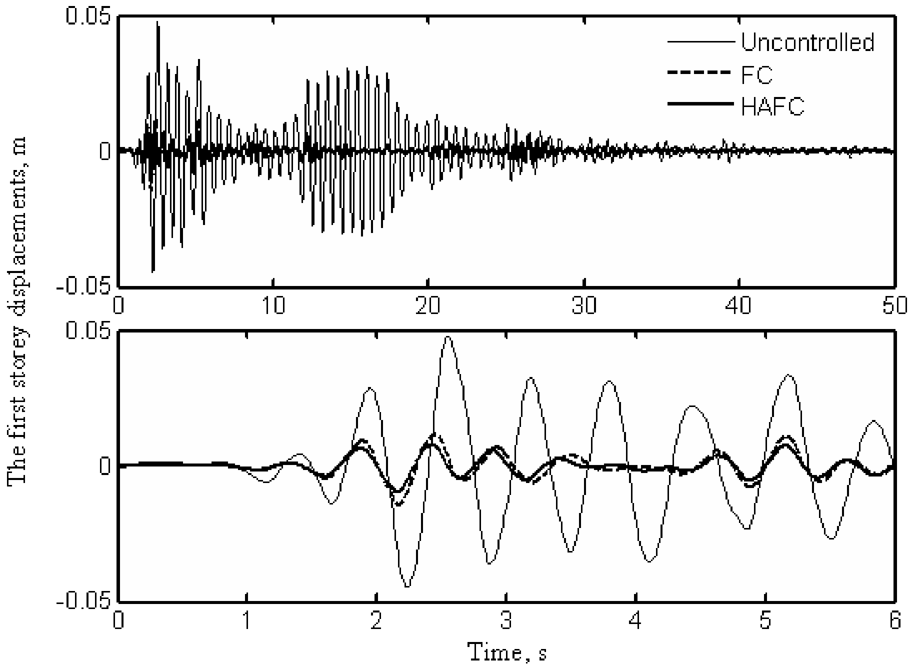

Fig. 13. Time responses of the first storey displacements - El Centro earthquake

Figs 13 and 14 show the time responses of the first and top storey displacements, respectively. The maximum storey drifts are shown in Fig. 15. Comparison of the effectiveness of the two controllers is presented in Table 7.

Table 7. Comparison of the effectiveness of the three controllers - El Centro earthquake

Building Storey	Maximum uncontrolled displacement, m	Controlled to uncontrolled displacement ratio (reduction ratio)	
		FC	HAFC
1	0.048	0.302	0.204
2	0.084	0.558	0.502
3	0.107	0.607	0.586

5.2. Results for the structure excited by the Northridge earthquake

In this subsection, the structural data will be changed as follow: $m_1 = m_2 = m_3 = m_0 +\ 10\% m_0$; $k_1 = k_2 = k_3 = k_0$ - $10\% k_0$.

Figs 16 and 17 show the time response of the top storey displacement and the maximum storey drifts, respectively. Comparison of the effectiveness of the three controllers is presented in Table 8.

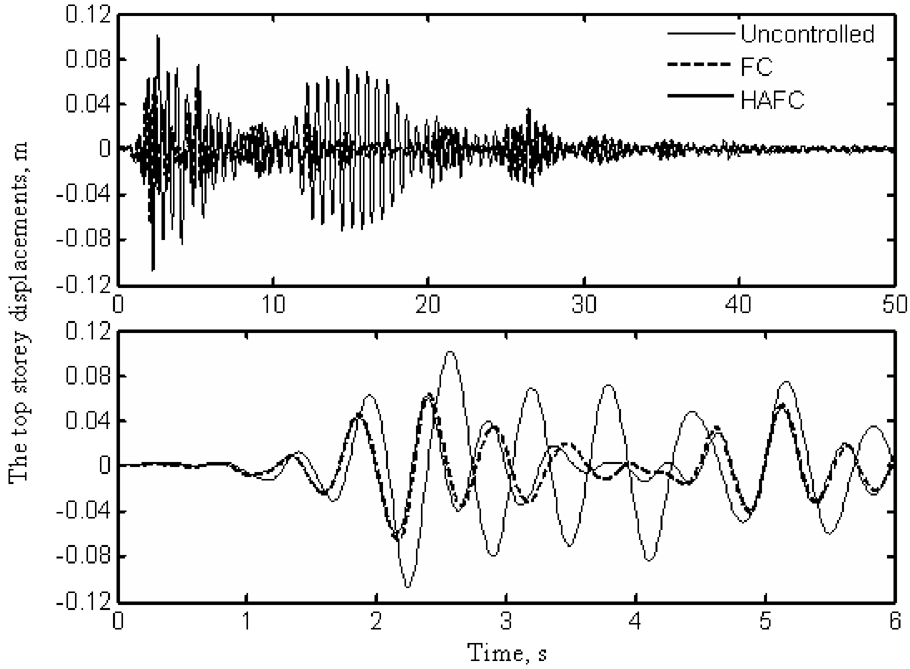

Fig. 14. Time responses of the top storey displacements - El Centro earthquake

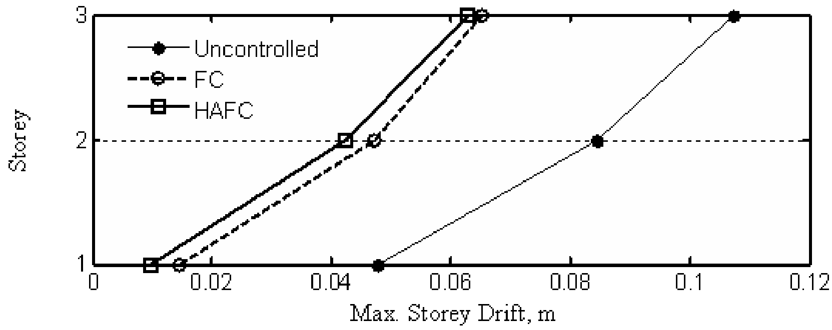

Fig. 15. The maximum storey drifts - El Centro earthquake

Table 8. Comparison of the effectiveness of the three controllers - Northridge earthquake

Building Storey	Maximum uncontrolled displacement, m	Controlled to uncontrolled displacement ratio (reduction ratio)	
		FC	HAFC
1	0.070	0.224	0.166
2	0.125	0.481	0.467
3	0.156	0.575	0.574

5.3. Results for the structure excited by the Kobe earthquake

In this subsection, another structural parameter will be used as follow: $m_1 = m_2 = m_3 = m_0 - 10\%m_0$, $k_1 = k_2 = k_3 = k_0 + 10\%k_0$.

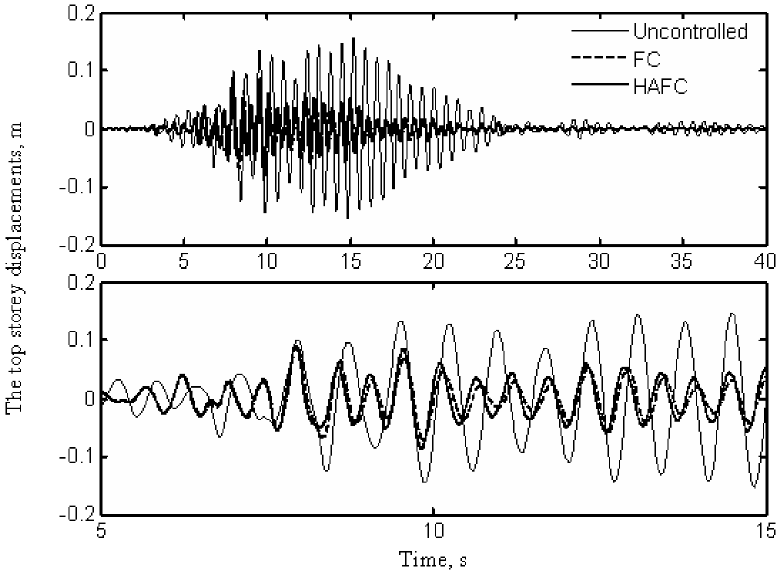

Fig. 16. Time responses of the top storey displacements - Northridge earthquake

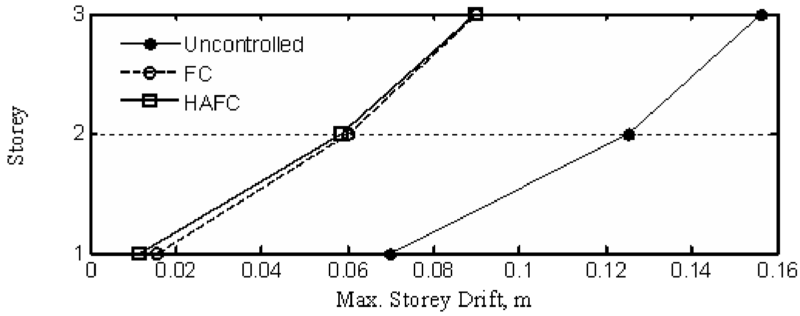

Fig. 17. The maximum storey drifts - Northridge earthquake

Figs 18 and 19 show the time response of the top storey displacement and the maximum storey drifts, respectively. Comparison of the effectiveness of the three controllers is presented in Table 9.

Table 9. Comparison of the effectiveness of the three controllers - Kobe earthquake

Building Storey	Maximum uncontrolled displacement, m	Controlled to uncontrolled displacement ratio (reduction ratio)	
		FC	HAFC
1	0.067	0.259	0.179
2	0.118	0.496	0.461
3	0.145	0.563	0.546

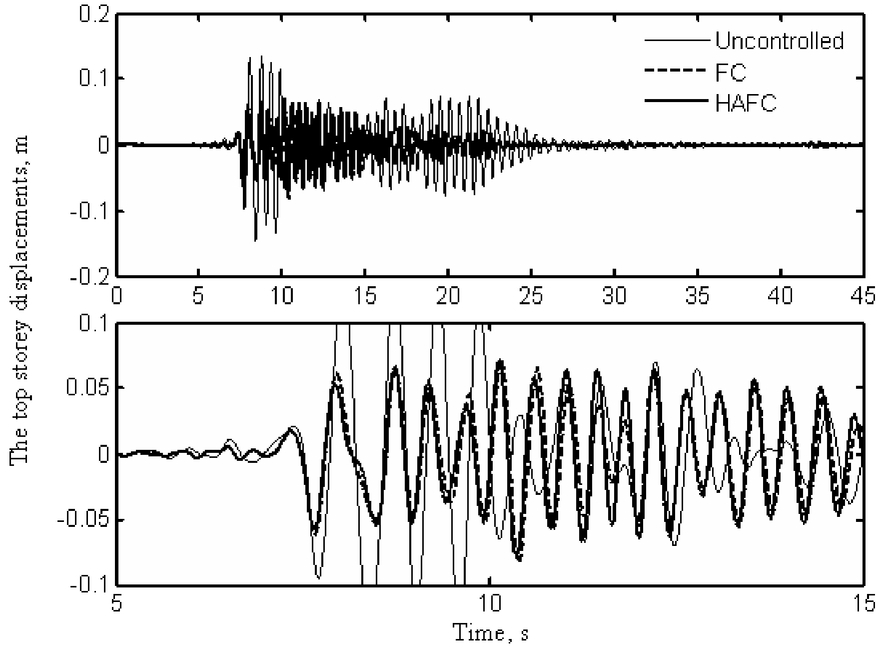

Fig. 18. Time responses of the top storey displacements - Kobe earthquake

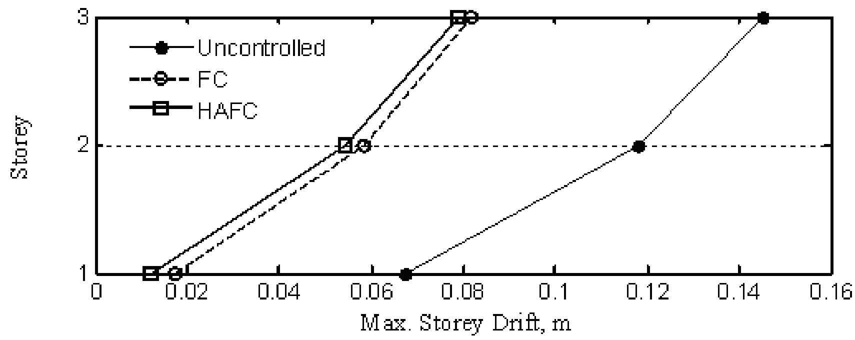

Fig. 19. The maximum storey drifts - Kobe earthquake

5.4. Discussion

As shown in above - mentioned figures and tables, vibration amplitudes of the storeys are decreased successfully with FC and HAFC for the structure with the different structural data excited by three different earthquakes. It allows partially evaluating the stability and robustness capacities the proposed controller - HAFC.

With the case of 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 61% and 59% for the FC and HAFC, respectively (Fig. 15 and Table 7). Therefore, it is seen that the HAFC is more effective than the FC in view of reducing the displacement response of the structure.

The effectiveness of two controllers in reducing the response of the structure due to other two earthquakes (Northridge and Kobe) is also shown for comparison in Figs. 17 and 19 and Tables 8 - 9. Almost the same behavior as for the El Centro earthquake can be observed for these earthquakes too.

From Tables 2 - 5, it can be conceded that the semantic order of HAFC is always guaranteed. The semantization method (Figs. 9 - 11), the desemantization one (Fig. 11) and the inference one (Fig. 12) of HAFC are simpler than the fuzzification method (Figs. 5 - 7), the centroid defuzzification one and the inference one (Mamdani method) of FC, respectively.

In order to describe three, five, seven,. . . , n linguistic labels by HAs, only two independent parameters (θ and α, 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.

6. CONCLUSIONS

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 allows linearly establishing the Quantifying Semantic Curve through the points corresponding to the control rules. It is obtained that HAFC is simpler, effective and more understandable in comparison with FC. 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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