Fuzzy Control Strategy for Semiactive or Active Structural Control System

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ABSTRACT :

The main advantage of the fuzzy controller for structural control is its inherent robustness and ability to handle any nonlinear behavior of structures. A new strategy is presented to design the control force of the structural control system. The feasibility and validity of the proposed strategy are verified by the numerical simulations.

KEYWORDS: civil engineering, vibration control, control algorithm, fuzzy control, seismic excitation

1. INTRODUCTION

So far, structural control theory has made considerable progress. There are many algorithms that can be used for structural control(Housner,1997;Soong,1990;Gu,1997). However, due to the complexity of the structural modeling, the multiplicity of material characteristics, and the uncertainties of load information, designing a proper and simple algorithm for structural control has not yet been possible. In most of the existing algorithms, a mathematical model is established for the considered system. Errors in modeling, measurement and computation are common, and can be serious in some cases. On the contrary, fuzzy control is well-suited for this challenge. Compared to a classical controller, a fuzzy controller does not need an exact model, and is capable of achieving an effective control including rapid response, slight overshooting, high resistance against disturbances, and so on. On the other hand, since fuzzy control is an experience-based method, the rule table for the corresponding system must be derived based on experience and knowledge, and is improved through trial and error. At present, it is difficult to develop a control rule table for a structural control system due to the lack of a systematic design method.
In this context, the authors presented a new strategy for design of fuzzy control rules. In this paper, the proposed strategy is described first, and then its implementation is also discussed. Based on this strategy, the control rule table for a Fuzzy Logic Controller (FLC) can be established. A numerical example is given to illustrate the validity of the proposed strategy using an active tendon system and compared to the linear quadratic regulator (LQR) strategy.

2. FUZZY RULES

Assume a MDOF system with active or semi-active control devices under external excitation. The dynamic equation can be expressed as:

$$\mathbf{M}\ddot{\mathbf{x}}(t)+\mathbf{C}\dot{\mathbf{x}}(t)+\mathbf{K}\mathbf{x}(t)=\mathbf{D}\mathbf{u}(t)+\mathbf{E}\mathbf{f}_e(t) \tag{2.1}$$

where $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$ are the mass, the damping and the stiffness matrices of the system including the structure and installed devices, respectively; $\mathbf{x}(t)$ is the displacement vector; $\mathbf{u}(t)$ is the control force vector; $\mathbf{f}_e(t)$ is the excitation vector; $\mathbf{D}$ and $\mathbf{E}$ are location matrices which define locations of the control force and the excitation vectors, respectively.
According to the optimal control theory, the feedback control vector can be designed to be a linear function of

the measured displacement vector $\mathbf{x}$ and velocity vector $\dot{\mathbf{x}}$ as

$$\mathbf{u}(t) = \mathbf{G}_{\mathbf{x}}\mathbf{x} + \mathbf{G}_{\dot{\mathbf{x}}}\dot{\mathbf{x}} \tag{2.2}$$

in which $\mathbf{G}_{\mathbf{x}}$ and $\mathbf{G}_{\dot{\mathbf{x}}}$ are the feedback gain matrices of the displacement and the velocity, respectively.From Eq. (2.2), it can be seen that the instantaneous control force of a system depends on its instantaneous state.

Note that there are two basic types of control force: direct, and indirect(Yang,2002a,2002b,and 2003). Direct refers to the external force exerted on a structure directly through the active control devices, while indirect refers to the force exerted on the structure induced by modifying its variable dynamic parameters through semiactive control devices. Generally, in semiactive control systems, the indirect control force can be converted into some adjustable dynamic parameters. In this paper, the control force has this generalized meaning unless stated otherwise. Two aspects of the problem need to be considered to determine the instantaneous control force: the direction of the control force and the control force level (or magnitude).

In analyzing a shear building model with multiple-degree-of-freedoms (MDOFs) as shown in Fig. 1, it is assumed that the control force directly acts upon the mass *i*. Let x_i and $\dot{x}_i$ be the relative displacement and the relative velocity of the controlled mass, with respect to the ground, respectively; u is the generalized control force. According to the motion characteristics, a typical vibration cycle may be divided into four phases. The fuzzy control rules are described in IF-THEN forms. Assume x_i and $\dot{x}_i$ are defined as input variables, whereas u is defined as the output or control variable. Values of linguistic variables are defined as the following fuzzy sets: $x_i, \dot{x}_i, u$ ={ NB: negative big, NM:negative medium, NS: negative small, ZR: zero, PS: positive small, PM:positive medium, PB: positive big}. These fuzzy sets can be used to describe the motion states of the controlled mass.

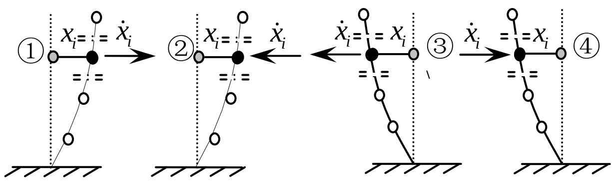

Figure 1 Division of a vibration cycle of the controlled mass

From a pair of the fuzzy sets corresponding to the variables x_i and $\dot{x}_i$, the detailed motion phase of the controlled mass can be identified, and consequently, the corresponding control phase will be determined. The fuzzy control rule table is shown in Table 2.1. From the positive or negative characteristics of the fuzzy sets corresponding to the input variables and the output variable, both the motion phases of the controlled mass and the control force directions can be distinguished; the variety regularity of the control force level can also be observed according to the meaning of the semantic values of the fuzzy sets from Table 2.1. Especially, the control method, i.e., the suppressing action or intensifying action, can be determined according to the relationship between the positive and negative characteristics of the fuzzy sets of the control force and the relative velocity of the controlled mass. Four sets of key rules, which are provided in the leading diagonal line, the minor diagonal, the vertical bisection line and the horizon bisection line, correspond to four representative control cases. Although the whole rule base of the FLC is difficult to be constructed at one time, these key rules are easy to be determined. Then, the other rules of the FLC can be determined through interpolation(Yang, 2005,2006).

The cases corresponding to the leading diagonal line represent the special cases in the phases ① and ③ of the controlled mass. Under these cases, the fuzzy sets of two input variables are identical, but an inverse number relationship exists between their fuzzy sets and the fuzzy sets of the control variable. The control force acts in the reverse direction of either of the input variables, and in a mathematical sense, the control force level shows a monotonic increase when either of the two input variables change. From the viewpoint of fuzzy logic concepts, the positive or negative characteristics are not considered. For example, when the fuzzy sets of x_i and $\dot{x}_i$ change from NS to NB, the fuzzy sets of the control force are also shifted from PS to PB. It is obvious that the positive or negative characteristics of the fuzzy sets of the input variables are different from the control variable, and the corresponding control force behaves as a suppressing action. Meanwhile, the control force level transfers from low to high.

The cases corresponding to the minor diagonal line represent the special cases in the phases ② and ④. Under these cases, the fuzzy sets of two input variables are in an inverse number relationship from the viewpoint of the semantic values of the fuzzy sets. Consequently, the influence of the relative displacement on the control force is offset by the relative velocity, and vice visa. Hence, the returning velocity can be regarded as optimal and accordingly the control forces belong to the fuzzy set ZR. For instance, when the fuzzy set of x_i is PB and $\dot{x}_i$ is NB, i.e., their semantic values are the positive big and the negative big, respectively, one will counteract the other. Hence, the fuzzy sets of the control forces may be chosen ZR. Once there is a deviation from the minor diagonal line, the returning velocity will be no longer be optimal and will need to be tuned. If the returning velocity is insufficient on one side of the minor diagonal line and is excessive on the other side, both the suppressing and the intensifying actions will happen simultaneously and the control force will take on a polarizing trend along the minor diagonal line.

The cases corresponding to the vertical bisection line indicate that the controlled mass is in the vicinity of its equilibrium position. The relative velocity of the control mass is mapped to different fuzzy sets with a constant fuzzy set "ZR" corresponding to the relative displacement, and as a result, the control force levels only vary with the relative velocity. Actually, the rules located at the vertical bisection line are representative across equilibrium control, and are aimed at restraining the crossing velocity that corresponds to the equilibrium position of the controlled mass and isolate one vibration cycle from the next. For instance, when the fuzzy sets of $\dot{x}_i$ corresponding to the vertical bisection line change from NS to NB, the control force also shifts from PS to PB. The corresponding control force and the motion of the controlled mass are in the opposite direction. The control force behaves as the suppressing action, and its levels transfer from low to high.

The cases corresponding to the horizon bisection line indicate that the controlled mass is in the vicinity of its extremal position. The relative displacement of the control mass is mapped to different fuzzy sets with a constant fuzzy set "ZR" corresponding to the relative velocity, and as a result, the control force levels only vary with the relative displacement. For instance, when the fuzzy sets of x_i corresponding to the horizon bisection line change from NS to NB, the control force also shifts from PS to PB. The corresponding control force and the displacement of the controlled mass are in the opposite direction, and its levels transfer from low to high.

Table 2.1 Key rules of fuzzy control

u		x_i						
		NB	NM	NS	ZR	PS	PM	PB
$\dot{x}_i$	NB	PB			PB			ZR
	NM		PM		PM		ZR	
	NS			PS	PS	ZR		
	ZR	PB	PM	PS	ZR	NS	NM	NB
	PS			ZR	NS	NS		
	PM		ZR		NM		NM	
	PB	ZR			NB			NB

3. NUMERICAL EXAMPLE

The control system analyzed in this example is a three-story shear structure with an active tendon installed in the first story. The control scheme of the entire control system is outlined in Fig. 2. In order to evaluate the proposed strategy, three cases are compared, i.e., the uncontrolled case (NC), a conventional LQR, and a FLC.

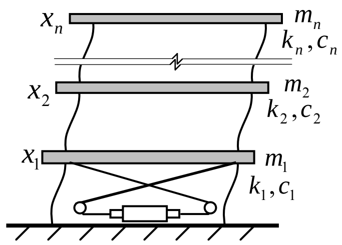

Figure 2 A 3DOF system with ATS

3.1. Active tendon system

The control principle of the active tendon system is as follows: when the story drift of the controlled structure occurs under external excitations, the controller changes the stretch degree of the tendon by setting the displacement of the actuator to an approximate value according to a given algorithm; consequently the corresponding horizontal control force can be generated and exerted on the structure. In this numerical example, the fuzzy control rule table is established according to the proposed strategy, and the control force of the system is designed by using a FLC.

3.2. Fuzzy control

For the control system shown in Fig. 2, the relative displacement x_1 and the relative velocity $\dot{x}_1$ are defined as the input variables, whereas the tensile (control) force is defined as the control variable. Although the actuator changes the tendon displacement directly, the control force can be calculated through a simple conversion. Thus, the displacement of the actuator can be mapped to the control force one by one. Therefore, the control force is chosen as the output variable.

For convenience of calculation, the triangular membership function shown in Fig. 3 is chosen (Table 3.1). Three sets of parameters [a1, a2, α], [b1, b2, β] and [c1, c2, γ] are used to tune the corresponding membership function(Goto 1994). The values $|x_1|_{\max}$ and $|\dot{x}_1|_{\max}$ in the universe of discourse of the input membership functions are prescribed, referring to the uncontrolled case or accepted levels, and the value $|F_c|_{\max}$ of the output universe of discourse is determined according to the maximum output force of the actuator.

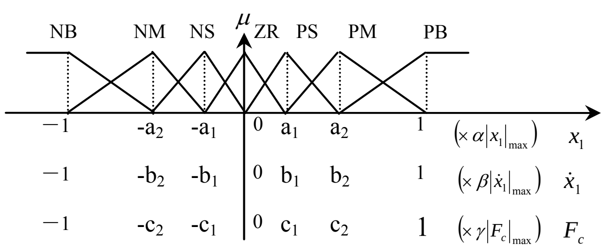

Figure 3 Membership functions for the input/output variables

Referring to Table 2.1, the control rule table listed in Table 3.2 is established via gradual interpolation. This table shows that all of the adjacent rules vary smoothly, and a minor variety is good for the smooth control of a system.

Table 3.1 Tuning parameters of membership functions

Parameters	Values
a_1	0.28
a_2	0.57
α	0.9
b_1	0.22
b_2	0.56
β	0.90
c_1	0.33
c_2	0.67
γ	1

Table 3.2 Control rule table used

F_c		x_i						
		NB	NM	NS	ZR	PS	PM	PB
$\dot{x}_i$	NB	PB	PM	PS	PB	PM	PS	ZR
	NM	PM	PM	PS	PM	PS	ZR	NS
	NS	PS	PS	PS	PS	ZR	NS	NM
	ZR	PB	PM	PS	ZR	NS	NM	NB
	PS	PM	PS	ZR	NS	NS	NS	NS
	PM	PS	ZR	NS	NM	NS	NM	NM
	PB	ZR	NS	NM	NB	NS	NM	NB

3.3. Numerical calculation and results

The parameters of the example structure are listed in Table 3.3, and its dynamic characteristics have been studied thoroughly(Chung,1989) . The 1/4-scaled El Centro earthquake record (1940-05-18, S00E) is used as the input excitations. Linear behavior of the building is assumed in the simulation of the dynamic responses. The dynamic response of the structure is limited in the elastic range.

Table 3.3 Parameters of the example building

Parameters	Values
Mass matrix **M** (kg)	$\begin{bmatrix} 981 & 0 & 0 \\ 0 & 981 & 0 \\ 0 & 0 & 981 \end{bmatrix}$
Stiffness matrix **K** (N/m)	$\begin{bmatrix} 2.7417 & -1.6416 & 0.3691 \\ -1.6416 & 3.0222 & -1.6248 \\ 0.3691 & -1.6248 & 1.3336 \end{bmatrix} \times 10^6$
Damping matrix **C** (N.s/m)	$\begin{bmatrix} 382.8 & -57.3 & 61.7 \\ -57.3 & 456.9 & -2.6 \\ 61.7 & -2.6 & 437.5 \end{bmatrix}$

In the design of the LQR controller, the weighting matrices ***Q*** and ***R*** are the time invariant weights of the state and control force, respectively. They imply the relative importance of the state and the control force, and need to be predetermined based on the expected magnitude of the system response and of the control force. Therefore, the choice of matrices $\boldsymbol{Q}$ and $\boldsymbol{R}$ is important for computing the optimal controller gains. The control performance of each strategy is evaluated under prescribed criteria. The weighting matrices have been chosen according to the evaluation criteria specified for all simulations to ensure the equal peak of the instantaneous control force. In this study, the weighting matrix $\boldsymbol{Q}$ is chosen as the identity matrix, and $\boldsymbol{R}$ is condensed into a scalar R. By considering the acceptable maximum force levels of the actuator, R is set as follows:

$$R = 1.03 \times 10^{-8} \tag{3.1}$$

Table 3.4 lists the maximum responses of the top floor, the maximum control forces and the reduction ratios of the structural responses by using the LQR strategy or the FLC to the uncontrolled case shown in the brackets under the scaled El Centro. The results show that the FLC is more effective in reducing both the peak and RMS of the relative displacement and the absolute acceleration than LQR under the scaled El Centro earthquake.

Table 3.4 Top-floor responses of the example building and control force (1 / 4 El_Centro)

Control Cases	Relative displacement (m)		Absolute Acceleration (m/s^2)		Control Force（kN）	
	Peak	RMS	Peak	RMS	Peak	RMS
NC	0.0132	0.0025	2.3700	0.4868	-	-
LQR	0.0077 (41.7%)	0.0014 (44.0%)	1.8467 (22.1%)	0.2987 (38.6%)	1.19	0.19
FLC	0.0069 (47.7%)	0.0012 (52.0%)	1.6779 (29.2%)	0.2896 (40.5%)	1.19	0.27

Note: numbers in the brackets denote reduction ratios of the responses of a controlled system to those of the uncontrolled system.

Figures 4 plots the time histories of the relative displacement and the absolute acceleration of the top floor and the control force under the scaled El Centro. It is observed that there are overall reductions of responses during the entire periods of vibrations using either strategy. Compared to LQR, however, the FLC results in smaller responses from the structure.

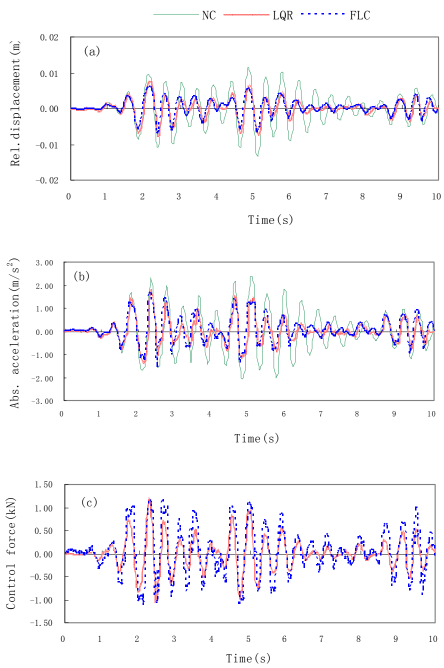

Figure 4 The time histories of the responses of the top floor and the control force under the scaled El Centro

earthquake input

4. CONCLUSION

In this paper, a new strategy for generation of the fuzzy control rules is presented, and applied to a three-story shear building with an active tendon system installed in the ground story. Through computer simulation, the control effectiveness of the proposed strategy is studied and compared with the LQR strategy. The numerical results show that the proposed strategy is more effective in reducing both the peak and the RMS of the responses than LQR under the scaled El Centro earthquake.

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