FLC BASED SEMI-ACTIVE CONTROL OF BUILDINGS USING MAGNETO-RHEOLOGICAL DAMPERS

Sk. Faruque Ali[1] and Ananth Ramaswamy[2]

[1]Research Scholar, Department of Civil Engineering, Indian Institute of Science, Bangalore, Karnataka-560 012, India

e-mail: skfali@civil.iisc.ernet.in

[2]Associate Professor, Department of Civil Engineering, Indian Institute of Science, Bangalore, Karnataka-560 012, India

e-mail: ananth@civil.iisc.ernet.in

Abstract: Use of Magneto-rheological (MR) damper as a semi-active device to control structural vibration makes the overall system nonlinear due to the inherent nonlinear behaviour of these devices. Therefore, the challenge remains in the selection of a suitable algorithm to operate these MR dampers. This paper develops a fuzzy logic rule base to operate the voltage of the magneto-rheological dampers using the acceleration and velocity feedback from the structure. Efficiency of FLC under structural nonlinearity, uncertainty of input excitation, sensor and actuator dynamics provides added robustness to the control mechanism. Unlike the clipped optimal control strategy, the present study makes use of the full range of voltage to operate the MR damper using FLC. Consequently, the present approach provides better vibration control for structures under earthquake excitations. The study evaluates the control of a three storey building model using a FLC driven MR Damper placed at the ground floor of the building and subjected to both far field and near field earthquake excitations. The results obtained are compared with the corresponding results of an LQR driven control of the same building.

Keywords: FLC; Clipped optimal; Magnetorheological Damper; Control

1. Introduction

Protection of a structure, its material content and the human occupants, against damage induced by large environmental loads, e.g., earthquake, is, without doubt, a worldwide priority. The extent of protection may range from safe and reliable operation, comfort to human occupants, to structural survival. Inelastic deformation based design methods have become a thing of the past and the focus is now on structural control. Classical control algorithms need an exact mathematical model for an actual structure to minimize its vibration. Today, structures that are built are more slender and flexible and contain complex features. Therefore, obtaining a reduced order model becomes erroneous and control mechanism based on this approach never becomes optimal. Fuzzy logic based control neither needs an accurate mathematical model nor does it depend on a reduced order model [1]. As a consequence, FLC provides reliable control mechanism with improved performance on measured responses.

Introduction of semi-active control mechanism has given a new dimension to the structural control mechanism. It provides equivalent control performance, if not better, in comparison to active control. Therefore, use semi-active control as a means of hazard reduction has become increasingly popular. The MR damper, which employs MR fluids to provide its controllable characteristics, is one of the newest additions to the family of dampers. Besides its low-power requirements, the MR damper is reliable, fail-safe, and is relatively inexpensive [2]. The MR damper however is an intrinsically nonlinear device, which makes the design of suitable control algorithms an interesting and challenging task. The problem with the use of MR damper is that one cannot directly change the force delivered by the MR damper but only modify the operating voltage. Since, the relation between damper voltage and the damper force is nonlinear there exist no direct rule to operate the voltage to be supplied. One widely used method, proposed by Dyke [3] is clipped optimal control, where damper voltage is changed in between zero and the highest value based on a difference of forces proposed by LQG algorithm and the MR damper force. Therefore, proper utilization of the available range of force by the damper is not realized. The present study proposes a FLC based operation of voltage across the damper, where one can have any voltage value within the range circumventing this limitation.

2. MR Damper

MR damper is composed of a hydraulic cylinder filled with MR fluid, a suspension of micron-sized magnetically polarized particles in water, glycol, mineral or synthetic oil [2]. The damping capabilities of this device can be controlled by introduction and/or variation of magnetic field that can change the fluid from free flowing, linear, Newtonian fluid (at zero voltage) to nonlinear, semi-solid, visco-plastic and Bingham fluid in milliseconds, on application of a magnetic field of varying intensity. A wide range of theoretical and experimental studies has been performed to assess the efficacy of MR dampers. The first application of MR dampers to protect civil engineering structures was conducted by Spencer and coworkers [3, 5].

To accurately predict the behavior of the controlled structure, adequate modeling of the control device is essential. The phenomenological model of MR dampers is based on the Bouc-Wen hysteretic model [2] shown in Fig. 1. The equations governing the force produced by this model is given as:

$$\mathrm{f} = c_0\, \dot{x} + \alpha\, z \tag{1}$$

$$z = -\gamma \left|\dot{x}\right| z \left|z\right|^{n-1} - \beta \dot{x} \left|z\right|^{n} + A\, \dot{x} \tag{2}$$

where, 'x' is the displacement of the device; 'z' is the evolutionary variable, and 'γ', 'β', 'n', 'A' are parameters controlling the linearity in the unloading and the smoothness of the transition from the pre-yield to the post-yield region. The functional dependence of the device parameters on the command voltage 'u_c' is expressed as:

$$\alpha(u_c) = \alpha_a + \alpha_b\, u_c \; ; \; c_0(u_c) = c_{0a} + c_{0b}\, u_c \tag{3}$$

In addition, the resistance and inductance present in the circuit introduce dynamics into this system. The dynamics is accounted for by applying a first order filter on the control input given by:

$$\dot{u}_c = -\eta\,(u_c - v) \tag{4}$$

where, 'η' is the time constant associated with the first order filter and 'v' is the command voltage applied to the current driver. The following parameters of the MR damper were selected so that the device has a capacity of 1000 kN, [4]: α_a=1.0872e5 N/cm, α_b = 4.9616e5 N/(cm V), c_{oa} = 4.40 N sec/cm, c_{ob}= 44 N sec/(cm V), n = 1, A = 1.2, γ= 3; β = 3, η = 50 sec^{-1}.

3. Control Algorithms

Several control algorithms have been proposed for use with the MR dampers. Control strategies based on Lyapunov functions [5], continuous sliding mode (CSM) control [6], linear quadratic Gaussian (LQG/LTR) control [5], Clipped optimal algorithm [3,5] and intelligent Neural control have also been successfully employed [7]. The advantage of the intelligent algorithm is in the ease with which they handle nonlinearity in the system. The advantages of fuzzy control include simplicity and intrinsic robustness since it is not affected by the plant model selection [1,8]. Fuzzy control is based on *if-then* rules that correlate the controller inputs to the desired outputs and therefore can easily approximate nonlinear functions.

3.1 Clipped Optimal Algorithm

The clipped optimal control algorithm is used to calculate required control input signal to the MR damper [3]. In the clipped optimal controller, the desired control forces, F_c are calculated based on the measured structural response vector and the measured control force vector:

$$\mathrm{F}_c = L^{-1}\left\{-K_c(s)L\left\{\begin{matrix} y \\ \mathrm{F_m}\end{matrix}\right\}\right\} \tag{5}$$

where $L\{.\}$ is the Laplace transform operator, and $K_c(s)$ is the selected primary controller. Because the force generated in the MR damper is dependent on the local responses of the structural system, only the control voltage can be directly controlled to increase or decrease the force produced by the device. To induce the MR damper to generate approximately the corresponding desired optimal control force, the command signal is selected as follows. When the i^{th} MR damper is providing the desired optimal force (*i.e.*, f_i=f_{ci}), the voltage applied to the damper should remain at the present level. If the magnitude of the force produced by the damper is smaller than that of the desired optimal force and the two forces have the same sign, the voltage applied to the current driver is increased to the maximum level so as to increase the force produced by the damper to match the desired control force. Otherwise, the command voltage is set to zero. This algorithm for selecting the command signal for the i^{th} MR damper is graphically represented in Fig. 2 and can be stated as [3, 5]:

$$v_i = v_{\max}\mathrm{H}\left(\{f_{ci} - f_i\} f_i\right) \tag{6}$$

where, v_{max} is the voltage to the current driver associated with saturation of the MR effect in the physical device, and H(.) is the Heaviside step function.

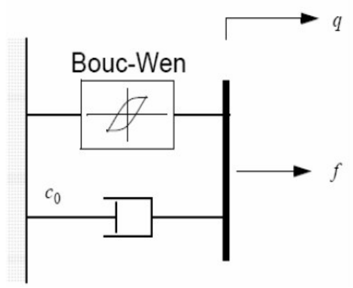

Fig. 1. Bouc-Wen Model For MR Damper

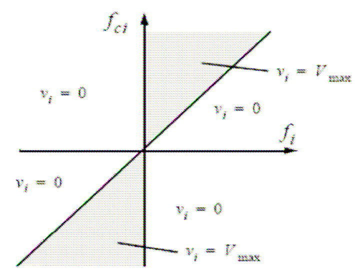

Fig. 2. Clipped Optimal Strategy

3.2 FLC Based MR Damper Control

The problem with the use of MR damper is that one cannot directly change the force delivered by the MR damper but can only modify the operating voltage. Since, the relation between damper voltage and the force provided by the damper is nonlinear (Equation 1-4) there exist no direct rule to operate the voltage to be supplied. Fuzzy based reasoning can approximate nonlinear relations with the help of linguistic variables. The present study develops a fuzzy rule base to determine the voltage required for the MR damper to provide necessary control force. Acceleration and velocity feedback are taken as input to the fuzzy system and required commanded voltage is obtained as an output. The input-output membership functions are shown in Fig. 3. The input subsets are: NL=negative large, NE=negative, ZE=zero, PO=positive, PL=positive large. The output subsets are: ZE=zero, PS=positive small, PO=positive, PL=positive large. The domain of discourse for output voltage is taken as [0 1]. The fuzzy inference rules are given in Table 1. The control mechanism flow is shown in Fig. 4.

The main advantage of using FLC to drive MR damper is that unlike in clipped optimal strategy it can switch to any voltage required within the range of damper. The present study takes acceleration and pseudo velocity as an input to the FLC, thereby error due to estimation of the states of the system is not present.

4. Numerical Results and Discussions

A three-storey shear-building model has been taken for the analysis and testing of the proposed FLC based MR damper control. The equation of motion can be written as:

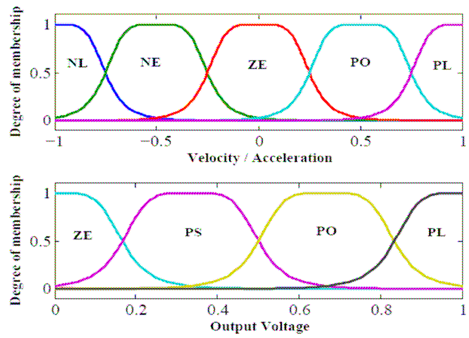

Fig. 3. Input / Output Fuzzy Membership Functions

Table 1 Inference Rules for FLC used in the Study

		Acceleration				
		NL	**NE**	**ZE**	**PO**	**PL**
Velocity	**NL**	PL	PO	PS	PS	ZE
	NE	NE	PS	ZE	ZE	ZE
	ZE	PS	ZE	ZE	ZE	PS
	PO	ZE	ZE	ZE	PS	PO
	PL	ZE	PS	PS	PO	PL

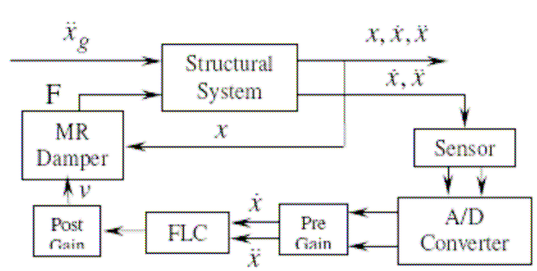

Fig. 4. Flow Diagram for FLCMRD

$$\mathrm{M}\,\ddot{x}+\mathrm{C}\,\dot{x}+\mathrm{K}\,x=\Lambda\,u-\mathrm{M}\,\Gamma\,\ddot{x}_g \qquad (7)$$

where, x_i,[i=$1,2,3$] is the horizontal displacement of the i^{th} floor relative to the base, $\ddot{x}_g$ is the horizontal ground acceleration. The control force, u, is acting only at the ground floor. Γ is vector of ones and Λ is a coefficient vector determined by the position of the control actuator. *M, C, K,* [9] are given as:

$$\mathrm{M}=\begin{bmatrix}3&0&0\\0&3&0\\0&0&3\end{bmatrix}^{x\,10^3};\ \mathrm{C}=\begin{bmatrix}19.49&-14.57&0\\-14.57&34.26&-19.69\\0&-19.69&19.69\end{bmatrix}^{x\,10^3};\mathrm{K}=\begin{bmatrix}20&-8&0\\-8&20&-12\\0&-12&12\end{bmatrix}^{x\,10^5} \qquad (8)$$

$$\Lambda=[1\quad 0\quad 0]^{\mathrm{T}};\quad \Gamma=[1\quad 1\quad 1]^{\mathrm{T}}$$

Analysis has been performed with five different control algorithms: 1) LQR. 2) LQR clipped MR damper. 3) FLC driven MR damper. 4) Passive Off condition and 5) Passive On condition, for Elcentro (1940), NorthPalm Spring (1986), Northridge (1994), KobeNIS (1995), Chichi (1999), and Terkey Bolu (1999) seismic records. The details of the results for Northridge and Chichi are shown in Table 2-3, where the values are normalized with respect to the corresponding maximum values in the uncontrolled case. It is evident from the tables that fuzzy based MR damper provides better control than LQR and LQR clipped MR damper control. Except for the passive-on case (high voltage demand), the present method provides better control to the displacement at ground floor than other methods. The column under heading '*Volt*' shows that full damper voltage is not required. Switching between full voltage and zero voltage that can result in problems due to saturation of the damper has been avoided in the present study.

Table 2 Comparisons of Results from different control strategies (Northridge-Rinaldi Earthquake)

	RINALDI													
	Displacement			Inter Storey Drift			Velocity			Acceleration			Force	Volt
	1st Floor	2nd Floor	3rd Floor	1st Floor	2nd Floor	3rd Floor	1st Floor	2nd Floor	3rd Floor	1st Floor	2nd Floor	3rd Floor	x e5	–
LQR	0.8726	0.8611	0.8633	0.8726	0.8101	0.6906	0.6024	0.7806	0.8588	0.6917	0.7182	0.6380	0.1404	0.0000
Clipped Optimal	0.4553	0.5515	0.5709	0.4553	0.6250	0.5692	0.4620	0.6052	0.7581	1.3001	0.5929	0.5417	0.3843	10.0000
Fuzzy MRD	0.1288	0.4330	0.4829	0.1288	0.7468	0.6819	0.1304	0.6416	0.8006	1.1279	0.6318	0.6115	0.5297	1.0101
Passive Off	0.4471	0.5437	0.5633	0.4471	0.6174	0.5634	0.4578	0.5978	0.7530	1.0304	0.6183	0.5391	0.2186	0.0000
Passive On	0.0014	0.4250	0.4930	0.0014	0.7836	0.7331	0.0025	0.6362	0.7969	0.5510	0.6394	0.6366	0.5756	10.0000

Table 3 Comparisons of Results from different control strategies (Chichi Earthquake)

	CHICHI													
	Displacement			Inter Storey Drift			Velocity			Acceleration			Force	Volt
	1st Floor	2nd Floor	3rd Floor	1st Floor	2nd Floor	3rd Floor	1st Floor	2nd Floor	3rd Floor	1st Floor	2nd Floor	3rd Floor	x e5	–
LQR	0.6070	0.6099	0.6104	0.6070	0.6061	0.6105	0.6318	0.6076	0.6048	0.6308	0.6200	0.6218	0.1235	0.0000
Clipped Optimal	0.2461	0.3296	0.3343	0.2461	0.4015	0.3884	0.4011	0.3379	0.3838	4.3145	0.4503	0.4147	0.2271	10.0000
Fuzzy MRD	0.0567	0.2791	0.3152	0.0567	0.4904	0.5096	0.0891	0.3534	0.4077	1.3452	0.4610	0.4771	0.4434	0.4242
Passive Off	0.2454	0.3289	0.3335	0.2454	0.4008	0.3872	0.3999	0.3365	0.3827	1.2188	0.4488	0.4115	0.2243	0.0000
Passive On	0.0009	0.2837	0.3263	0.0009	0.5192	0.5481	0.0014	0.3509	0.4059	0.6653	0.4750	0.5073	0.4658	10.0000

Third floor acceleration and displacement response of the building under El-Centro earthquake is shown in Fig.5. Figure 6. shows the damper force and voltage required for the control of the building response.

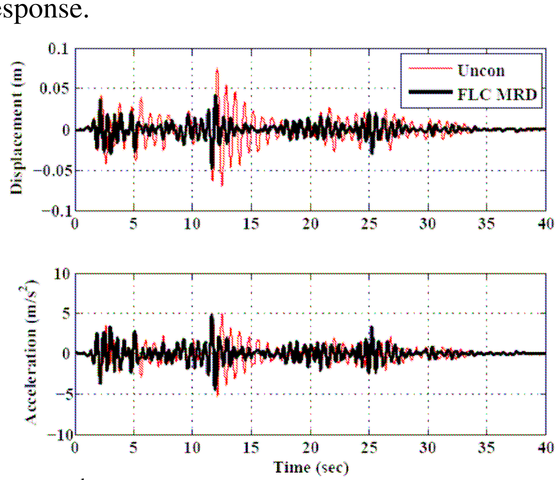

Fig.5. 3rd Floor Displacement & Acceleration response.

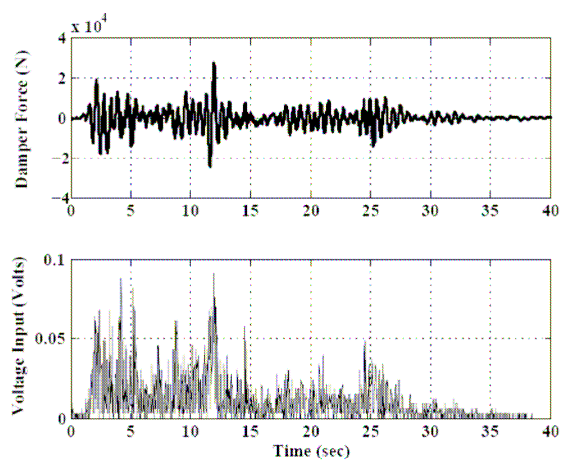

Fig.6. Damper Force & Voltage Plot

4.1 Stability Test

Tests simulations were run with worst initial condition (ground floor displacement = 10m) for the building controlled by FLCMR damper. Figure 7 show that the building displacement as well as velocity is bought down to rest within five seconds of the excitation. Figure 8 shows the corresponding force exerted by the damper and the voltage required.

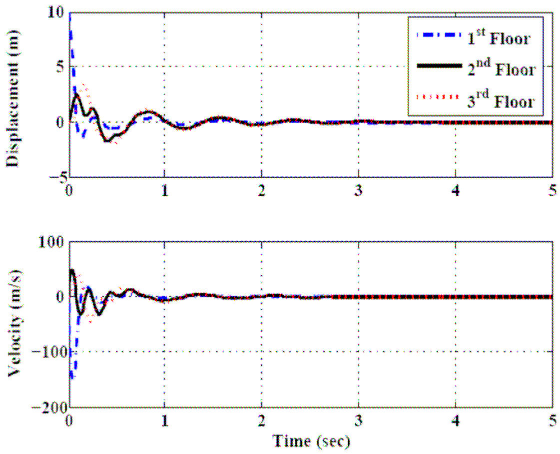

Fig. 7. Displ. & Accel. response (Stability Test)

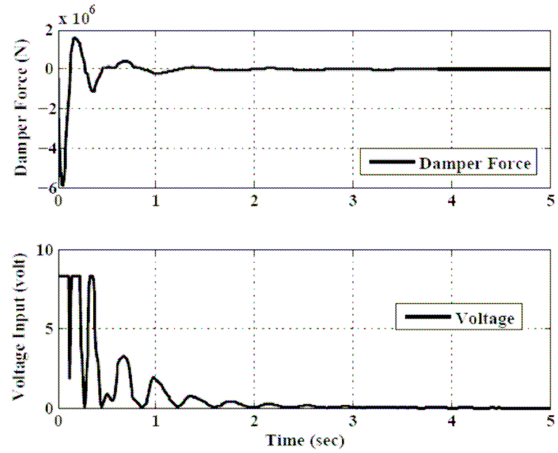

Fig. 8. Damper Force & Voltage (Stability Test)

5. Conclusions

FLC based MR damper voltage control for a three-storey building under earthquake has been developed. The present method is compared with the clipped optimal algorithm and LQR control approach that are very popular. Results show that FLC based MR damper provides better control than other approaches and is comparable to the clipped optimal case. The main advantage in using FLC based strategy is that it does not need system state feedback, and thus, error due to state estimate are not present. Furthermore, it uses any voltage value required to control the system, avoiding, switch between extreme voltage values and damper saturation at full voltage value. Stability test is shown with worst initial condition and the result obtained is satisfactory.

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