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대형 구조물의 진동제어를 위한 반능동형 댐퍼의 설계

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Design of Semi-Active Tendon for Vibration Control of Large Structures

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ABSTRACT

In this paper, magneto-rheological (MR) damper is studied for vibration control of large infra structures under earthquake. Generally, active control devices need a large control force and a high power supply system to reduce the vibration effectively. Large and miss tuned control force may induce the dangerous situation such that the generated large control force acts to amplify the structural vibration. Recently, to overcome the weaknesses of the active control, the semi-active control method is suggested by many researchers. Semi-active control uses the passive control device of which the characteristics can be modified. Control force of the semi-active device is not generated from the actuator with power supply. It is generated as a dynamic reaction force of the device same as in the passive control case, so the control system is inherently stable and robust. Unlike the case of passive control, control force of semi-active control is adjusted depending on the measured response of the structure, so the vibration can be reduced more effectively against various unknown environmental loads. Magneto-rheological (MR) damper is one of the semi-active devices. Dynamic characteristics of the MR material can be changed by applying the magnetic fields. So the control of MR damper needs only small power. Response time of MR to the input voltage is very short, so the high performance control is possible. MR damper has a high force capacity so it is adequate to the vibration control of large infra structure. Because MR damper has a nonlinear property, normal control method used in active control may not be effective. Clipped optimal control, modified bang-bang control etc. have been suggested to MR damper by many researchers. In this study, sliding mode fuzzy control (SMFC) is applied to MR damper. Genetic algorithm is used for the controller tuning. To verify the applicability of MR damper and suggested algorithm, numerical simulation on the aseismic control is carried out. Simulation model is three-story building structure, which was used in the paper of Dyke, et al. The control performance is compared with clipped optimal control. The present results indicate that the SMFC algorithm can reduce the earthquake-induced vibration very effectively.

1. INTRODUCTION

Vibration control is one of the effective methods to reduce the excessive vibration by installing additional control devices. Active control devices for reducing the vibration of the structures have to generate the control force, which acts on the structure and makes the structure to resist the external environmental loads such as wind, earthquake and sea wave forces. To reduce the vibration effectively, active devices require large control force, and so high power system must be equipped. Moreover, to prevent dangerous situation such that the generated control force acts to amplify the vibration, the protection system has to be equipped too. Recently, semi-active control methods are suggested by many researchers to overcome the weaknesses of the active control. Semi-active control methods use passive control devices of which the characteristics can be modified. The control force of semi-active device is not generated from the power system of the control device. It is generated as a dynamic reaction force of the device same as in the passive control case, so inherently stable and robust. Unlike the case of passive control, control force of semi-active control is adjusted according to the measured response of the structure, so the vibration can be reduced more effectively against various unknown environmental loads. This

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control force can be modified by tuning the characteristics of the device. Magneto-rheological (MR) damper is one of the semi-active devices. Dynamic characteristics of the MR material can be changed by applying magnetic fields. So control of the MR damper needs only small power. Response time of the MR on the input voltage is very short, so high performance control is possible. The MR damper has a high capacity of the actuating force so it is adequate to the vibration control of a large infra structure. Because the MR damper has a nonlinear property, normal control method used in active control may not be effective. Many control algorithms, such as clipped optimal control and modified bang-bang control have been suggested for the MR damper by many researchers. In this study, sliding mode fuzzy control (SMFC) is applied to the MR damper in conjunction with earthquake vibration control of a 3-story building structure.

2. MODEL OF CONTROL SYSTEM

2.1 Modeling of Structure

Referring to a building structure for a vibration control, the dynamic behavior of the structure with a control device can be modeled as

$$\mathbf{M}_s\ddot{\mathbf{y}}_s(t) + \mathbf{C}_s\dot{\mathbf{y}}_s(t) + \mathbf{K}_s\mathbf{y}_s(t) = \mathbf{f}_s(t) + \mathbf{f}_{MR}(t, v_{in}) \quad (1)$$

where $\mathbf{y}_s(t)$, $\mathbf{f}_s(t)$, $\mathbf{f}_{MR}(t, v_{in})$, and v_{in} = displacement, external environmental loads, damping force vectors of MR damper, and input voltage; and $\mathbf{M}_s$, $\mathbf{C}_s$, and $\mathbf{K}_s$ = mass, damping, and stiffness matrices. By converting into a state space form and selecting appropriate control and measurement variables, the following state and measurement equations can be obtained

$$\begin{aligned}
\dot{\mathbf{x}}(t) &= \mathbf{A}\mathbf{x}(t) + \mathbf{B}_d\mathbf{f}_{MR}(t, v_{in}) + \mathbf{B}_f\mathbf{f}_s(t) + \mathbf{B}_w\mathbf{w}(t) \\
\mathbf{y}_c(t) &= \mathbf{C}_c\mathbf{x}(t) + \mathbf{D}_{cd}\mathbf{f}_{MR}(t, v_{in}) + \mathbf{D}_{cf}\mathbf{f}_s(t) + \mathbf{D}_{cw}\mathbf{w}(t) \quad (2) \\
\mathbf{y}_m(t) &= \mathbf{C}_m\mathbf{x}(t) + \mathbf{D}_{md}\mathbf{f}_{MR}(t, v_{in}) + \mathbf{D}_{mf}\mathbf{f}_s(t) + \mathbf{D}_{mw}\mathbf{w}(t) + \mathbf{v}(t)
\end{aligned}$$

where $\mathbf{x}(t)$, $\mathbf{y}_c(t)$, $\mathbf{y}_m(t)$, $\mathbf{w}(t)$, and $\mathbf{v}(t)$ = state, control signal, measured signal, un-modeled error, and measurement noise vectors; and $\mathbf{A}$, $\mathbf{B}_d$, $\mathbf{B}_f$, $\mathbf{B}_w$, $\mathbf{C}_c$, $\mathbf{D}_{cd}$, $\mathbf{D}_{cf}$, $\mathbf{D}_{cw}$, $\mathbf{C}_m$, $\mathbf{D}_{md}$, $\mathbf{D}_{mf}$, and $\mathbf{D}_{mw}$ = system matrices.

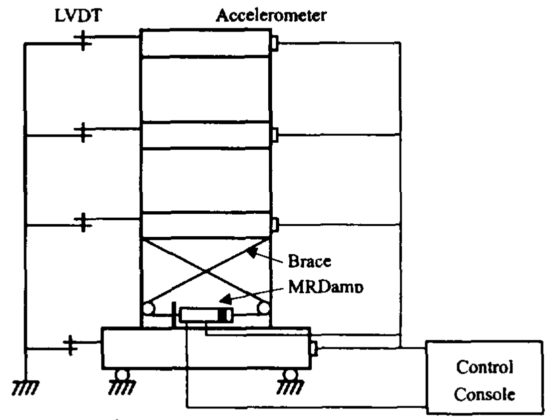


Figure 1. Model Structure for Aseismic Control

2.2 Model of MR Fluid Damper

MR fluid has several unique characteristics, such as high dynamic yield strength, wide operating temperature range, high viscosity at no magnetic filed, and short response time. Many researchers have studied the modeling of the MR fluid. In this paper, modified Bouc-Wen model suggested by *Dyke et al.* is used.

Force of damper is modeled as (*Spencer et al. 1996*)

$$f_{MR} = \alpha z + c_0(\dot{x} - \dot{y}) + k_0(x - y) + k_1(x - x_0) \quad (3)$$

where the evolutionary variable z is governed by

$$\dot{z} = -\gamma|\dot{x} - \dot{y}|z|z|^{n-1} - \beta(\dot{x} - \dot{y})|z|^n + A(\dot{x} - \dot{y}) \quad (4)$$

$$\dot{y} = \frac{1}{(c_0 + c_1)}\{\alpha z + c_0\dot{x} + k_0(x - y)\} \quad (5)$$

Coefficients used in the above equations can be determined by system identification procedure (*Dyke et al. 1996*).

Figure 2 shows the harmonic responses of MR damper, and it can be certified that the dynamic characteristics of MR damper is varied by the strength of induced magnetic field. Typical coefficients of MR dampers are listed in *Table 1*.

Table 1. Coefficients of the MD Damper

Coefficient	Value	Coefficient	Value
C_{0a}	21.0 N· sec/cm	α_a	140 N/cm
C_{0b}	3.50 N·sec/cm·V	α_b	695 N/cm·V
k_0	46.9 N/cm	γ	363 cm^{-2}
C_{1a}	283 N· sec/cm	β	363 cm^{-2}
C_{1b}	2.95 N·sec/cm·V	A	301
k_1	5.00 N/cm	n	2
X_0	14.3 cm	η	190 sec^{-1}

To consider the dependence of the force on the voltage applied to the current driver and the resulting magnetic current, *Spencer, et al.* have suggested.

$$\begin{aligned} \alpha &= \alpha(u) = \alpha_a + \alpha_b(u) \\ c_1 &= c_1(u) = c_{1a} + c_{1b}(u) \\ c_0 &= c_0(u) = c_{0a} + c_{ob}(u) \end{aligned} \tag{6}$$

where $\dot{u} = -\eta(u - v_{in})$ and v_{in} is the applied voltage.

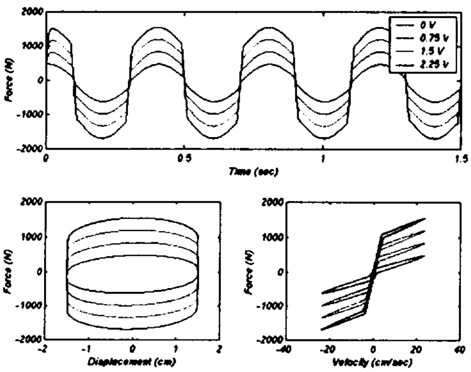


Figure 2. Harmonic Responses of the MD Damper

3. DESIGN OF CONTROLLER

3.1 Sliding Mode Fuzzy Control for MR Damper

Conventional control algorithms based on the ordinary linear optimal control have inherent limitations for applying to the semi-active control. Skyhook control, modified bang-bang control, modulated homogeneous friction control, clipped optimal control, etc. have suggested to control the MR damper (*Dyke et al., 1996, Koh et al., 1999*). In this research, sliding mode fuzzy control (SMFC) is used to control the MR fluid damper (Kim and Yun, 2000).

As in the sliding mode control (SMC), the basic strategy of the sliding mode fuzzy control (SMFC) is forcing the state of the system to stay in some region, so called the sliding surface, whereas the response of the system on the sliding surface can be reduced rapidly. Using the Lyapunov's direct method, the structure of the SMFC can be constructed as

$$v_{in}(t) = v_{max} H(diag(-\mathbf{B}_d^T \mathbf{P}\mathbf{x})\mathbf{f}_{MR}) \tag{1}$$

where $\mathbf{P} = [P_1 \ \cdots \ P_{n_u}]^T$; P_i = direction vector of the sliding surface for the i-th control force.

Converting the above control law into a fuzzy form, a SMFC can be obtained.

3.2 Sliding Mode Fuzzy Control for MR Damper

To optimize the tuning parameters of the SMFC, genetic algorithm is applied (Goldberg, 1989, Potvin, 1994).

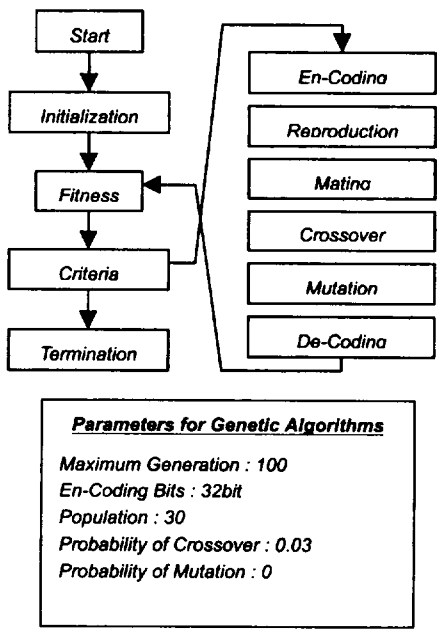
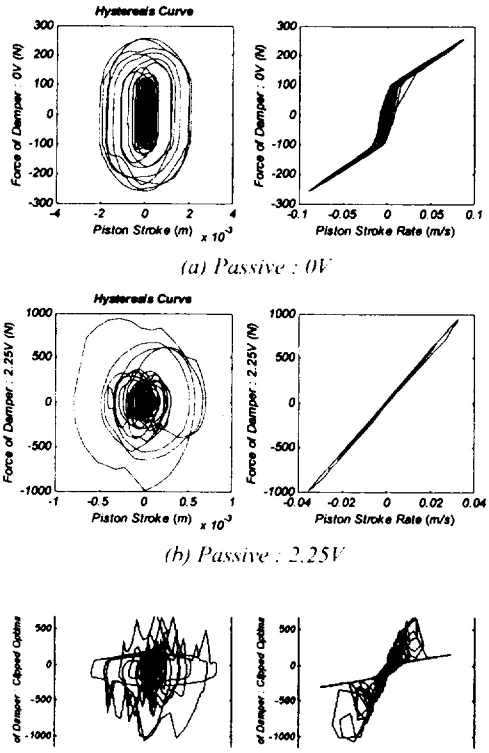


Figure 3. Procedure of Genetic Algorithm

4. NUMERICAL SIMULATION STUDY

3-story building frame structure is used for the numerical simulation study to examine the effectiveness of the proposed approach. To verify the proposed control algorithm, model structure's specifications are adopted from the paper of Spencer, et al. (*Spencer, et al., 1996*). Scaled El Centro (1940) earthquake time history is used as a seismic load. *Figure 4* shows the hysteresis curve during the control. *Figure 5* shows the structural responses. Control results are listed in *Table 2*.



(a) Passive : 0V

(b) Passive : 2.25V

(c) SMFC

Figure 4. Hysteresis Curves

5. CONCLUSIONS

MR fluid damper is researched as a semi-active control device. Sliding mode fuzzy control is used to control the strength of the applied magnetic filed. Genetic algorithm is used for the optimal design of the controller. To verify the applicability of MR damper and suggested algorithm, numerical simulation on the aseismic control is carried out. Simulation model is three-story building structure, which was used in the paper of Dyke, et al. The control performance is compared with clipped optimal control. The results indicate that the present control algorithm can reduce the earthquake-induced vibration very effectively.

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Table 2. Control Responses of Structure

		Un Controlled	Passive : 0V	Passive : 2.25V	Clipped-Optimal	SMFC
Displ. (cm)	1	0.5405	0.2118	0.0788	0.114	**0.1391**
	2	0.8243	0.3586	0.1950	0.185	**0.1579**
	3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Accel. (m/s^2)	1	8.6786	4.2324	2.9123	6.96	**6.4060**
	2	10.4560	4.8377	4.9839	[illegible]	[illegible]
	3	[illegible]	[illegible]	[illegible]	7.03	**6.9736**
Damper Force (kN)		0	0.2587	0.9960	0.941	**0.9321**

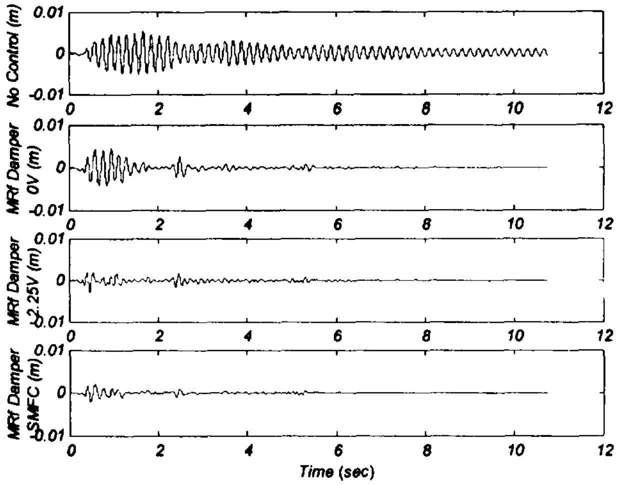

Figure 5. Structural Responses

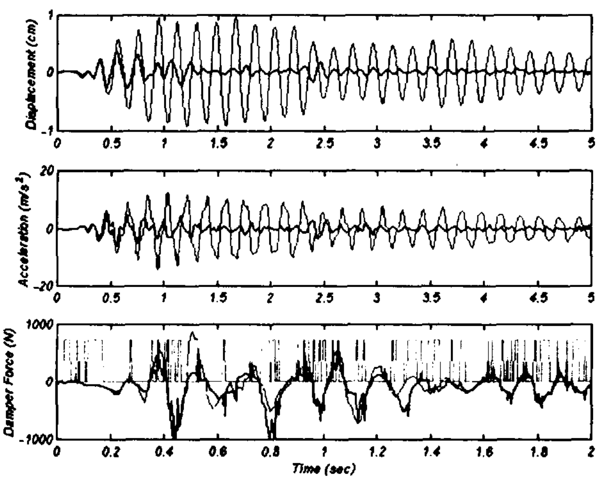

Figure 6. Control Force and Control Voltage Command