반능동 제어를 위한 MR 유체 댐퍼의 설계
Design of MR Fulid Dampers for Semi-Active Control

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국문요약

대형 구조물의 진동제어를 위하여 MR 유체 댐퍼를 사용한 반능동 제어기법에 대하여 연구하였다. 기존에 많이 사용되고 있는 수동제어기법은 일단 제어장치를 설치한 후에는 구조물에 실제로 작용하고 있는 외부 하중의 현재 특성에 대해서 적절히 반응할 수 없다는 제한을 가지고 있으며, 이를 극복하기 위하여 연구되어온 능동제어기법은 구조물의 진동을 감소시키기 위하여 구조물에 직접적으로 가해지는 커다란 제어력을 요구하며, 이로 인해 경우에 따라서는 불안정한 상태가 유발될 수도 있다는 점이 단점으로 지적되고 있다. 최근에 Spencer 등은 반능동 제어기법을 제안하였는데, 이는 수동제어장치의 제어특성을 On-Line 으로 조절하는 방식으로서 제어 가능한 수동제어기법으로도 불리운다. 구조물의 진동제어에 필요한 제어력이, 특수한 제어기구에서 발생되는 인위적인 힘이 아니라, 적절한 구조부재에서 발생되는 자연적인 부재력이므로, 무엇보다 강인하고 신뢰할 수 있는 제어기법이며, 이때 제어장치의 구조적 특성을, 측정된 구조물의 응답에 맞추어 적절히 조절함으로써 다양한 외부하중에 대해 보다 효율적인 제어가 이루어질 수 있도록 한 방법이다.

반능동제어를 위한 제어기구로서는 Variable Orifice Dampers, Friction Controllable Isolators, Variable Stiffness Devices, Electro-Rheological (ER) Fluid Damper, Magneto-Rheological (MR) Fluid Damper 등이 제안되고 있으며, 본 논문에서는 반응속도가 빠르고, 적은 파워만을 요구하며, 커다란 제어력을 낼 수 있는 MR Damper 를 사용하여 지진하중을 받는 구조물의 반능동 제어게 대하여 연구하였다.

MR Damper 의 특성이 비선형이므로 이에 적합한 Sliding Mode Fuzzy Control (SMFC) 기법을 사용하였으며 이때 SMFC 의 최적 설계를 위하여 Genetic Algorithm 을 적용하였다. 제안된 제어기법의 실제 적용성을 검증하기 위하여 기존의 제어결과와 비교 검토하였으며, 그 결과로부터 MR Damper 를 사용한 반능동 제어기법이 구조물의 진동제어에 매우 효과적임을 확인할 수 있었다.

1. Introduction

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,

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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 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 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.

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 about 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 is not 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.

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.

2. Modeling 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*)

$$f_{MR} = \alpha z + c_0(\dot{x} - \dot{y}) + k_0(x - y) + k_1(x - x_0) \tag{1}$$

where the evolutionary variable z is governed by

$$\dot{z} = -\gamma|\dot{x} - \dot{y}|z|z|^{n-1} - \beta(\dot{x} - \dot{y})|z|^n + A(\dot{x} - \dot{y}) \tag{2}$$

$$\dot{y} = \frac{1}{(c_0 + c_1)}\{\alpha z + c_0\dot{x} + k_0(x - y)\} \tag{3}$$

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

Figure 1 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}

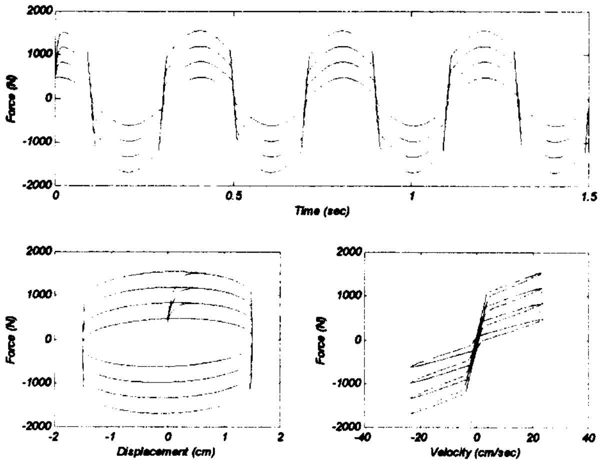


Figure 1. Harmonic Responses of the MD Damper

3. Nonlinear Control Strategy

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).

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

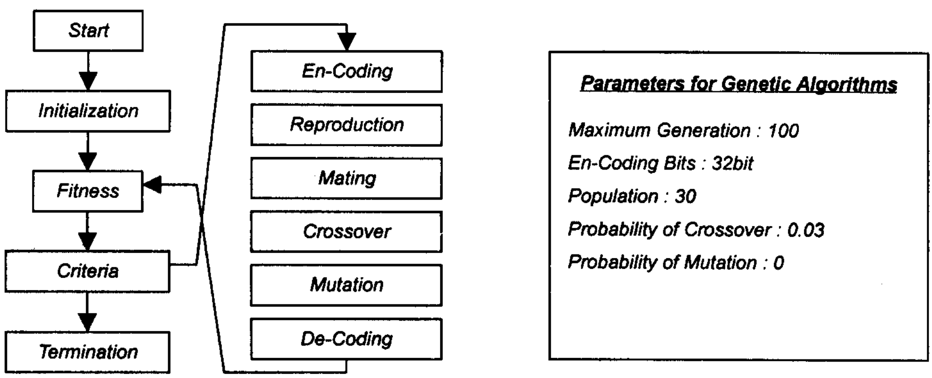


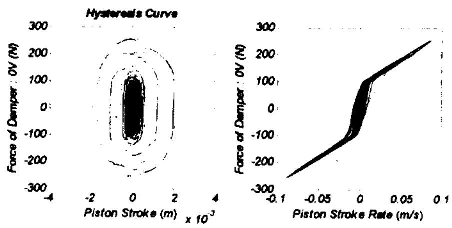
Figure 2. Procedure of Genetic Algorithm

4. Numerical example

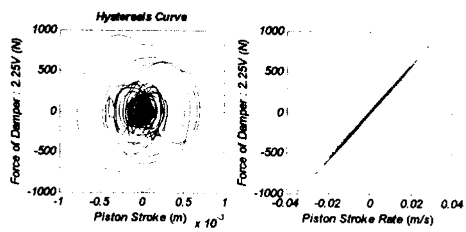
3-story building frame structure is used for the numerical simulation study to examine the effectiveness of the proposed approach. To verify the proposed control algorithm, model structure's specifications are adopted from the paper of Spencer, et al. (*Spencer, et al., 1996*). Scaled El Centro (1940) 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*.

Table 2. Control Responses of Structure

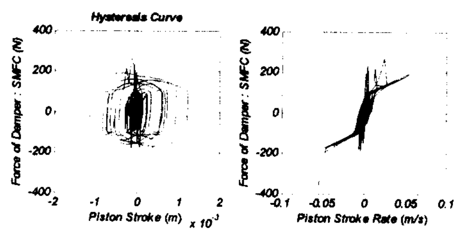
		Un Controlled	Passive : 0V	Passive : 2.25V	Clipped-Optimal	**SMFC**
Displ. (cm)	1	0.5405	0.2118	0.0788	0.114	**0.1228**
	2	0.8243	0.3586	0.1950	0.185	**0.2133**
	3	0.9643	0.4572	0.3055	0.212	**0.2743**
Accel. (m/s^2)	1	8.6786	4.2324	2.9123	6.96	**6.9343**
	2	10.4560	4.8377	4.9839	7.39	**7.1104**
	3	14.0792	7.1956	7.6893	7.03	**7.1527**
		0	0.2587	0.9960	0.941	**0.3877**



(a) Passive : 0V



(b) Passive : 2.25V



(c) SMFC

Figure 3. Hysteresis Curves

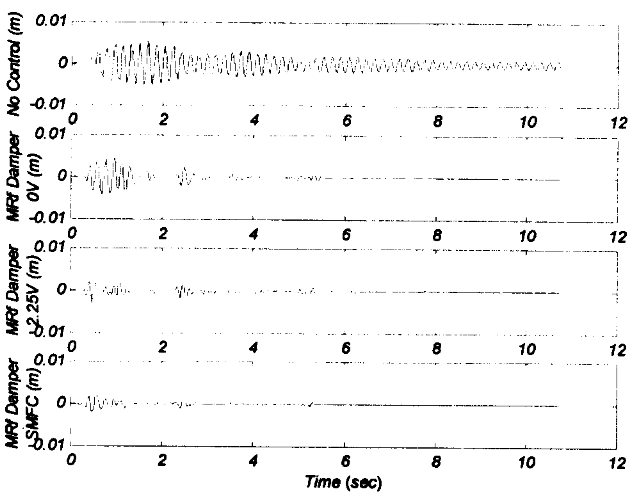


Figure 4. Structural Responses

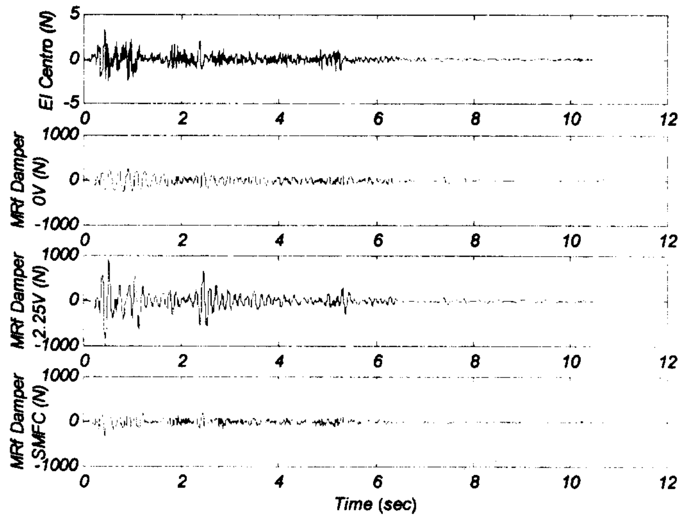


Figure 5. Earthquake Load and Control Forces

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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