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Experimental Study on Smart Passive System based on MR Damper

*Jung-Hyun Hong[1], Kang-Min Choi[2], Jong-Heon Lee[3], Ju-Won Oh[4], and In-Won Lee[5]

[1, 2, 5]*Department of Civil and Environmental Engineering, Korea Advanced Institute of Science and Technology, Daejeon, Korea*
rolling@kaist.ac.kr, kmchoi@kaist.ac.kr, iwlee@kaist.ac.kr
[3]*Department of Civil Engineering, Kyungil University, Gyeongsan, Korea*
leejh@kiu.ac.kr
[4]*Department of Civil Engineering, Hannam University, Daejeon, Korea*
ohgod@hannam.ac.kr

ABSTRACT

This paper verifies the efficiency of a smart passive system based on MR damper through the experimental study. A Magnetorheological (MR) damper is one of the most promising control devices for earthquake hazard mitigation, because it has many advantages such as small power requirement, reliability, and low price to manufacture. However, it is not easy to apply the MR damper-based control system to large-scale civil structures because of the difficulties of building up with power supply and maintaining the control system individually. An Electromagnetic induction (EMI) system for MR dampers can be used to resolve these problems. According to the Faraday's law of induction, the EMI system changes kinetic energy of the structure to electric energy, and then the electric energy is used to vary the damping characteristics of the MR damper to control the vibration of structure. The experiments of EMI system for MR damper are performed and the results are compared with the passively operated MR damper-based control systems.

INTRODUCTION

The unexpected seismic events have caused economic and even human losses. As the resistibility of civil structures, such as buildings and bridges, becomes important, great development of structural control systems is resulted in. Representative types of supplemental control strategies are passive, active, and semiactive system.

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[1] Graduate Student
[2] Ph. D. Candidate
[3] Professor
[4] Professor
[5] Professor

Passive supplemental damping strategies, including base isolation systems, viscoelastic dampers, and tuned mass dampers are widely applied for mitigating the seismic effects to structures because they are reliable and require low cost without any power. However, these passive damping systems are unable to adapt to structural changes, various usage patterns, and loading conditions. Active control systems, such as AMD, are adaptable to varying dynamic loads, but require enormous power for efficient control. It causes high cost and danger in case of failure in power supplement.

For recent decades, semiactive control systems have received considerable attention, because they have both the reliability of passive control systems and the adaptability of active control systems. Among semiactive system, such as variable stiffness dampers, variable friction dampers, and magnetorheological/electrorheological (MR/ER) fluid dampers, an MR fluid damper is one of the most prospective semiactive control devices because of its mechanical simplicity, high dynamic range, low operation power requirements, large force capacity, and environmental robustness (Dyke et al. 1996; Dyke et al. 1998; Jung et al. 2003, 2004a,b; Kamath and Wereley 1997; Spencer and Sain 1997; Spencer et al. 1997).

To reduce the responses of structures with MR fluid dampers with effect, a control system requires a power supply, a controller, and sensors (Soong 1990; Dyke et al. 1996; Spencer et al. 1997). However, when a lot of MR fluid dampers are used in a large-scale structure such as a high-rise building and a cable-stayed bridge, the control devices become complex: many MR fluid dampers are used and then each MR fluid damper must be connected to individual power supply and controller. Also, many sensors are needed to measure structural responses and determine the control command voltages for each MR damper in the case of using semiactive control algorithms. To resolve the above difficulties, a smart passive control system that consists of an MR fluid damper and an electromagnetic induction (EMI) part was proposed by Cho et al. (2004, 2005).

In this study, the efficiency of the smart passive control system for mitigating structural responses due to ground accelerations has been investigated experimentally using a shaking table test. The experiment validates that the EMI part induces suitable command voltage to change the characteristic of MR damper and the control performance of the smart passive control system is compared with other passive control systems.

SMART PASSIVE CONTROL SYSTEM

This study verifies the efficiency of electromagnetic induction (EMI) system for MR damper without extra power supply like a battery. Of course, the MR damper is a semiactive device that needs an external power source to change the damping characteristics of MR fluids. The EMI system is worthy of such a power source. The EMI control system which is attached to MR damper is a self-powered and self-controlled system. The EMI system that consists of permanent magnets and a solenoid changes kinetic energy of reciprocation motion of a solenoid to the electric energy according to the Faraday's law of induction (Reitz et. al. 1993; Marshall and Skitek 1990; Miner 1996) and then the electric energy is used to change the damping characteristics of the MR damper. Another excellent fact is that EMI system has the capacity of a control algorithm in addition to an external power source. Fast relative motions of a solenoid between the permanent magnets of EMI system make high current to MR damper, while slow relative motions of a solenoid between the permanent magnets make low current to MR damper. Thus, the MR damper with the EMI system is able to reduce the vibrations of structures by itself without any power supply and controller. That is the reason why the MR damper with EMI system can be named a 'smart passive control system' although the MR damper is for a semiactive device.

Faraday's law of induction

Faraday's law of induction is

$$\varepsilon = -N\frac{d\Phi_B}{dt} \tag{1}$$

where ε is induced electromotive force (EMF) that has unit of volt(V), N is the number of turns of coil, and Φ_B is magnetic flux. Negative sign in (1) is the direction of induced current. In (1), magnet flux can be defined

$$d\Phi_B = \vec{B}\cdot d\vec{A} = BdA\cdot\cos\phi \tag{2}$$

where $\vec{B}$ is magnetic field, $\vec{A}$ is area of cross section, and ϕ is the angle between $\vec{B}$ and $d\vec{A}$. Using (2), Faraday's law can be rewritten

$$\varepsilon = -N\frac{d\Phi_B}{dt} = -N\,B\frac{dA}{dt} \tag{3}$$

Faraday's law of induction states that the induced emf in a closed loop equals the negative of the time rate of change of magnetic flux through the loop. External loads such as earthquakes and winds cause the reciprocal motion of the MR damper. In consequence, the coil in the EMI system moves back and forth with inducing the emf. Thus, the faster MR damper moves, the higher EMF is induced and the more slowly MR damper moves, the lower emf is induced. This induced emf is carried to an electromagnet in the piston head and generates magnetic field around the electromagnet that changes the damping characteristics of the MR fluid.

EXPERIMENTAL SETUP

A three-story building configured with a single MR damper and EMI system is used as a model to verify effectiveness of the smart passive control system. A schematic of a smart passive system attached to a three-story building is shown in Fig. 1. The scaled building model is constructed of steel and has a height of 105 cm and weighs a total of 48.27 kg, which is distributed evenly between the three floors. The natural frequencies of the model are 2.05, 5.57, and 8.41Hz.

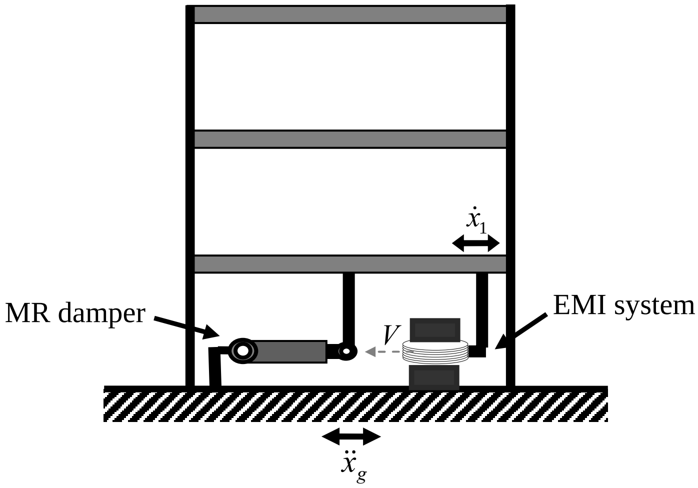


Fig. 1. Schematic of a smart passive system attached to a three-story building

The EMI system consists of two permanent magnets generating magnetic field lines and a solenoid moving between two magnets as explained at the previous section. The semiactive damper connected to EMI system is a magnetorheological (MR) friction damper RD-1097-01 from Lord Corporation. The MR damper is rigidly connected between the ground and the first floor of the structure as shown. This damper has a maximum stroke level of ± 2.9 cm, a maximum force level of approximately ± 100 N, and the maximum voltage we can apply is 10 Volts because of heat damage at the current more than 0.5 amp.

A shaking table is used as an equipment to apply seismic loads to the building. The shaking table is driven axially by a servo-controlled hydraulic actuator at the Structural Dynamics and Vibration Control Laboratory (SDVC) at Korea Advanced Institute of Science and Technology (KAIST). It has a testing platform with 110 cm by 100 cm, a maximum payload of 600 kg, a maximum acceleration of ± 1 g, and a maximum velocity of 21 cm/sec. The actuator was built by Dong Yang System Manufacturing.

Input ground motions

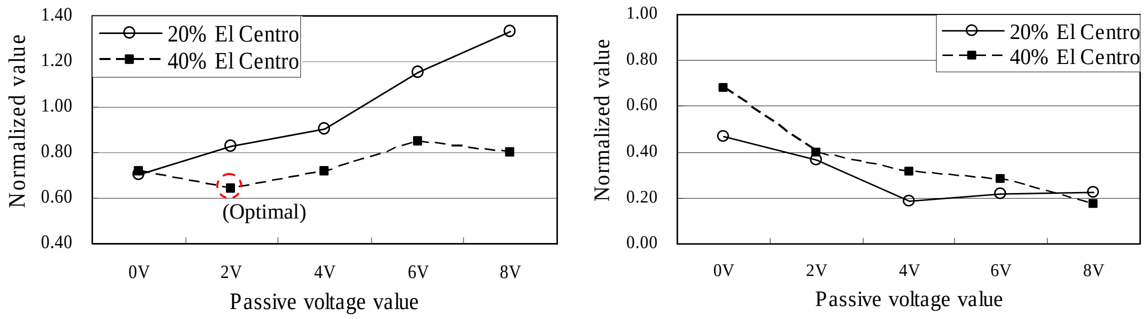
To evaluate the performance of the smart passive control system for various types of seismic events, four historical earthquake records are considered as ground excitations. Because the used building structure in this experiment is a scaled model, the earthquakes must be reproduced at the peak ground acceleration and at times the recorded rate. The input exciting ground motions are : (i) El Centro earthquake (The N-S component recorded at the Imperial Valley Irrigation District substation in El Centro, California, during the Imperial Valley, California earthquake of May 18, 1940) scaled to 40% amplitude and 2 times the recorded rate: PGA 0.1395g, (ii) El Centro earthquake (same as (i)) scaled to 20% amplitude and 2 times the recorded rate: PGA 0.0697g, (iii) Hachinohe earthquake (The N-S component recorded at Hachinohe City during the Tokachi-oki earthquake of May 16, 1968) scaled to 30% amplitude and 2 times the recorded rate: PGA 0.0811g, (iv) Kobe earthquake (The N-S component recorded at the Kobe Japanese Meteorological Agency (JMA) station during the Hyogoken Nanbu earthquake of January 17, 1995) scaled to 20% amplitude and 2 times the recorded rate: PGA 0.1643g, and (v) Northridge earthquake (The N-S component recorded at Sylmar County Hospital parking lot in Sylmar, California, during the Northridge, California earthquake of January 17, 1994) scaled to 10% amplitude and 2 times the recorded rate: PGA 0.0843g. The time history of the ground acceleration and power spectral density

EXPERIMENTAL RESULTS

Optimal passive control

Passive control system means for maintenance of constant voltage value, therefore it is required to determine appropriate value, from 0V to 8V, to control vibration passively. The N-S component of the El Centro earthquake with two intensities is considered to seek an optimal voltage value.

Fig. 2(a) and 2(b) show the normalized displacement at the 1st floor and the normalized maximum acceleration between the 1st and 3rd floor with increasing the voltage input, respectively. As shown in the Fig. 2(a), a constant voltage of 2V indicates the best performance for 40% El Centro earthquake and quite good performance also for 20% El Centro earthquake, hence the constant value of 2V can be optimal to reduce the maximum acceleration of the structure. Otherwise, Fig. 2(b) shows that higher input command voltage induces smaller displacement of structure. It is difficult to reduce the floor displacement and structural acceleration in the best level simultaneously. The performance of the smart passive control system is compared with that of passive-off (0 V), passive-on (8 V), and another passive-on (2V) as the optimal passive case.

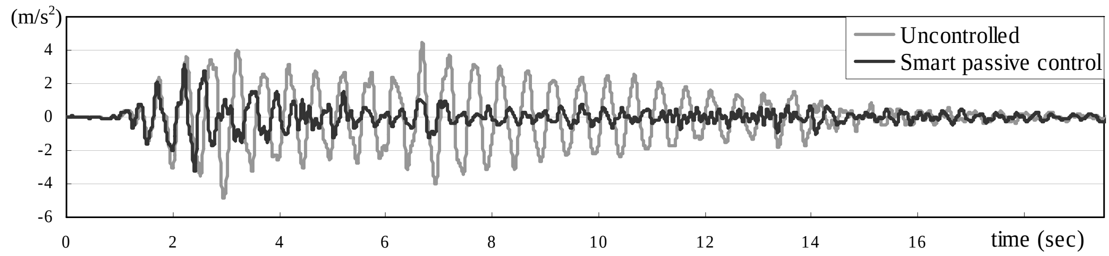


(a) Acceleration (b) Displacement

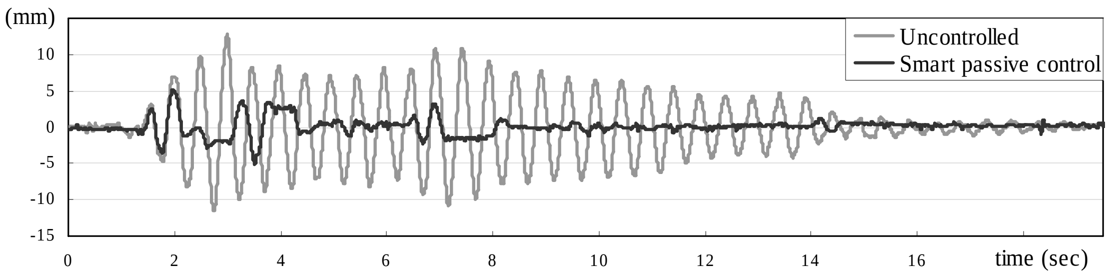
Fig. 2. Maximum responses in the passive cases normalized by the uncontrolled case

Smart passive control

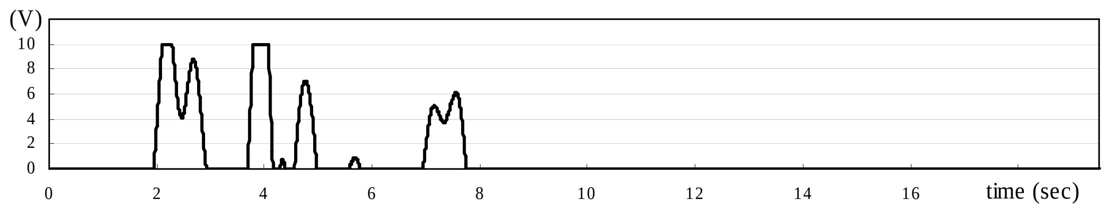
To evaluate the performance of the smart passive control system for the MR damper, five types of scaled earthquakes are applied and the results of the smart passive control system are compared with the passive-off (0 V), passive-on (8 V), and the optimal passive-on (2V) systems operated in constant voltage mode.



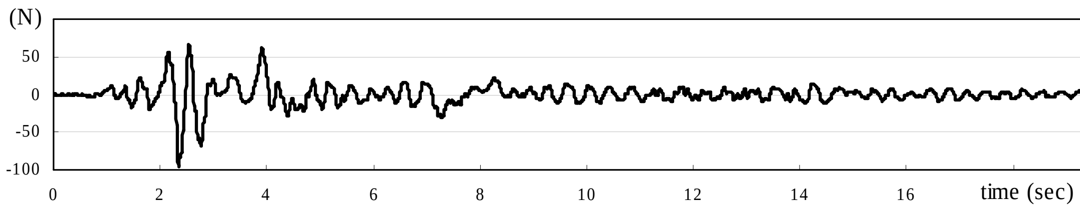
(a) Acceleration



(b) Displacement



(c) Command voltage



(d) Damper force

Fig. 3. Experimental results due to the 40% and 2 times record scaled El Centro earthquake

Fig. 3 shows experimental results of the smart passive control system for the 40% and 2 times record scaled El Centro earthquake. The maximum acceleration of the structure is reduced from 4.86 m/s^2 to 3.28 m/s^2 and the maximum displacement of the 1^{st} floor is reduced from 12.75 mm to 5.23 mm. Such tendencies are resulted also for the other earthquakes. The results normalized by uncontrolled response are shown in Table 1 and 2, and Fig. 4.

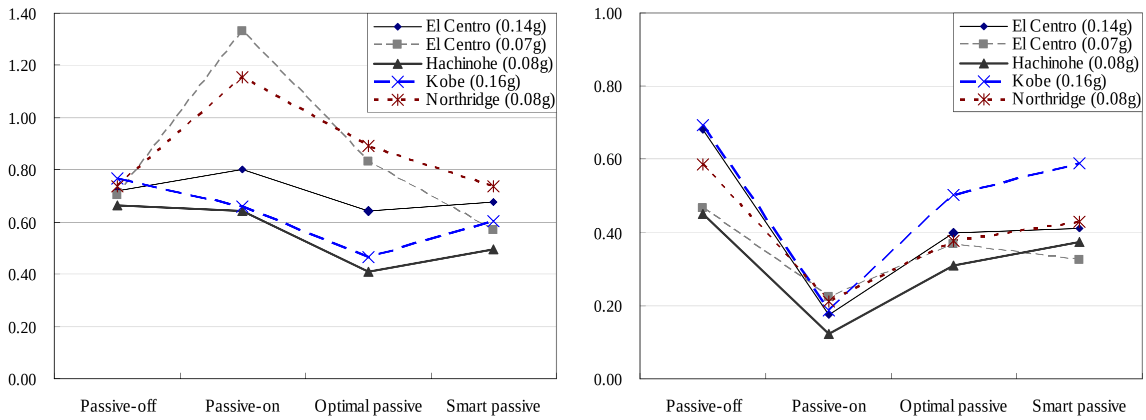
Table 1. Normalized maximum accelerations by uncontrolled response.

	El Centro (0.1395g)*	El Centro (0.0697g)	Hachinohe (0.0811g)	Kobe (0.1643g)	Northridge (0.0843g)
Passive-off (0V)	0.72	0.70	0.67	0.77	0.74
Passive-on (8V)	0.80	1.33	0.64	0.66	1.16
Optimal passive	0.64	0.83	0.41	0.47	0.89
Smart passive	0.67	0.57	0.50	0.60	0.73

* is peak ground acceleration

Table 2. Normalized maximum displacements by uncontrolled response.

	El Centro (0.1395g)	El Centro (0.0697g)	Hachinohe (0.0811g)	Kobe (0.1643g)	Northridge (0.0843g)
Passive-off (0V)	0.68	0.47	0.45	0.69	0.58
Passive-on (8V)	0.17	0.22	0.12	0.19	0.21
Optimal passive	0.40	0.37	0.31	0.50	0.38
Smart passive	0.41	0.32	0.37	0.59	0.43



(a) Acceleration (b) Displacement

Fig. 4. Normalized maximum responses by uncontrolled response

Comparing the responses of the smart passive system with those of the passive-off (0 V), passive-on (8 V), and optimal passive (2 V) as shown, the results of the smart passive is much better than the passive-on (8 V). The maximum accelerations with passive-on (8V) control system are even larger than uncontrolled state for El Centro (0.07g) and Northridge (0.08g) earthquakes. Otherwise, the maximum displacements represent the best performance with passive-on (8V) and results of the smart passive are quite better than passive-off case. That is, the acceleration and displacement have contrary tendencies along the input voltage intensities, therefore the smart passive system has significantly better performance than passive-on and passive-off system.

In the case of the optimal passive, the smart passive makes similarly effective results to the optimal passive system overall; several cases are better and other cases are worse. However, the types of earthquakes derive wider range of accelerations in the optimal passive than the smart passive. It means that the smart passive control system can maintain robustness, while the improper optimal passive system causes unexpected results.

CONCLUSION

In this study, the smart passive control system consisting of the MR fluid damper and the electromagnetic induction (EMI) part has been verified through experiments applying various historical earthquakes. The smart passive control system using the EMI part composed of permanent magnets and a solenoid can be much more compact, convenient, and economic than a conventional active/semiactive control system that needs a power supply, a controller and sensors. It is demonstrated that the smart passive control system has the better performance than the passive-off and -on cases and the comparable performance to the passive optimal case.

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