스마트 수동 감쇠기를 이용한 구조물의 진동제어 기법

Vibration Control Technique Using Smart Passive Damper

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1. Introduction

Smart damping systems (i.e., semiactive control systems) have recently received considerable attention, because they have both the reliability of passive control systems and the adaptability of active control systems. For more than two decades, a lot of smart damping devices have been developed such as variable stiffness dampers, variable friction dampers, and magnetorheological/electrorheological (MR/ER) fluid dampers. Among them, an MR fluid damper is one of the most promising smart damping devices, because of its mechanical simplicity, high dynamic range, low operating power requirements, large force capacity, and environmental robustness (Dyke et al. 1996; Jung et al. 2003, 2004; Kamath and Werely 1997; Spencer and Sain 1997). Recently, an MR fluid damper-based control system was applied to the Nihon-Kagaku-Miraikan building and the base isolated building in Japan for seismic protection of response of the structures, which are the world's first full-scale implementations in civil engineering structures (Spencer and Nagarajaiah 2003; Jung et al. 2004).

To reduce the responses of structures with MR fluid dampers, a control system including a power supply, a controller, and sensors is required (Dyke et al. 1996; Spencer et al. 1997). However, when a lot of MR fluid dampers are used in a large-scale civil structure such as a cable-stayed bridge and a high-rise building, the control system becomes complex: many MR fluid dampers are used and then each MR fluid damper must be connected to one or more power supplies and controllers. Also, many sensors are needed to measure structural responses. Thus, it is not easy to install and maintain the MR fluid damper-based control system for a large-scale civil structure. 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). They numerically verified the effectiveness of the smart passive system by comparing its control performance with the normal MR fluid damper-based semiacitve control system.

In this paper, the feasibility and efficacy of the smart passive control system for suppressing vibration of building structures subjected to ground accelerations has been experimentally investigated by using a shaking table test. First, the feasibility test is conducted to verify that the EMI part can generate the reasonable level of the electromotive force to be used as the control command voltage to the MR fluid damper and efficiently change the level of the damping force. And then, the shaking table test of a small-scale three-story building model including an MR fluid damper with an EMI part attached between the first and second floors is preliminarily conducted to reduce structural vibration due to ground excitation. The control performance of the smart passive control system is compared with that

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of the passively operated MR damper-based control systems.

2. Smart Passive Control System

A conventional MR fluid damper-based control system needs sensors, a controller and an external power source to reduce structural responses. Fig. 1 shows the schematic diagram of the conventional control system using the MR fluid damper. Although it seems to be simple, the control system becomes more complicated to build up and maintain when many MR fluid dampers are used for large-scale civil engineering structures such as cable-stayed bridges and high-rise buildings.

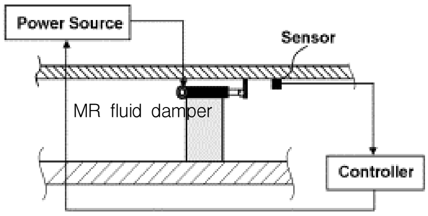


Fig.1. Schematic diagram of an MR fluid damper-based control system

To overcome previous disadvantages, the smart passive control system including the normal MR fluid damper with the EMI part has been developed (Cho et al. 2005).The EMI part consists of a permanent magnet and coils as shown in Fig. 2. The EMI part changes the kinetic energy of the reciprocation motion of the MR fluid damper to the electric energy according to the Faraday law of induction. The induced current can be estimated by the Faraday law of induction (Marshall and Skitek 1990; Miner 1996; Reitz et al. 1993) as follows:

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

where ε is the induced electromotive force (*emf*) that has the unit of volts (V), N is the number of turns of coils, Φ_B is the magnet flux, A is the area of the cross section, and B is the magnet field. The negative sign in Eq. (1) means the direction of the induced current.

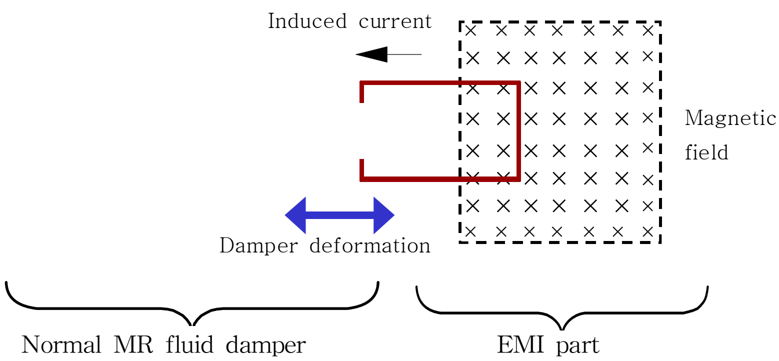


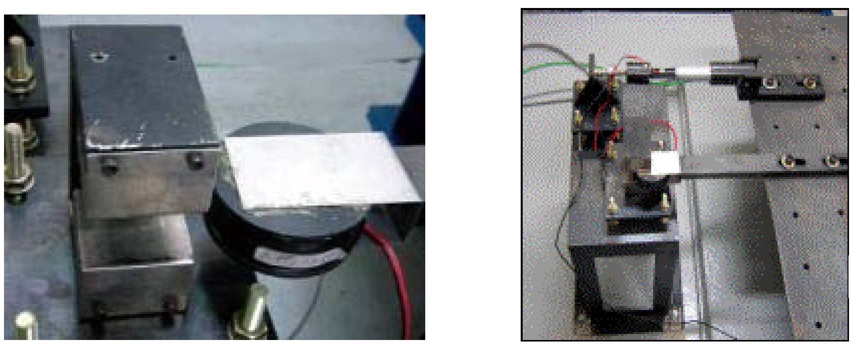
Fig.2. Smart passive control system with MR fluid damper and EMI part

The Faraday law of induction states that the induced *emf* in a closed loop is equal to the negative of the time rate of a change in the magnet flux through the loop. In other words, the relative motion between a coil and a permanent magnet causes a change in the magnet flux, which induces an *emf* in the coil. The amount of the induced *emf* can be regulated by the turns of the coil or the intensity of the permanent magnet as in Eq. (1). This induced electric energy in the MR fluid damper is used to make magnet fields that solidify the MR fluid inside the damper, which results in a change in damping characteristics of the MR fluid damper.

Thus, the MR fluid damper adopting the EMI part can be considered as a passive-type control device that does not require any external power at all. Also, the MR fluid damper with the EMI part is capable of being adjusted to the vibration of structures by itself without any controller, because the output of the induced electric energy is proportional to the magnitude of input loads such as earthquakes. In other words, the fast relative motion between the permanent magnet and the coil gives high current and the slow relative motion gives low current according to the Faraday law of induction. Hence, the MR fluid damper-based control system including the EMI part has the adaptability that other passive control systems cannot have. This is one of the main attractive features of the EMI part in the smart passive control system. More detailed information on the EMI system can be found in Cho et al. (2004, 2005).

3. Experimental Verification

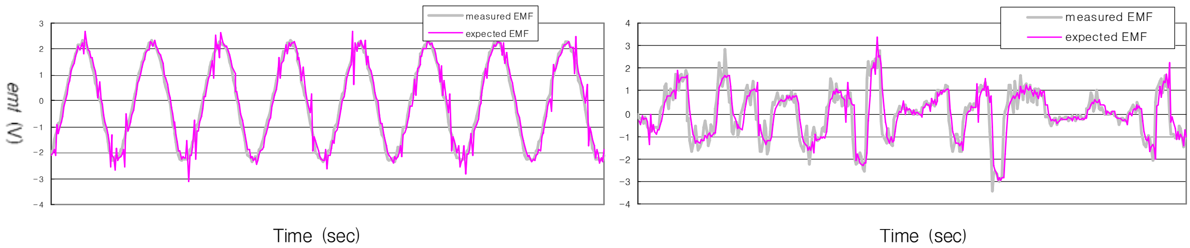
The feasibility and efficacy of the smart passive control system for seismic protection of building structures is experimentally investigated in this study. First, the feasibility test is conducted to verify that the EMI part explained at the previous section can be applied to the MR fluid damper-based control system. To do this, the EMI part is formed by combining a permanent magnet and a solenoid coil as shown in Fig. 3a. Fig. 3b shows the experimental setup for the test using a shaking table uni-axially driven by a servo-controlled hydraulic actuator. The shaking table has a testing platform with 110 cm by 100cm, a maximum payload of 600 kg, a maximum acceleration of ±1.0 g and a maximum velocity of 21 cm/sec. Also, an MR fluid damper used in the test is a MR controllable friction damper (Model No.: RD-1097-01) from Lord Corporation which has a maximum force level of approximately ± 100 N and a maximum voltage of 1.4 V because of heat damage at the current more than 0.5 A.



(a) EMI part (b) Experimental setup

Fig. 3. Experiment for the feasibility study

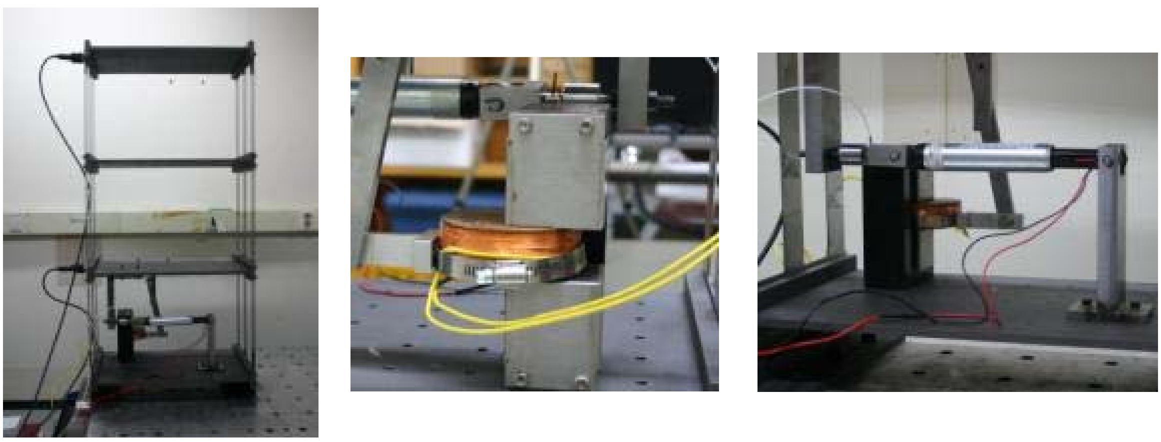
Fig. 4 shows the experimental results of the feasibility test using the shaking table. Figs. 4a and 4b represent the time histories of the *emf* under the sinusoidal input and under the random input, respectively. As shown in the figures, the measured values from the test are quite similar to the expected values calculated through the Faraday law of induction. Moreover, the maximum level of the induced *emf* is almost 4 V. It is demonstrated from the experimental results that the EMI part can generate the reasonable level of the electromotive force to be used as the control command voltage to the MR fluid damper and efficiently change the level of the damping force. Therefore, it is feasible to apply the EMI part to the MR fluid damper-based control system for changing damping characteristics of the MR fluid damper.



(a) The induced emf under the sinusoidal input (b) The induced emf under the random input

Fig. 4. Experimental results from the feasibility test

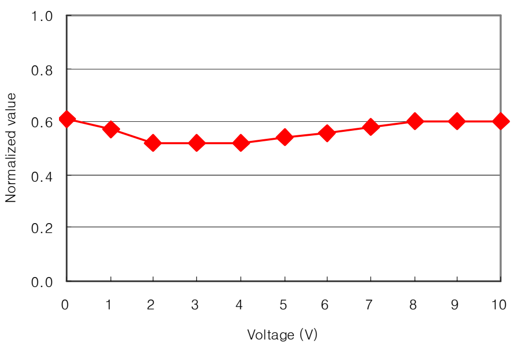
To evaluate the control performance of the smart passive control system considered in this study for seismic protection of building structures, the shaking table test is conducted with a small-scale three-story building model employing the MR fluid damper with the EMI part between the first and second floors as shown in Figs.5a and 5b. The detailed description of the EMI part is shown in Fig 5c. The absolute acceleration at the third floor and the relative displacements at the second and third floors are measured by the accelerometer and the displacement sensors, respectively. In the experiment, the model of the structure is subjected to the NS component of the 1940 El Centro earthquake. Because the structure under consideration is a scaled model, the earthquake must be reproduced at 0.4 times the peak ground acceleration and at 2 times the recorded rate, respectively.



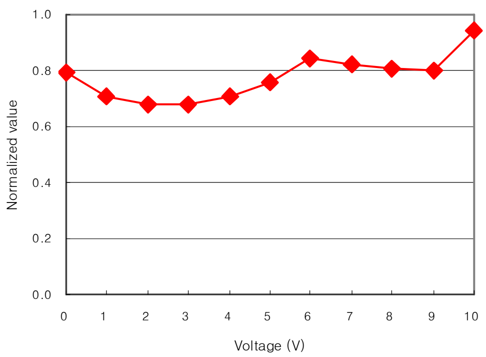
(a) small-scale building model (b) MR fluid damper with EMI part (c) EMI part

Fig. 5. Experimental setup for the shaking table test

Before conducting the test using the smart passive control system, the optimal passive control case is investigated by using the conventional MR fluid damper-based control system. In this case, the MR fluid damper is only passively operated. To change damping characteristics of the MR fluid damper, the voltage input to the damper is changed from 0 V to 10 V. Figs. 6a and 6b show the normalized inter-story drift between the 2nd and 3rd floors and the normalized acceleration at the 3rd floor with increasing the voltage input, respectively. As seen from the figures, the optimal voltage input to the MR fluid damper is 3 V. The performance of passive-off (0 V), passive-on (10 V) and smart passive case swill be compared to that of this optimal passive case with 3 V.



(a) Inter-story drift between the 2nd and 3rd floors



(b) Acceleration at the 3rd floor

Fig. 6. Maximum responses in the passive cases normalized by the uncontrolled case

(a)

(a)

(b)

(b)

(c)

(c)

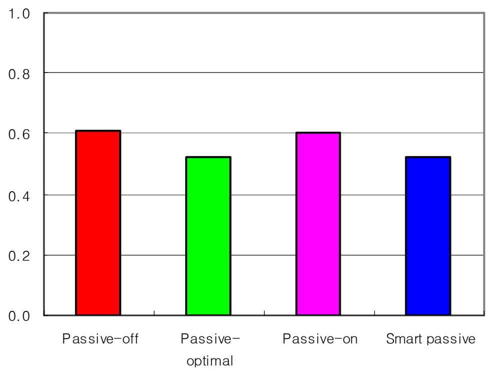
(d)

(d)

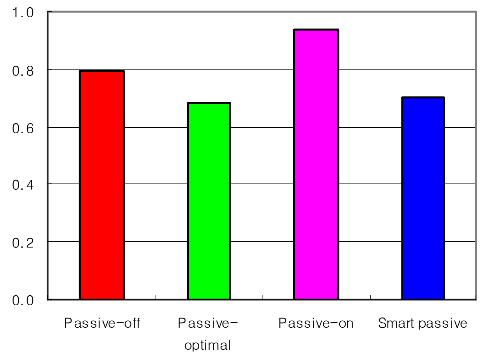
Fig. 7. Inter-story drift between the 2nd and 3rd floors (mm): (a) the passive-off case; (b) the passive-on case; (c) the passive-optimal case; (d) the smart passive case

Fig. 8. Acceleration at the 3rd floor (m/s^2): (a) the passive-off case; (b) the passive-on case; (c) the passive-optimal case; (d) the smart passive case

Figs. 7 and 8 demonstrate the time histories of the inter-story drift between the second and third floors and the acceleration at the third floor, respectively. As shown in Fig. 7, the maximum value in the smart passive case is slightly smaller than that in the passive-off and -on cases. On the other hand, the passive optimal case similarly reduces the inter-story drift compared to the smart passive case. The measured results in the acceleration at the 3rd floor show the similar trend as seen from Fig. 8. In other words, the experimental results during the scaled El Centro earthquake indicate the effectiveness of the smart passive and passive optimal cases in reducing the acceleration at the 3rd floors well as the inter-story drift between the 2nd and 3rd floors.



(a) Inter-story drift between 2nd and 3rd floors



(b) Acceleration at 3rd floor

Fig. 9.Comparison of maximum responses normalized by the uncontrolled case

Figs. 9a and 9b represent the maximum values of the inter-story drift between the 2nd and 3rd floors and the acceleration at the 3rd floor normalized by the uncontrolled case, respectively. As seen from the figures, the effectiveness of the smart passive and passive optimal cases is more clearly demonstrated. Moreover, all the control systems are more effective to reduce the peak inter-story drift than to decrease the peak acceleration.

4. Conclusions

In this study, the newly developed smart passive control system consisting of the MR fluid damper and the electromagnetic induction (EMI) part has been preliminarily verified for application in a seismically excited building structure. The smart passive control system using the EMI part composed of permanent magnet and a coil can be much more compact, convenient, and economic than a conventional active/semiactive control system that needs a power supply, a controller and sensors. The shaking table test of a small-scale building model employing the MR fluid damper and the EMI part has been conducted to verify the effectiveness of the smart passive control system. It is demonstrated from the preliminary test that the proposed smart passive control system has the better performance han the passive-off and -on cases and the comparable performance to the passive optimal cases. The additional shaking table test using the smart passive system including the more appropriately designed EMI part is in progress.

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