AN MR DAMPER-BASED CONTROL SYSTEM INTRODUCING ELECTROMAGNETIC INDUCTION PART

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Abstract

This paper investigates the feasibility and efficacy of an MR damper-based control system introducing an electromagnetic induction (EMI) part, for suppressing vibration of building structures subjected to seismic loadings. In the proposed control system, the EMI part composed of a permanent magnet and a coil converts the kinetic energy of the relative motion between a building and an MR fluid damper into the electric energy, which is used for a change in damping characteristics of the MR fluid damper. Since the EMI part can be used as a controller, which determines the command voltage input according to structural responses, as well as a power source, the proposed control system can be much more compact, convenient, and economic than a conventional active/semiactive system that needs a power supply, a controller and sensors. To verify the feasibility and efficacy of the proposed control system, a shaking table test of a small-scale building model employing the MR fluid damper with the EMI part is conducted. The performance of the proposed control system is compared with that of conventional control systems using an MR fluid damper.

Introduction

Recently, considerable attention has paid to semiactive control systems, 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 semiactive control 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 semiactive control devices, because of its mechanical simplicity, high dynamic range, low operating 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). Recently, an MR fluid damper-based semiactive 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*. 2004a).

To reduce the responses of structures with MR fluid dampers, a control system including a power supply, a controller, and sensors is required (Soong 1990; 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 new passively operated 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 proposed control system by comparing its control performance with the normal MR fluid damper-based semiacitve control system.

In this paper, the feasibility of the proposed control system for suppressing vibration of building structures subjected to ground accelerations has been experimentally investigated. To do this, a 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 proposed control system is compared with that of the conventional MR fluid damper-based control systems.

Proposed Control System

A conventional MR fluid damper-based semiactive control system needs sensors, a controller and an external power source to reduce structural responses. Figure 1 shows the schematic diagram of the conventional semiactive 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.

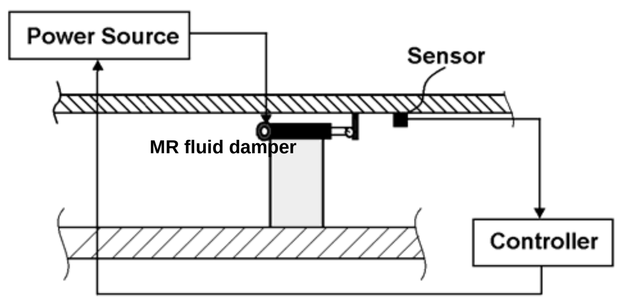


Figure 1. Schematic diagram of an MR fluid damper-based semiactive control system

To overcome previous disadvantages, the adaptive passive control system including the normal MR fluid damper with the EMI part has been developed (Cho *et al*. 2004, 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 (Reitz *et al*. 1993; Marshall and Skitek 1990; Miner 1996) as follows:

$$\varepsilon = -N\frac{d\Phi_B}{dt} = -NB\frac{dA}{dt} \qquad (1)$$

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, B is the magnet field, and A is the area of the cross section. The negative sign in (1) means the direction of the induced current.

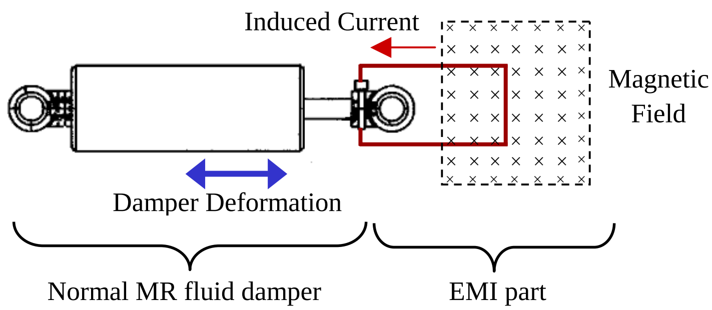


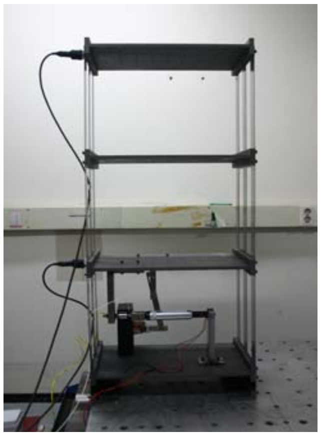
Figure 2. Proposed control system with MR fluid damper and EMI part

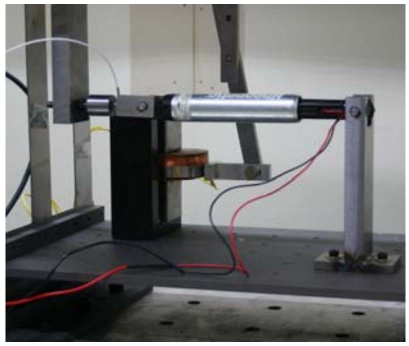
The Faraday law of induction states that the induced *emf* in a closed loop is equal to the negative of the time rate of a change in the magnet flux through the loop. In other words, the relative motion between a coil and a permanent magnet causes a change in the magnet flux, which induces an *emf* in 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 (1). This induced the 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.

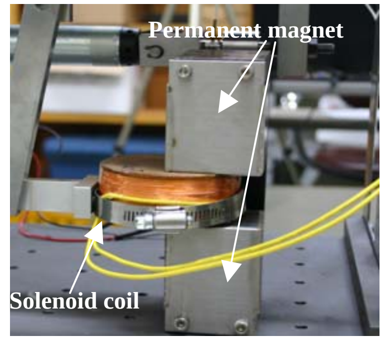
Thus, the MR fluid damper adopting the EMI part can be considered as a passive-type control device that does not require any external power at all. Also, the MR fluid damper with the EMI part is capable of being adjusted to the vibration of structures by itself without any controller, because the output 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 proposed control system. More detailed information on the EMI system can be found in Cho *et al*. (2004, 2005).

Experimental Verification

The feasibility of the proposed control system for seismic protection of building structures is experimentally investigated in this study. To do this, a 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 Figures 3a and 3b. The scaled building has a height of 105 cm and weighs a total of 48.27 kg, which is distributed evenly in each floor. Figure 3c describes the EMI part in detail, which is formed by combining a permanent magnet and a solenoid coil. A shaking table has a testing platform with 110 cm by 100 cm, a maximum payload of 600 kg, a maximum acceleration of ±1.0 g and a maximum velocity of 21 cm/sec. The table is uni-axially driven by a servo-controlled hydraulic actuator. 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 10 V because of heat damage at the current more than 0.5 A. 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.



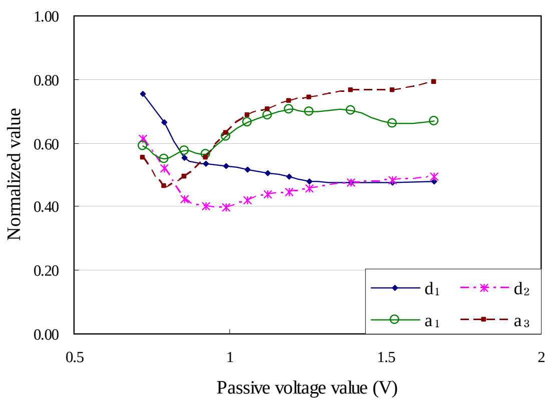


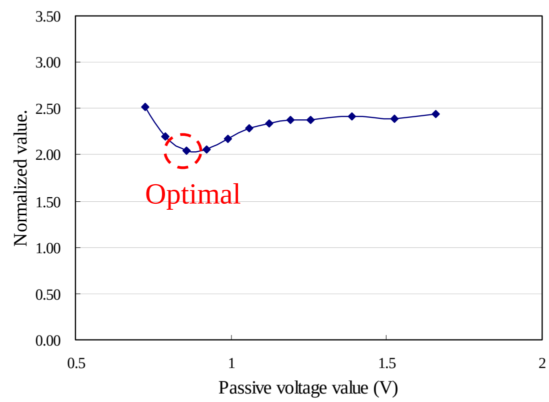


(a) small-scale building model (b) MR fluid damper with EMI part (c) EMI part in detail

Figure 3. Experimental setup for the performance test of the adaptive passive system

Before conducting the test using the adaptive 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 1.6 V. Figures 4a and 4b show the normalized inter-story drifts and accelerations at all floors and the sum of normalized responses, respectively. As seen from Figure 4b, the optimal voltage input to the MR fluid damper is 0.85 V. The performance of passive-off (0 V), passive-on (1.6 V) and adaptive passive cases will be compared to that of this optimal passive case with 0.85 V.

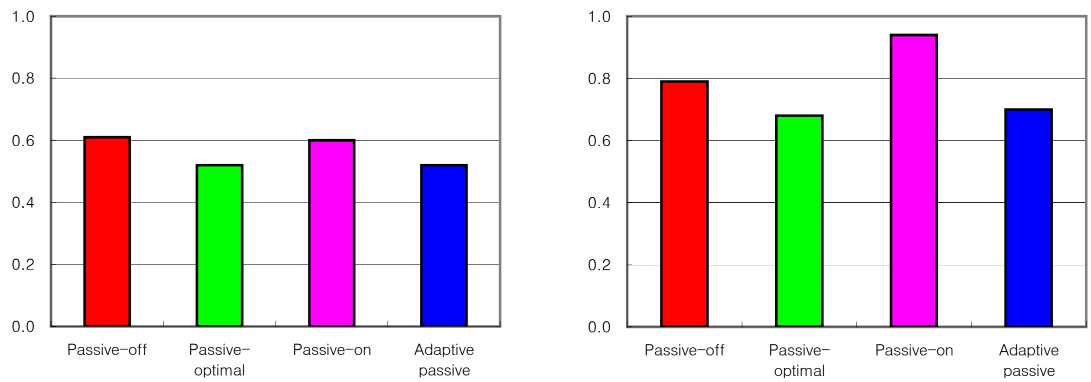




(a) Inter-story drifts and accelerations (b) Sum of responses

Figure 4. Maximum responses in the passive cases normalized by the uncontrolled case

Figures 5a and 5b represent the maximum values of the inter-story drift between 2^{nd} and 3^{rd} floors and the acceleration at 3^{rd} floor normalized by the uncontrolled case, respectively. As seen from the figures, the effectiveness of the proposed control cases and the 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.



(a) Inter-story drift between 2nd and 3rd floors **(b) Acceleration at 3rd floor**

Figure 5. Comparison of maximum responses normalized by the uncontrolled case

As demonstrated in the previous experimental results, the proposed control shows the similar performance to the optimal passive system. However, the main advantage of the proposed system compared with the passive optimal system is clearly shown in Figure 6. In this figure, energy consumption for each control system is normalized with respect to the energy consumed for the passive-on case. While the electric power input to the MR fluid dampers in the proposed control system is not needed due to the EMI part, the passive optimal system requires some amount of the electric power.

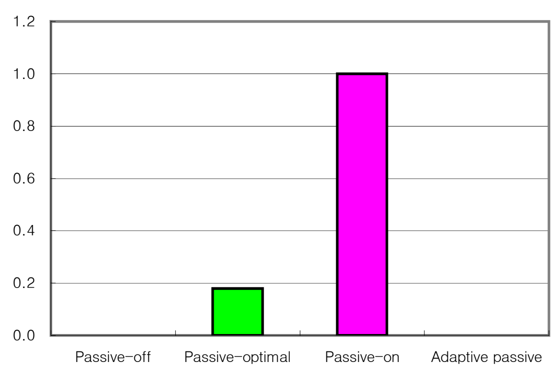


Figure 6. Energy consumption for each control system normalized by the passive-on case

Conclusions

In this study, the newly developed 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 proposed MR fluid damper-based 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. A 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 proposed control system. It is demonstrated from the preliminary test that the proposed control system has the better performance than the passive-off and –on cases and the comparable performance to the passive optimal cases. In addition, the electric power input to the MR fluid dampers in the proposed control system is not needed due to the EMI part, whereas the passive optimal system requires some amount of the electric power. The additional shaking table test using the proposed control system including the MR fluid damper and the more appropriately designed EMI part is in progress.

Acknowledgements

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