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Application of Smart Passive Damping System Using MR Damper to Highway Bridge Structure

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Abstract

Magnetorheological (i.e., MR) dampers are one of the most prospective semiactive control devices for civil engineering applications to earthquake hazard mitigation, because they have many advantages such as small power requirement, reliability, and low price to manufacture. A smart passive system based on an MR damper system without including a power supply, controller, and sensors consists of an MR damper and an electromagnetic induction (i.e., EMI) system that uses a permanent magnet and a coil. The electromotive force induced by movement of a structure can control MR damper effectively without any external power supply and control algorithm. This smart passive control system is implemented to verify the effectiveness for seismic protection of benchmark structural control problem for the seismically excited highway bridge, which is based on the newly constructed 91/5 highway over-crossing in Southern California. The results of the numerical simulations show that the presented control system can be beneficial in reducing seismic responses of benchmark bridge structure.

Keywords: Magnetorheological damper; Smart passive damping

1. Introduction

As the resistibility of civil structures, such as buildings and bridges, becomes important, great development of structural control systems is resulted in.

For recent decades, there has been a growing trend toward utilization of semiactive control systems for seismic response reduction because they combine the reliability associated with passive control systems and the adaptability associated with active control systems. Magnetorheological (MR) dampers are on the most prospective control devices because of their mechanical simplicity, large force capacity, high dynamic rage, low operation power requirement such as a battery, and environmental robustness (Kamath and Wereley, 1997 ; Dyke and Spencer, 1996 ; Spencer *et al.,* 1997a ; Dyke *et al.,* 1998).

To reduce the responses of structures with MR dampers with effect, a control system requires a power supply, controller, and sensors. However, when a lot of control devices are used in large-scale structures such as high-rise buildings and towers, and cable-stayed and suspended bridges, the control system becomes complex: many devices are used and then each device must be connected to individual power supply and controller. Also, many sensors are needed to measure structural responses and determine the control command voltage for each device in the case of using semiactive control algorithms. Therefore, it is difficult to build up and maintain the device based control system. To resolve the above difficulties, a smart passive control system that

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consists of an MR damper and an electromagnetic induction (EMI) part without extra power supply was proposed by Cho *et al.* (2005). The EMI system is worthy of such a power source. They numerically verified the effectiveness of the smart passive system by comparing its control performance with the normal MR damper-based semiactive control system. And Hong *et al.* (2005) verified through for application in a seismically excited building structure preliminarily.

This paper examines the use of a smart passive control system for controlling the benchmark structural control problem for a seismically excited highway bridge (Agrawal *et al.*, 2005).

2. Benchmark highway bridge structure

The benchmark highway bridge structure considered is based on the newly constructed 91/5 highway bridge in southern California, USA. It is a continuous two-span, cast-in-place prestressed concrete box-girder bridge. The Whittier-Ellsinore fault is 11.6 km to the northeast, and the Newport-Inglewood fault zone is 20 km to the southwest of the bridge. The bridge has two spans, each of 58.5 m long spanning a four-lane highway and has two abutments skewed at 33°. The width of the deck along east span is 12.95 m and it is 15 m along west direction. The cross section of the deck consists of three cells. The deck is supported by a 31.4 m long and 6.9 m high prestressed outrigger which rests on two pile groups, each consisting of 49 driven concrete friction piles. The columns are approximately 6.9 m high. Additional details of the bridge are presented in the definition paper (Nagarajaiah *et al.*, 2005). The bridge is isolated using four non-linear lead-rubber bearings on each abutment and one bearing on each bent column at the center in Fig. 1. A total of twenty control devices (ten in each direction) are placed; four locations (two devices per location) between the deck and each abutment and two locations on the center columns (one on each side of the deck).

3. Smart passive control system

The smart passive control system including the normal MR damper with the EMI part has been developed (Cho *et al.*, 2005). 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.

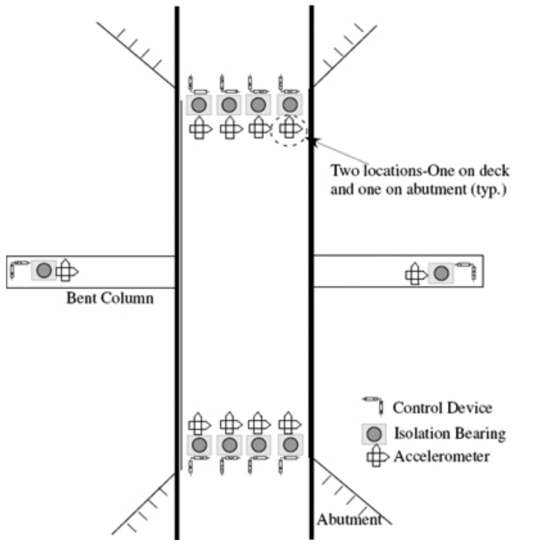

Fig. 1. Locations of control devices and sensors on the bridge.

The EMI control system which is attached to MR damper is a self-powered and self-controlled system. The EMI system that consists of a permanent magnet and a coil changes kinetic energy of reciprocation motion of a coil to the electric energy according to the Faraday's law of induction (Reitz *et al.*, 1993 ; Marshall and Skitek, 1990 ; Miner, 1996) and 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 between the permanent magnet and coil of EMI system make high current to MR damper, which slow relative motions between the permanent magnet and coil make low current. Thus, the smart passive system is able to reduce by itself without any power supply and controller according to external conditions. That is the reason why the MR damper is for a semiactive device.

An initial schematic model of the smart passive system is shown in Fig. 2. The EMI part changes the kinetic energy of the reciprocation motion of the MR damper to the electric energy according to the Faraday's law of induction. The induced current can be estimated by the Faraday's law of induction (Marshall and Skitek, 1990 ; Miner, 1996 ; Reitz *et al.*, 1993) as follows:

$$\varepsilon = -kN\frac{d\Phi_B}{dt} = -kN \cdot B\frac{dA}{dt} = -kN \cdot B \cdot w\frac{dx}{dt} \tag{1}$$

where ε is induced electromotive force (EMF) that

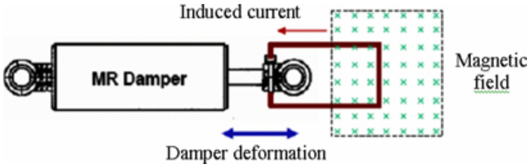

Fig. 2. Schematic model of the MR damper equipped with EMI system.

has unit of volt (V), k is a constant, N is the number of turns of coil, Φ_B is magnetic flux, B is the magnet filed, A is the area of the cross section, and w is the width of magnet. Negative sign in Eq. (1) is the direction of induced current.

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. The relative motion between a coil and a permanent magnet causes a change in the magnet flux, which induces an EMF in the coil. Thus, the faster MR damper moves, the higher EMF is induced and the more slowly MR damper moves, the lower EMF is induced. And 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 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.

4. Numerical simulation results

The highway bridge is modeled as a multi-degree of freedom (MDOF) system. However, the deck system is rigid and the deck isolated with the LRB isolation system will essentially behave like a SDOF. This SDOF assumption is applied to the isolated rigid deck in both x and y directions, resulting in two SDOF systems, one in the x direction, and another in y direction.

MR dampers are used a control devices at the locations shown in Fig. 1. The parameters of the MR damper are described in the sample control design of the benchmark definition paper (Agrawal *et al.*, 2005). The MR damper has a maximum force level of approximately ± 1000kN, and the maximum voltage we can apply is 10 Volts.

Six earthquake ground motions are selected for the highway bridge. These earthquakes are: North Palm Springs (1986), TCU084 component of Chi-Chi earthquake, Taiwan (1999), El Centro component of 1940 Imperial Valley earthquake, Rinaldi component of Northridge (1994) earthquake, Bolu component of Duzce, Turkey (1999) earthquake and Nishi-Akashi component of Kobe (1995) earthquakes.

To systematically evaluate the control performance, a set of 21 normalized evaluation criteria defined in the benchmark problem statement as follows (Agrawal *et al.*, 2005): peak base shear force (J_1), peak overturning moment (J_2), peak displacement at midspan (J_3), peak acceleration at midsapn (J_4), peak deformation of bearings (J_5), peak curvature at bent column (J_6), peak dissipated energy of curvature at bent column (J_7), the number of plastic connections (J_8), normed base shear force (J_9), normed overturning moment (J_{10}), normed displacement at the midspan (J_{11}), normed acceleration at midspan (J_{12}), normed deformation of bearings (J_{13}), normed curvature at bent column (J_{14}), peak control force (J_{15}), peak stroke of the control devices (J_{16}), peak instantaneous power (J_{17}), peak total power (J_{18}), number of control devices (J_{19}), number of sensors (J_{20}), and dimension of the discrete state vector (J_{21}).

5. Optimal passive control

Before simulation using the smart passive system, the optimal passive control case is investigated by using the conventional MR damper-based control system. In this case, MR damper is only passively operated. To change damping characteristics of the MR damper, the voltage input to the damper is changed from 0 V to 10 V.

Figure 3 shows the average of the evaluation criteria summations from J_1 to J_{16} for six earthquakes. As shown in the figure, a constant voltage of 5 V indicates the best performance; hence the constant value of 5 V can be optimal passive control.

6. Smart passive system

The induced EMF, V, is give by the Faraday's law of induction in Eq. (1). Thus, the amount of EMF can be regulated by the turns of the coil with a fixed capacity of the permanent magnet. In this study, the capacity of the permanent magnet is selected to 0.45 T (tesla), and the width of used magnets is 5 cm. The appropriate number of coils turns should be determined for better performance of the smart passive system.

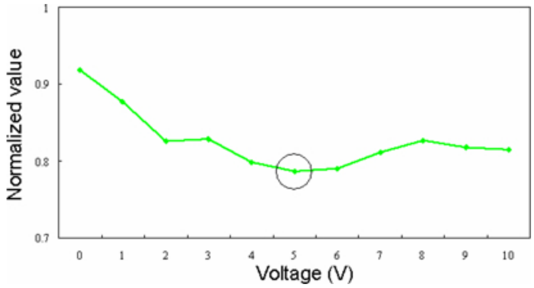

Fig. 3. The envelop curve for optimal passive control.

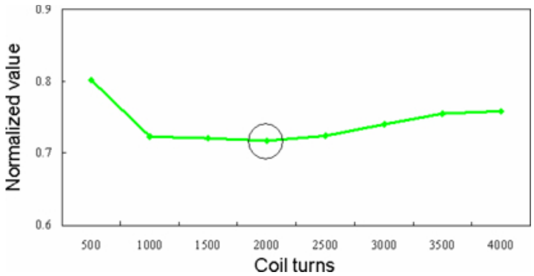

Fig. 4. The envelop curve for design of smart passive system.

Figure 4 displays average of sum of evaluation criteria from J_1 to J_{16}. From this figure, we can determine the optimal coil turns, N = 2000, which is the minimum point of the envelope.

Figure 5 represents the average values of each evaluation criteria for all earthquakes of optimal passive control, semiactive Lyapunov [(i.e., sample controller given by benchmark problem definition (Agrawal *et al.*, 2005)], and smart passive system. As seen the figure, the effectiveness of the smart passive and semiactive Lyapunov cases is clearly demonstrated. In addition, the smart passive system has the significant advantage that it requires no power supply during controlling structures with similar function to other control systems. Thus, the smart passive system was able to reduce efficiently by itself without any power supply and controller according to external conditions.

7. Conclusions

A smart passive system consisting for the MR damper and the electromagnetic induction (EMI) part are presented for seismic isolated highway bridge benchmark problem. According to the Faraday's law of induction, the EMI system generates induced voltages that can supply electricity and control commands to the MR damper, replacing a normal control system such as a power supply, a controller,

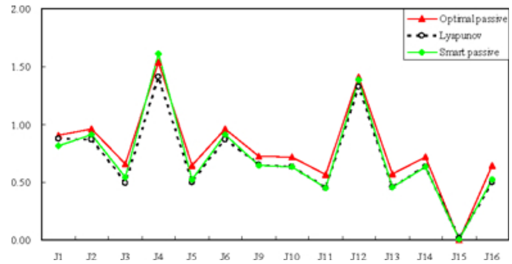

Fig. 5. Numerical results.

and sensors. The performances of the smart passive system are better than optimal passive, and comparable to semiactive Lyapunov control.

Acknowledgements

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References

Agrawal, A. K., Tan, P., Nagarajaiah, S. and Zhang, J., 2005, "Benchmark Structural Control Problem for a Seismically Excited Highway Bridge, Part I: Problem Definition," *http://www-ce.engr.ccny.cuny.edu/People/Agrawal.*

Cho, S. W., Jung, H. J. and Lee, I. W., 2005, "Smart Passive System Based on Magnetorheological Damper," *Smart Materials and Structures*, Vol. 14, pp. 707~714.

Dyke, S. J., Spencer Jr. and B. F., 1996, "Seismic Response Control Using Multiple MR Dampers," *2nd International Workshop on Structural Control*, Hong Kong, pp. 163~173.

Dyke, S. J., Spencer Jr., B. F., Sain, M. K. and Carlson, J. D., 1998, "An Experimental Study of MR Dampers for Seismic Protection," *Smart Materials and Structures*, Vol. 7, pp. 693~703.

Hong, J. H., Choi, K. M., Lee, J. H., Oh, J. W. and Lee, I. W., 2005, "Experimental Study on Smart Passive System Based on MR Damper," *The 18th KKCNN*

Symposium on Civil Engineering, Kaohsiung, pp. 701~708.

Kamath, G. M. and Wereley, N. M., 1997, "A Nonlinear Viscoelastic-Plastic Model for Electrorheological Fluids," *Smart Materials and Structures*, Vol. 6, pp. 351~359.

Marshall, S. V. and Skitek, G. G., 1999, *Electromagnetic Concepts and Applications*, Englewood Cliffs, NJ: Prentice-Hall.

Miner, G. F., 1996, *Lines and Electromagnetic Fields for Engineers*, Oxford: Oxford University Press.

Nagarajaiah, S., Narasimhan, S., Agrawal, A. K. and Tan, P., 2005, "Semiactive Lyapunov Controller for Phase II Seismic Isolated Highway Bridge Benchmark," *http:// www-ce.engr.ccny.cuny.edu/People/Agrawal*.

Reitz, J. R., Milford, F. J. and Christy, R. W., 1993, *Foundations of Electromagnetic Theory*, Reading, MA: Addison-Wesley.

Spencer, Jr., B. F., Dyke, S. J., Sain, M. F. and Carlson, J. D., 1997a, "Phenomenological Model of a Magnetorheological Damper," *ASCE Journal of Engineering Mechanics*, Vol. 123, pp. 230~238.