Journal of Mechanical Science and Technology 21 (2007) 875~880

Journal of
Mechanical
Science and
Technology

Vibration Control of a Cable-Stayed Bridge Using Electromagnetic Induction Based Sensor Integrated MR Dampers

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(Manuscript Received November 16, 2006; Revised January 8, 2007)

Abstract

This paper presents a novel electromagnetic induction (EMI) system integrated in magnetorheological (MR) dampers: The added EMI system converts reciprocal motions of MR damper into electiral energy (electromotive force or emf) according to the Faraday's law of electromagnetic induction. Maximum energy dissipation algorithm (MEDA) is employed to regulate the MR dampers because it strives to simplify a complex design process by employing the Lyapunov's direct approach. The emf signal, produced from the EMI, provides the necessary measurement information (i.e., realtive velocity across the damper) for the MEDA controller. Thus, the EMI acts as a sensor in the proposed MR-EMI system. In order to evaluate the performance and robustness of the MR-EMI sensor system with the MEDA control, this study performed an extensive simulation study using the first generation benchmark cable-stayed bridge. Moreover, it compared the performance and the robustness of proposed system with those of Clipped-Optimal Control (COC) and Sliding Mode Control (SMC), which were previously studied for the benchmark cable-stayed bridge. The results show that the MR-EMI system reduced the vibrations of the bridge structure more than those of COC and SMC and show more robust performance than that of SMC. These results suggest that EMIs can be used cost-effective sensing devices for MR damper control systems without compromising the performance of them.

Keywords: Electromagnetic induction; Magnetorheological damper; Maximum energy dissipation algorithm

1. Introduction

Magnetorheological (MR) dampers are one type of semi-active control devices, which use MR fluids to provide controllable damping forces. Since Spencer first introduced MR dampers to civil engineering applications in the mid-1990s, MR dampers have received considerable attention because of their mechanical simplicity, high dynamic force range, and low operating robustness (Dyke et al., 1998). A control system based on MR damper should include power supply, controller, and sensors, which may cause maintenance and cost problems, especially for large-scale civil engineering structures such as a cable-stayed bridge.

This paper presents a novel EMI sensor system integrated in MR dampers. An electromagnetic induction (EMI) system is added to an MR damper and converts reciprocal motions of the MR damper into electrical energy according to the Faraday's law of electromagnetic induction. This converted electrical energy or electromotive force (emf) signal can be used as relative velocities across the damper. Re-

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cently, an EMI system was adopted to control an engine mount of the vehicle (Korean patent 2000-004066), and to control an electrorheological (ER) damper (Japan patent 2-145337). Moreover, S.W. Cho and I.W. Lee proposed a smart passive system for civil structures (Korean patent 2002-0061823), which used EMIs as an alternative power source for MR dampers.

In this study, maximum energy dissipation algorithm (MEDA) is employed to regulate MR dampers. MEDA strives to simplify a complex design process by employing the Lyapunov's direct approach to stability analysis in the design of a feedback controller (Brogan, 1991). We will use the EMI emf signal to provide the necessary measurement information for the MEDA controller.

In order to evaluate the performance and robustness of the MR-EMI sensor system with the MEDA control, this study will perform an extensive simulation study using the benchmark structures: The first generation benchmark cable-stayed bridge model provided by Dyke et al. (2003). Benchmark structural control problems allow researchers to apply various algorithms, devices, and sensors to a specified problem and make direct comparisons of the results in terms of a specified set of performance objectives.

2. Electromagnetic Induction (EMI) system

Figure 1 shows an MR damper with an EMI system that consists of a permanent magnet and coil 1. The EMI system changes kinetic energy of reciprocation motion of the MR damper to electric energy according to the Faraday's law of induction (Reitz et al., 1993). The induced current in coil 1 can be estimated by the Faraday's law of induction in Eq. (1).

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

where ε is induced electromotive force (emf) that has

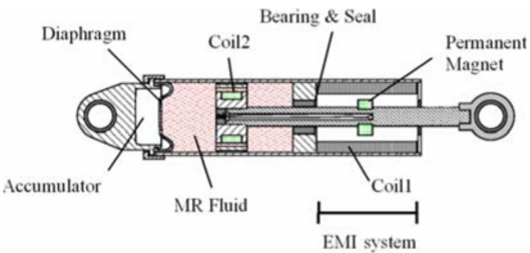

Fig. 1. An EMI system attached MR damper.

unit of volt (V); N is number of turns of coil, Φ_B is magnetic flux; A is area of cross section; and B is magnetic field. Negative sign in Eq. (1) is the direction of induced current.

The 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. This induced emf is basically an alternating current, which can indicate the direction of the piston. Also, it is proportional to the relative velocity across the MR damper because the time rate of change of magnetic flux is identical to relative velocity. Because of this, the EMI system can be used as a sensor for those control methods that uses the relative velocity information to implement them. Maximum energy dissipation algorithm is one of such control laws, so it is used in this study.

3. Maximum Energy Dissipation Algorithm (MEDA)

A seismically excited structure controlled with n MR dampers can be modeled as;

$$M\ddot{x} + C\dot{x} + Kx = \Lambda f - M\Gamma \ddot{x}_g \tag{2}$$

where M, C, and K = mass, damping, and stiffness matrices, respectively; x is vector of the relative displacements of the floors of the structure; $\ddot{x}_g$ = one dimensional ground acceleration; $f = [f_1, f_2, \ldots, f_n]^T$ = vector of measured control forces generated by n MR dampers; Γ = column vector of ones; and Λ = matrix determined by the placement of MR dampers in the structure. This equation can be written in state-space form as

$$\dot{z} = Az + Bf + E\ddot{x}_g \tag{3}$$

$$y = Cz + Df + v \tag{4}$$

where z = state vector; y = vector of measured outputs; and v = measurement noise vector.

Numerous control algorithms have been adopted for semiactive systems including MR dampers. While other control algorithms have their own benefits, the maximum energy dissipation algorithm (MEDA) can offer simplicity of control design by employing the Lyapunov's direct approach. Lyapunov's direct approach requires the use of a Lyapunov function, denoted $V(x)$, which must be a positive definite function of the states of the system x. Jansen and Dyke (2000) instead considered a Lyapunov function that represents the relative vibratory energy in the structure as in

$$V = \frac{1}{2}x^T Kx + \frac{1}{2}\dot{x}^T M\dot{x} \quad (5)$$

According to Lyapunov stability theory, if the rate of change of the Lyapunov function $\dot{V}(x)$ is negative semidefinite, the origin is stable in the sense of Lyapunov. Thus, in developing the control law based on Lyapunov stability theory, the goal is to choose control inputs for each device that will result in making the rate of change of the Lyapunov function as negative as possible. Using Eq. (5), the rate of change of the Lyapunov function is then

$$\dot{V} = x^T K\dot{x} + \dot{x}^T M(-C\dot{x} - Kx - M\Gamma\ddot{x}_g + \Lambda f) \quad (6)$$

In this expression, the only way to directly effect $\dot{V}$ is through the last term containing the force vector f. To control this term and make $\dot{V}$ as large and negative as possible, the following control law is obtained

$$v_i = V_{\max} H(-\dot{x}\Lambda_i f_i) \quad (7)$$

where Λ_i = i-th column of the Λ matrix; f_i = i-th column of the f matrix; and $H(\cdot)$ = Heaviside step function. Notice that once the location of MR dampers are chosen, the control law in Eq. (7) is automatically determined by using only local measurements: velocities and control forces. Besides, MEDA is, similar to Bang-Bang controller, based on the sign of the measured control force and the states of the system not the magnitude of the measured data. The sign term of, $-\dot{x}\Lambda_i$, can be determined by the emf induced from the EMI system and f_i can be obtained from the load cell. Thus, in absence of the EMI system, additional sensors are necessary to measure the velocity of the damper. This is a key benefit of using MEDA with an EMI system.

4. Benchmark cable-stayed bridge

The cable-stayed bridge used for this benchmark study is the Bill Emerson Memorial Bridge (Dyke et al., 2003). As shown in Fig. 2. the bridge is composed of two towers, 128 cables, and 12 additional piers in the approach bridge from the Illinois side.

Through a series of numerical simulations of benchmark problem, the results are compared with those of other control algorithms: Clipped-optimal controller (COC; Yoshida and Dyke, 2004) and sliding mode controller (SMC; Moon et al., 2003). Also, MR damper model is came from Moon et al. (2003). Clipped-optimal controller was suggested and experimentally examined by Dyke et al. (1996). The clipped-optimal control approach is to design a linear optimal controller that calculates desired control forces based on the measured structural responses and the measured control force applied to the structure. A force feedback loop is incorporated to induce the MR damper to generate approximately the desired optimal control force. On the other hand, sliding mode controller was developed specifically for robust control of uncertain nonlinear systems. The fundamental idea of SMC is to design a controller to drive the state trajectory onto a sliding surface, where the motion is stable. Thus, SMC is known as a robust controller.

5. Controller performance analysis

Table 1 shows the values for the evaluation criteria (Moon et al., 2003) of the benchmark cable-stayed bridge under various earthquakes: El Centro, Mexico, and Gebze earthquakes. Each controller employs 24 MR dampers between the deck and abutment and the deck and tower of the bridge, all oriented to apply forces longitudinally. Four devices are located between each of the following pairs of nodes on bent 1 and pier 3; and, two devices are located between

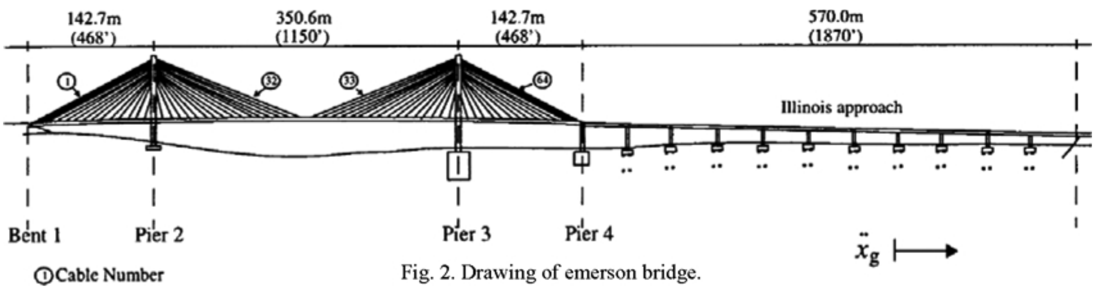

Fig. 2. Drawing of emerson bridge.

Table 1. Comparisons of the Evaluation Crit+eria for Benchmark Cable-Stayed Bridge.

	J_1, Peak base shear			J_2, Peak shear at deck level		
Controller	El Centro	Mexico	Gebze	El Centro	Mexico	Gebze
COC	0.391	0.469	0.415	1.084	1.179	1.376
SMC	0.397	0.453	0.392	1.090	1.068	1.146
MEDA	0.337	0.659	0.459	1.102	1.183	1.444
	J_3, Peak overturning moment			J_4, Peak moment at deck level		
Controller	El Centro	Mexico	Gebze	El Centro	Mexico	Gebze
COC	0.267	0.466	0.395	0.537	0.472	0.953
SMC	0.300	0.488	0.382	0.557	0.408	1.053
MEDA	0.245	0.481	0.365	0.429	0.383	0.708
	J_5, Peak deviation of cable tension			J_6, Peak deck displacement		
Controller	El Centro	Mexico	Gebze	El Centro	Mexico	Gebze
COC	0.189	0.060	0.142	0.933	1.282	2.519
SMC	0.205	0.056	0.159	0.880	1.578	2.941
MEDA	0.200	0.064	0.149	0.700	0.674	1.419
	J_7, Normed base shear			J_8, Normed shear at deck level		
Controller	El Centro	Mexico	Gebze	El Centro	Mexico	Gebze
COC	0.234	0.440	0.328	0.975	1.147	1.331
SMC	0.217	0.372	0.286	0.903	0.902	1.271
MEDA	0.233	0.451	0.316	0.815	0.970	1.157
	J_9, Normed overturning moment			J_{10}, Normed moment at deck level		
Controller	El Centro	Mexico	Gebze	El Centro	Mexico	Gebze
COC	0.300	0.393	0.391	0.624	0.656	1.194
SMC	0.193	0.315	0.380	0.577	0.720	1.487
MEDA	0.228	0.433	0.364	0.557	0.502	1.352

	J_{11},Norm.deviation of cable tension		
Controller	El Centro	Mexico	Gebze
COC	0.020	0.007	0.012
SMC	0.018	0.006	0.012
MEDA	0.019	0.010	0.010

Table 2. Evaluation Criteria for ±7% Stiffness perturbed System under El Centro.

Evaluation Criteria	SMC (Moon et al. 2003)			MEDA		
	$\varepsilon = 0$	$\varepsilon = -7\%$	$\varepsilon = +7\%$	$\varepsilon = 0$	$\varepsilon = -7\%$	$\varepsilon = +7\%$
J_1,Peak base shear	0.394	0.432	0.353	0.331	0.371	0.355
J_2,Peak shear at deck level	1.130	1.323	1.005	1.108	1.2356	1.063
J_3,Peak overturning moment	0.296	0.335	0.256	0.255	0.263	0.256
J_4,Peak moment at deck level	0.560	0.540	0.527	0.464	0.446	0.403
J_5,Peak deviation of cable tension	0.213	0.224	0.197	0.185	0.212	0.205
J_6,Peak deck displacement	0.870	0.862	0.793	0.709	0.674	0.690
J_7,Normed base shear	0.218	0.235	0.207	0.234	0.222	0.213
J_8,Normed shear at deck	0.887	0.901	0.880	0.883	0.859	0.834
J_9,Normed overturning moment	0.189	0.198	0.180	0.233	0.209	0.198
J_{10},Normed moment at deck level	0.551	0.556	0.515	0.552	0.518	0.460
J_{11},Normed deviation of cable tension	0.016	0.017	0.016	0.020	0.019	0.017

each of the following pairs of nodes on piers 2 and 4. Note that each controller is able to achieve a significant reduction in the base shear force when compared with the uncontrolled system; the base shears in MEDA are reduced to 34 ~ 66% levels in the peak value (J_1) and to 23 ~ 45% levels in the normed values (J_7) for the three earthquake excitations. Overturning moments are reduced to 25 ~ 48% levels in the peak values (J_3) and to 23 ~ 43% (J_9). It is clear that most of structural responses generated by three earthquakes are controlled well. Furthermore, the numerical results show that the proposed system performs slightly better than two other controllers.

6. Controller robustness analysis

Even though the designed controller were confirmed to have good performance in the numerical simulation, it dose not necessarily guarantee good performance in the actual system, because dynamic characteristics of the real structure may not be identical to those of the evaluation model and can be changed after construction. Therefore, the controller robustness was examined with respect to uncertainties in stiffness. The stiffness matrix was perturbed by a factor ε, and the resulting bridge model was simulated using the controller for the nominal system. The perturbed stiffness was calculated as

$$K_{pert} = K(1+\varepsilon) \tag{8}$$

where K = nominal stiffness of the bridge; ε = perturbation parameter; and K_{pert} = perturbed stiffness. Perturbation of 7% was considered. The configuration of MR dampers are followings; Four devices are located between each of the following pairs of nodes on bent 1 and pier 4; and, two devices are located between each of the following pairs of nodes on piers 2 and 3.

Table 2 shows the evaluation criteria for ±7% stiffness perturbed system under El Centro earthquake. Robustness of MEDA is compared to that of SMC because SMC is known as robust controller (Moon et al, 2003) and the nominal performance is listed for comparison purpose. MEDA shows stable performances for ±7% perturbed system. MEDA even shows more robust performance than SMC except the peak shear J_2, the normed overturning moment J_9, and the normed deviation of cable tension J_{11}.

7. Conclusions

In this paper, a relative velocity sensor was integrated into an MR damper by using electromagnetic sensing technique: an EMI system was added to MR damper and MEDA using local measurements at damper location was implemented. For the benchmark cable-stayed bridge, the numerical results showed that the proposed system can reduce the vibration of the seismically excited cable-stayed bridge structures effectively. A comparison of results with two other controllers indicated slightly better performance than other two controllers: clipped optimal and sliding mode controllers. Also, for the ±7% perturbed system, it showed more robust performance than SMC in the most evaluation criteria. In summary, the MR damper with EMI system showed promising benefits of convenient implementtation with competitive and robust performances for the benchmark cable-stayed bridges.

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