SEISMIC PROTECTION OF CABLE-STAYED BRIDGES
USING MAGNETORHEOLOGICAL DAMPERS

Hyung-Jo Jung¹, Billie F. Spencer, Jr.², and In-Won Lee³

ABSTRACT

This paper examines the first generation benchmark problem for a seismically excited cable-stayed bridge, and proposes a new semi-active control strategy focusing on inclusion of effects of control-structure interaction. This benchmark problem provides a three-dimensional linearized evaluation bridge model as a testbed structure. Magnetorheological (MR) fluid dampers, which belong to the class of controllable fluid dampers, are the supplemental damping devices proposed for this study, and a clipped-optimal control algorithm, shown to perform well in previous studies involving MR fluid dampers, is employed. The dynamic model for MR fluid dampers is considered as a modified Bouc-Wen model. Because the MR fluid damper is a controllable energy-dissipation device that cannot add mechanical energy to the structural system, the proposed control strategy is fail-safe in the bounded-input, bounded-output stability of the controlled structure. Numerical simulation results show that the performance of the proposed semi-active control strategy using MR fluid dampers is quite effective.

Introduction

In the field of civil engineering, many control algorithms and devices have been proposed over the last two decades for the purpose of protecting structures against natural hazards such as severe earthquakes and strong winds. However, because standard structures are generally not considered, direct comparison of different control strategies has proven to be a challenging task. This problem can be addressed by employing testbed structures, that is, by developing benchmark problems. To compare results of various control strategies such as passive, active, semi-active or a combinations thereof and to direct future research efforts toward the most promising structural control strategies, benchmark control problems have been initiated and developed by the American Society of Civil Engineers Committee on Structural Control and the International Association of Structural Control (Spencer et al. 1997a, 1998a, b; ASCE 1997; EESD 1998; IASC 1998; Ohtori et al. 2000; http://www.nd.edu/~quake/nlbench.html). Until recently, however, all of benchmark problems considered have focused on the control of buildings (Spencer et al. 1997a; EESD 1998; IASC 1998; Ohtori et al. 2000).

Because there are a growing number of cable-stayed bridges throughout the world, more

¹Postdoc. Res. Assoc., Dept. of Civil Engrg., Korea Adv. Inst. of Sci. and Tech., Daejeon 305-701, Korea
²Leo Linbeck Professor, Dept. of Civil Engrg. and Geo. Sci., Univ. of Notre Dame, Notre Dame, IN 46545
³Professor, Dept. of Civil Engrg., Korea Adv. Inst. of Sci. and Tech., Daejeon 305-701, Korea
research on the seismic protection of such structures is needed. These structures are very flexible, presenting unique and challenging problems. To effectively study the seismic response control of cable-stayed bridges, a benchmark problem for seismic protection has been developed by Dyke et al. (2000). This first generation benchmark control problem for seismically excited cable-stayed bridges considers a bridge currently under construction in Cape Girardeau, Missouri, USA, which will be completed in 2003. Based on detailed drawings of this cable-stayed bridge, a three-dimensional linearized evaluation model has been developed to represent the complex behavior of the bridge. For the control design problem, evaluation criteria have been provided.

Semi-active control strategies not only offer the reliability of passive control devices but also maintain the versatility and adaptability of fully active control system. Magnetorheological (MR) fluid dampers are a new class of semi-active control devices that utilize MR fluids to provide controllable damping forces. Because of their mechanical simplicity, high dynamic range, low power requirements, large force capacity and robustness, MR fluid dampers are one of the most promising devices for structural vibration control. Also, these devices overcome many of the expenses and technical difficulties associated with semi-active devices previously considered. Recent studies indicate that for certain applications, MR fluid dampers can achieve the majority of the performance of fully active systems (Dyke et al. 1996, Jansen and Dyke 2000, Johnson et al. 2001).

Recently, some researches have been performed based on the first generation benchmark control problem provided by Dyke et al. (2000). Jung et al. (2001) proposed a semi-active control strategy for seismic protection of the benchmark cable-stayed bridge. They accomplished an extensive parametric study to obtain the optimal weighting parameters for the control system design, and incorporated a Kanai-Tajimi shaping filter into the model of the structure to better inform the controller about the frequency content of the ground motion. Moon et al. (2001) performed the application of MR fluid dampers to control of the benchmark cable-stayed bridge. They considered the dynamics of an MR fluid damper as a simple Bouc-Wen model, and also addressed the effect of varying control device configurations.

The focus of this paper is to use the benchmark cable-stayed bridge model provided by Dyke et al. (2000) to investigate the effectiveness of semi-active control strategies using MR fluid dampers for the seismic protection of such structures. In this study, the dynamic model for MR dampers is considered as a modified Bouc-Wen model (Spencer et al. 1997b). Also, a clipped-optimal control algorithm, shown to perform well in previous studies involving MR fluid dampers (Dyke et al. 1996; Dyke and Spencer 1997), is employed. Since the MR fluid damper is an energy-dissipative device that cannot add mechanical energy to the structural system, the proposed control strategy is fail-safe, in that it guarantees the bounded-input, bounded-output stability of the controlled structure. Following an overview of the benchmark problem statement, including discussion of the benchmark bridge model and evaluation criteria, a seismic control design using MR fluid dampers is proposed. Numerical simulation results are then presented to demonstrate the effectiveness of the proposed control strategy.
Benchmark Problem Statement

Benchmark Bridge Model

This benchmark problem considers the cable-stayed bridge shown in Figure 1, which is scheduled for completion in Cape Girardeau, Missouri, USA in 2003. Because bearings at pier 4 do not restrict longitudinal motion and rotation about the longitudinal axis of the bridge, the Illinois approach has a negligible effect on the dynamics of the cable-stayed portion of the bridge. In this benchmark study, therefore, only the cable-stayed portion of the bridge is considered. Based on detailed drawings of the bridge, a three-dimensional linearized evaluation model has been developed to represent the complex behavior of the full-scale benchmark bridge. The stiffness matrices used in this linear model are those of the structure determined through a nonlinear static analysis corresponding to the deformed state of the bridge with dead loads. Because this bridge is assumed to be attached to bedrock, the effect of the soil-structure interaction has been neglected. A one-dimensional ground acceleration is applied in the longitudinal direction, which is considered to be the most destructive in cable-stayed bridges.

Figure 1. Drawing of the Cape Girardeau Bridge

The bridge model resulting from the finite element formulation, which is modeled by beam elements, cable elements, and rigid links, has a large number of degrees-of-freedom and high frequency dynamics. Application of static condensation to the full model of the bridge as a model reduction scheme resulted in a 419 DOF reduced-order model, designated the evaluation model. Each mode of this evaluation model has 3% of critical damping, which is consistent with assumptions made during the design of bridge.

Evaluation Criteria

Eighteen criteria have been defined (Dyke et al. 2000) to evaluate the capabilities of each proposed control strategy. Three historical earthquake records are considered, the 1940 El Centro NS, the 1985 Mexico City and the 1999 Gebze NS. The first six evaluation criteria ($J_1 - J_6$) consider the ability of the controller to reduce peak responses. $J_1$ and $J_2$ are non-dimensionalized measures of the shear forces at the tower base and the deck level in the towers, respectively. $J_3$ and $J_4$ are non-dimensionalized measures of the moments in the towers at the same locations. $J_5$ is a non-dimensionalized measure of the deviation of the tension in the stay cables from the nominal pretension. $J_6$ is a measure of the peak deck displacement at piers 1 and 4.
The second five evaluation criteria \((J_7 - J_{11})\) consider normed (i.e., \(rms\)) responses over the entire simulation time. \(J_7\) and \(J_8\) are non-dimensionalized measures of the normed values of the base shear and the shear at the deck level in the towers, respectively. \(J_9\) and \(J_{10}\) are non-dimensionalized measures of the overturning moment and the moment at the deck level in the towers. \(J_{11}\) is a non-dimensionalized measure of the normed value of the deviation of the tension in the stay cables.

The last seven evaluation criteria \((J_{12} - J_{18})\) consider the requirements of each control system itself. \(J_{12}\) deals with the maximum force generated by the control devices. \(J_{13}\) is based on the maximum stroke of the control devices. \(J_{14}\) is a non-dimensionalized measure of the maximum instantaneous power required to control the bridge. \(J_{15}\) is a non-dimensionalized measure of the total power required to control the bridge. \(J_{16}\) is a measure of the total number of control devices, \(J_{17}\) is a measure of the total number of sensors, and \(J_{18}\) is a measure of the resources required to implement the control algorithm.

**Seismic Control System Using MR Fluid Dampers**

In this section, a description of the proposed control system using MR fluid dampers is provided. Accelerometers, displacement transducers and force transducers are employed as sensors. MR fluid dampers are used as control devices. A clipped-optimal control algorithm, which has been successfully applied with MR fluid dampers in previous studies (Dyke et al. 1996; Dyke and Spencer 1997), is employed to determine the control action.

**Sensors**

Five accelerometers and four displacement transducers are used for feedback in the control algorithm. Four accelerometers are located on top of the tower legs, and one is located on the deck at mid span. Two displacement sensors are placed between the deck and pier 2, and the other two are placed between the deck and pier 3. Because the clipped-optimal control algorithm considered herein requires measurement of the damper control forces applied to the structure, 24 force transducers are installed. All sensors employed in this study are assumed to be ideal, having a constant magnitude and phase (Dyke et al. 2000), and the sensitivity of accelerometers \((G_a)\), the displacement transducers \((G_d)\) and the force transducers \((G_f)\) are 7/9.81 V/(m/sec²), 30 V/m and 0.01 V/kN, respectively. Thus, sensors can be modeled as

\[
y_s = \begin{bmatrix} G_a I_{5 \times 5} & 0 & 0 \\ 0 & G_d I_{4 \times 4} & 0 \\ 0 & 0 & G_f I_{8 \times 8} \end{bmatrix} y_m + v
\]  

where \(y_s\) is a vector of the measured responses, including noise, in Volts, \(y_m\) is a vector of the noise-free responses in physical units, and \(v\) is the measurement noise, which has an \(rms\) value of 0.003 V (Dyke et al. 2000).
Control Devices

A total of 24 MR fluid dampers are considered as control devices. Four between the deck and pier 2, eight between the deck and pier 3, eight between the deck and bent 1, and four between the deck and pier 4 are placed. To exactly predict the behavior of the controlled structure, an appropriate modeling of MR fluid dampers is very important. Herein, a modified Bouc-Wen model proposed by Spencer et al. (1997b) is considered as a dynamic model of the MR fluid damper, as shown in Figure 2. The model has been shown to accurately predict the behavior of the prototype MR damper over a broad range of inputs (Spencer et al. 1997b). The equation governing the force predicted by this model is

\[ F = \alpha \varepsilon + c_0 (\dot{x} - \dot{y}) + k_0 (x - y) + k_1 (x - x_0) = c_1 \dot{y} + k_1 (x - x_0) \]  

(2)

where \( x \) is the displacement of the damper, and the evolutionary variable \( z \) is governed by

\[ z = -\gamma |\dot{x} - \dot{y}| |\dot{z}|^{n-1} - \beta (\dot{x} - \dot{y}) |\dot{z}|^n + A(\dot{x} - \dot{y}) , \]  

(3)

and

\[ \dot{y} = \frac{1}{c_0 + c_1} \{ \alpha \varepsilon + c_0 \dot{x} + k_0 (x - y) \} . \]  

(4)

Figure 2. Dynamic Model of the MR Damper by Spencer et al. (1997b)

To determine a dynamic model that is valid for fluctuating magnetic fields, the functional dependence of the parameters on the applied voltage must be determined (Spencer et al. 1997b). In this model, therefore, the following relations are considered:

\[ \alpha = \alpha_a + \alpha_b u , \quad c_0 = c_{0a} + c_{0b} u , \quad \text{and} \quad c_1 = c_{1a} + c_{1b} u . \]  

(5)

In addition, the dynamics involved in the MR fluid reaching rheological equilibrium are accounted for through the first order filter

\[ \dot{u} = -\eta (u - v) \]  

(6)

where \( v \) is the command voltage applied to the current driver.

A constrained nonlinear optimization was used to obtain the parameters (Spencer et al.
The optimization was performed using the sequential quadratic programming algorithm available in MATLAB®. Table 1 provides the optimized parameters for the three dynamic models that were determined to best fit the data based on the experimental results of the 20-ton MR fluid damper (Yang et al. 2001).

The equations describing the forces produced by the dampers are

\[
\mathbf{f} = \mathbf{K}_f [f_1 f_2 \cdots f_n]^T = \begin{bmatrix} 2I_{2 \times 2} & 0 & 0 \\ 0 & 4I_{4 \times 4} & 0 \\ 0 & 0 & 2I_{2 \times 2} \end{bmatrix} [f_1 f_2 \cdots f_n]^T
\]

\[
y_f = [f_1 f_2 \cdots f_n]^T
\]

where \( \mathbf{f} \) is the force output of devices applied to the structure, \( y_f \) is the force output of devices used for feedback in the control algorithm, and \( \mathbf{K}_f \) is a matrix that accounts for the number of devices used at each device location.

Table 1. Parameters of Mechanical Models for the MR damper

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha_a )</td>
<td>46.2 kN/m</td>
<td>( k_0 )</td>
<td>0.002 kN/m</td>
</tr>
<tr>
<td>( \alpha_b )</td>
<td>41.2 kN/m/V</td>
<td>( k_1 )</td>
<td>0.0097 kN/m</td>
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<td>( c_{0a} )</td>
<td>110.0 kN/sec/m</td>
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<td>( c_{0b} )</td>
<td>114.3 kN/sec/m/V</td>
<td>( \gamma )</td>
<td>164.0 m²</td>
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<tr>
<td>( c_{1a} )</td>
<td>8359.2 kN/sec/m</td>
<td>( \beta )</td>
<td>164.0 m²</td>
</tr>
<tr>
<td>( c_{1b} )</td>
<td>7482.9 kN/sec/m/V</td>
<td>( A )</td>
<td>1107.2</td>
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<tr>
<td>( \eta )</td>
<td>100</td>
<td>( n )</td>
<td>2</td>
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Control Design Model

Because the evaluation model is too large for control design and implementation, a reduced-order model (i.e., design model) of the system should be developed. The design model (Dyke et al. 2000) has been derived from the evaluation model by forming a balanced realization of the system and condensing out the states with relatively small controllability and observability grammians to obtain (Laub et al. 1987):

\[
\dot{\mathbf{x}}_d = \mathbf{A}_d \mathbf{x}_d + \mathbf{B}_d \mathbf{u} + \mathbf{E}_d \ddot{\mathbf{g}}
\]

\[
\mathbf{z} = \mathbf{C}_d^\tau \mathbf{x}_d + \mathbf{D}_d \mathbf{u} + \mathbf{F}_d \ddot{\mathbf{g}}
\]

\[
\mathbf{y}_s = \mathbf{C}_d^y \mathbf{x}_d + \mathbf{D}_d^y \mathbf{u} + \mathbf{F}_d^y \ddot{\mathbf{g}} + \mathbf{v}
\]

where \( \mathbf{x}_d \) is the design state vector with a dimension \( d = 30 \), \( \ddot{\mathbf{g}} \) is the ground acceleration, \( \mathbf{u} \) is the control command input, \( \mathbf{z} \) the regulated output vector including shear forces and moments in the towers, deck displacements, and cable tension forces.
Control Schemes for MR Fluid Dampers

The strategy of a clipped-optimal control algorithm (Dyke et al. 1996; Dyke and Spencer 1997) for seismic protection of bridges using MR fluid dampers is as follows: First, an “ideal” active control device is assumed, and an appropriate primary controller for this active device is designed. Then a secondary bang-bang-type controller causes the MR fluid damper to generate the desired active control force, so long as this force is dissipative.

In this study, an $H_2$/LQG control design (Spencer et al. 1994; Zhou et al. 1996) is adopted as the primary controller. The ground excitation is taken to be a stationary white noise, and an infinite horizon performance index is chosen that weights appropriate parameters of the structure, i.e.,

$$J = \lim_{\tau \to \infty} \frac{1}{\tau} E \left[ \int_{0}^{\tau} \{ z^T Q z + u^T R u \} \, dt \right]$$

where $R$ is an identity matrix of order 8, and $Q$ is the response weighting matrix. A stochastic response analysis has been performed to determine appropriate values of the weighting parameters. Through the preliminary parametric study, the following combination of weighting parameters is considered:

- Overturning moments ($q_{om}$) and deck displacements ($q_d$)

$$Q_{om\&d} = \begin{bmatrix} q_{om} I_{4\times4} & 0 \\ 0 & q_d I_{4\times4} \end{bmatrix}$$

By employing the above weighting matrices to obtain the primary controller ($H_2$/LQG), we can get the “desired” active control command.

And then, a force feedback loop is appended to induce each MR damper to produce approximately the desired control force. The desired control force for the $i$th MR damper is denoted $f_{ci}$. A linear optimal controller $K_c(s)$ is designed that calculates a vector of desired control forces $f_c = [f_{c1} \ f_{c2} \ \cdots \ f_{cn}]^T$, based on the measured structural response vector $y_m$ and the measured control force vector $y_f$, i.e.,

$$f_c = L^{-1} \left\{-K_c(s)L \begin{bmatrix} y_m \\ y_f \end{bmatrix} \right\}$$

where $L\{\cdot\}$ is the Laplace transform.

Because the force generated in the $i$th MR damper are dependent on the responses of the structural system, the MR damper cannot always produce the desired optimal control forces $f_{ci}$. Only the control voltage $v_i$ can be directly controlled. Thus, a force feedback loop is incorporated to induce the MR damper to generate approximately the desired optimal control force $f_{ci}$. To this end, the $i$th command signal $v_i$ is selected according to the control law
where $V_{\text{max}}$ is the voltage to the current driver associated with saturation of the MR effect in the tested device, and $H(\cdot)$ is the Heaviside step function.

**Numerical Simulation Results**

To verify the effectiveness of the proposed control design, a set of simulations is performed for the three earthquakes specified. In the simulation, the digitally implemented controller has a sampling time of $T = 0.002$ sec, which is set equal to the integration time step of the simulation. Simulation results of the proposed control design are compared to those of an active control design, which adopted the $H_2$/LQG method as control algorithm, and those of two passive cases in which the MR damper is used in two passive modes. *Passive-off* and *passive-on* refer to the cases in which the voltage to the MR fluid damper is held at a constant value of $V = 0$ and $V = V_{\text{max}} = 10$ Volts, respectively.

In this preliminary study, the appropriate values of weighting parameters for the proposed semi-active control design and the active control design are chosen as follows (see (13)):

- $q_{\text{cm}} = 6 \times 10^{-9}$, $q_d = 6 \times 10^3$.

Table 2 shows the maximum evaluation criteria for all the three earthquakes. While the controller presented in Dyke *et al.* (2000) is not intended to be a competitive control design, the associated performance indices are given in these tables for the readers’ reference. For the semi-active control strategy, $J_{14}$ and $J_{15}$, which correspond to the non-dimensionalized maximum instantaneous power and total power, are not considered. The performance of the clipped-optimal control system is generally similar to that of the active control system as shown in the table. Note that the maximum overturning moment ($J_3$), the maximum moment at deck level ($J_4$), the maximum deck displacement at abutment ($J_6$), and the maximum device stroke ($J_{13}$) in the clipped-optimal control system are consistently smaller than the corresponding indices for the active control system for the three earthquake excitations. These results verify that semi-active control strategy has nearly the same effectiveness as the active control system for seismic protection of the benchmark cable-stayed bridge model.

The results of *passive-off* and *passive-on* systems are also shown in Table 2. Generally, the *passive-on* system reduces the responses more than the *passive-off* system. However, some of the responses in the *passive-on* system are larger than those of the *passive-off* system (e.g., the maximum base shear ($J_1$) and the maximum overturning moment ($J_3$)).

The performance of the semi-active control algorithm in this study is not quite different from that in Jung *et al.* (2001), in which the dynamics of control devices are not considered. The differences of the evaluation criteria in two cases are 0.2 % ~ 3.8 % except $J_4$ (15.2 %), $J_6$ (20.9 %), $J_{10}$ (11.1 %) and $J_{13}$ (20.9 %). On the other hand, the results of the proposed control strategy is much better than those of Moon *et al.* (2001) in the semi-active control system because they used the same weighting parameters as the sample controller (Dyke *et al.* 2000), that is, they did not perform the parametric study to obtain the optimal weighting parameters.
Table 2. Maximum Evaluation Criteria for All the Three Earthquakes

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Dyke et al. (2000)</th>
<th>Active control</th>
<th>Semi-active control</th>
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<tr>
<td></td>
<td></td>
<td>Passive-off</td>
<td>Passive-on</td>
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<tr>
<td>( J_1 )</td>
<td>0.45402</td>
<td>0.42768</td>
<td>0.44637</td>
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<tr>
<td>( J_2 )</td>
<td>1.3784</td>
<td>1.1988</td>
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<td>( J_3 )</td>
<td>0.44343</td>
<td>0.33411</td>
<td>0.63348</td>
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<td>( J_4 )</td>
<td>1.2246</td>
<td>0.86919</td>
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<td>( J_5 )</td>
<td>0.14807</td>
<td>0.10014</td>
<td>0.26859</td>
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<td>( J_6 )</td>
<td>3.5640</td>
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<td>( J_{18} )</td>
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Conclusions

In this paper, a semi-active control strategy using MR fluid dampers has been proposed by investigating the benchmark control problem for seismic responses of cable-stayed bridges. The proposed control design employs five accelerometers, four displacement transducers and 24 force transducers as sensors, a total of 24 MR fluid dampers as control devices, and the controller has 30 states. The dynamic model of MR fluid dampers is considered as the modified Bouc-Wen model. A clipped-optimal control algorithm is used to determine the control action for each MR fluid damper. The numerical simulation results demonstrate that the performance of the proposed control design is nearly the same as that of the active control system. In addition, a semi-active control strategy has many attractive features, such as the bounded-input, bounded-output stability and small energy requirements. The results of this preliminary investigation indicate that MR fluid dampers can effectively be used for control of seismically excited cable-stayed bridges.

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