SEISMIC RESPONSE CONTROL OF CABLE-STAYED BRIDGES CONSIDERING DYNAMIC MODELS OF FULL-SCALE MR DAMPERS

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Abstract

This paper examines the ASCE 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. In this paper, magnetorheological (MR) fluid dampers, which belong to the class of controllable fluid dampers, are proposed as the supplemental damping devices, 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, which is obtained from data based on experimental results for large-scale dampers. 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 that bounded-input, bounded-output stability of the controlled structure is guaranteed. Numerical 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 few 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 and the International Association of Structural Control (Spencer *et al.* 1998; EESD 1998; IASC 1998; Ohtori *et al.* 2000). Until recently, however, all of the benchmark problems considered have focused on the control of buildings.

Because there are a growing number of cable-stayed bridges throughout the world, more 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 first generation of benchmark structural control problem for seismically excited cable-stayed bridges was developed under the coordination of the ASCE Task Committee on Structural Control Benchmarks to investigate the effectiveness of various proposed seismic mitigation strategies (Dyke et al., 2000). This first generation benchmark control problem focuses on 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 also have been provided.

Magnetorheological (MR) fluid dampers are 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. MR damper-based control strategies not only offer the reliability of passive control devices but also maintain the versatility and adaptability of fully active control systems. 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, Spencer *et al.* 2000, Yoshioka *et al.* 2002).

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.* 1997). The parameters of the dynamic model are optimized by using the data based on the experimental results of a large-scale (i.e., 20-ton) MR fluid damper. Also, a clipped-optimal control algorithm, shown to perform well in previous studies involving MR fluid dampers (Dyke *et al.* 1996, 1997), is employed. Since the MR fluid damper is an energy-dissipation 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 a brief overview of the benchmark problem statement, including discussion of the benchmark bridge model and evaluation criteria, a seismic control design strategy 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. Note that 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, Dyke *et al.* (2000) developed and made available a three-dimensional linearized evaluation model that effectively represents 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 motion is applied in the longitudinal direction for the first generation benchmark problem of seismically excited cable-stayed bridges.

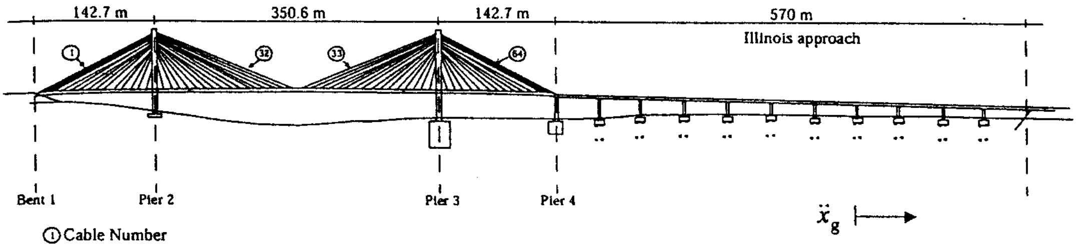

Figure 1. Schematic of the Cape Girardeau bridge (Dyke et al. 2000)

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, 1997), is employed to determine the control action.

Sensors

Five accelerometers and four displacement transducers are used for feedback in the control algorithm. Two accelerometers are located at the top of each of the two towers, 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.

Control devices: MR fluid dampers

A total of 24 MR fluid dampers are considered as control devices. Each device has a capacity of 1000 kN. 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 accurately predict the behavior of the controlled structure, an appropriate modeling of MR fluid dampers is essential. Herein, a modified Bouc-Wen is considered as a dynamic model of devices. In contrast to previous studies that were based on experimental data for small-scale prototype MR dampers, the dynamic models in this study are based on those for large-scale (i.e., 20-ton) MR fluid dampers.

Spencer *et al.* (1997) proposed the modified Bouc-Wen model 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. The equation governing the force predicted by this model is

$$f = \alpha z + c_0(\dot{x} - \dot{y}) + k_0(x - y) + k_1(x - x_0) = c_1\dot{y} + k_1(x - x_0) \tag{1}$$

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

$$z = -\gamma|\dot{x} - \dot{y}|z|z|^{n-1} - \beta(\dot{x} - \dot{y})|z|^{n} + A(\dot{x} - \dot{y}) \tag{2}$$

and

$$\dot{y} = \frac{1}{c_0 + c_1}\{\alpha z + c_0\dot{x} + k_0(x - y)\}. \tag{3}$$

In this model, the following three parameters depend on the command voltage u to the current driver:

$$\alpha = \alpha_a + \alpha_b u, \quad c_0 = c_{0a} + c_{0b}u, \quad \text{and} \quad c_1 = c_{1a} + c_{1b}u. \tag{4}$$

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

$$\dot{u} = -\eta(u - v_c) \tag{5}$$

where v_c is the command voltage applied to the current driver.

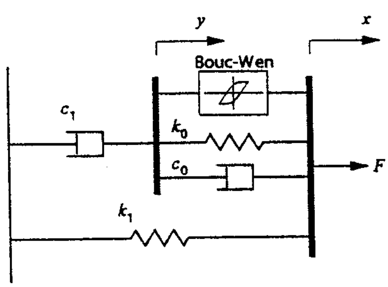

Figure 2. Dynamic model of the MR damper by Spencer *et al.* (1997)

A constrained nonlinear optimization was used to obtain the parameters. The optimization was performed using the sequential quadratic programming algorithm. Table 1 provides the optimized parameters for the dynamic model that were determined to best fit the data based on the experimental results of a 20-ton MR fluid damper (Yang *et al.* 2001). In order to obtain the data of a 100-ton (i.e., 1000 kN) damper considered in this study, the experimental data of the 20-ton damper have been linearly scaled up 5 times in the damper force and 2.5 times in the stroke of the device.

Table 1. Parameters of dynamic models for the MR damper

Parameter	Value	Parameter	Value
α_a	46.2 kN/m	k_0	0.002 kN/m
α_b	41.2 kN/m/V	k_1	0.0097 kN/m
c_{0a}	110.0 kN·sec/m	x_0	0.0 m
c_{0b}	114.3 kN·sec/m/V	γ	164.0 m^{-2}
c_{1a}	8359.2 kN·sec/m	β	164.0 m^{-2}
c_{1b}	7482.9 kN·sec/m/V	A	1107.2
η	100	n	2

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 given by Dyke *et al.* (2000) was 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):

$$\dot{\mathbf{x}}_d = \mathbf{A}_d\mathbf{x}_d + \mathbf{B}_d\mathbf{f} + \mathbf{E}_d\ddot{x}_g \tag{6}$$

$$\mathbf{z} = \mathbf{C}_d^z\mathbf{x}_d + \mathbf{D}_d^z\mathbf{f} + \mathbf{F}_d^z\ddot{x}_g \tag{7}$$

$$\mathbf{y}_s = \mathbf{G}(\mathbf{C}_d^y\mathbf{x}_d + \mathbf{D}_d^y\mathbf{f} + \mathbf{F}_d^y\ddot{x}_g + \mathbf{n}) \tag{8}$$

where $\mathbf{x}_d$ is the design state vector with a dimension d = 30, $\ddot{x}_g$ is the ground acceleration, $\mathbf{f}$ is the applied control force, $\mathbf{z}$ the regulated output vector including shear forces and moments in the towers, deck displacements, and cable tension forces, $\mathbf{y}_s$ is the output responses from the sensors that are used for control signal determination, $\mathbf{G}$ is the sensor gain matrix, and $\mathbf{n}$ is the vector of sensor noises.

Control schemes for MR fluid dampers

The strategy of a clipped-optimal control algorithm (Dyke *et al.* 1996) for seismic protection 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. This approach is adopted for control of the cable-stayed bridge.

In this study, an H_2/LQG control design (Spencer *et al.* 1994) 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.,

$$J = \lim_{\tau \to \infty} \frac{1}{\tau} E\left[\int_0^{\tau} \left\{ \mathbf{z}^{\mathrm{T}}\mathbf{Q}\mathbf{z} + \mathbf{f}^{\mathrm{T}}\mathbf{R}\mathbf{f} \right\} \quad dt \right] \tag{9}$$

where $\mathbf{R}$ is an identity matrix, and $\mathbf{Q}$ 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 (Jung *et al.* 2001), the following combination of weighting parameters is considered:

$$\mathbf{Q}_{\mathrm{om\&d}} = \begin{bmatrix} q_{\mathrm{om}}\mathbf{I}_{4\times4} & \mathbf{0} \\ \mathbf{0} & q_{\mathrm{d}}\mathbf{I}_{4\times4} \end{bmatrix} \tag{10}$$

where q_{om} and q_{d} weight the overturning moments and the deck displacements, respectively. By employing the above weighting matrix in the H_2/LQG to obtain the *primary* controller $\mathbf{K}_c(s)$, a "desired" active control command is obtained. This desired control force vector $\mathbf{f}_c = [f_{c1}\ f_{c2} \cdots f_{cn}]^T$ can then be written as

$$\mathbf{f}_c = L^{-1}\left\{ -\mathbf{K}_c(s) L \begin{Bmatrix} \mathbf{y}_m \\ \mathbf{y}_f \end{Bmatrix} \right\} \tag{11}$$

where f_{ci} is the desired control force signal for the *i*th MR damper, $\mathbf{y}_m$ is the measured structural response vector, $\mathbf{y}_f$ is the measured control force vector, and $L^{-1}\{\cdot\}$ is the inverse Laplace transform operator.

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. Only the control voltage v_i can be directly controlled. Thus, a force feedback loop is incorporated to induce the force in the MR damper f_i 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

$$v_i = V_{\max} H[(f_{ci} - f_i) f_i] \tag{12}$$

where $V_{\max}$ is the voltage to the current driver associated with saturation of the MR effect in the physical 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 benchmark problem statement (Dyke, *et al.* 2000). Simulation results for the proposed control design are compared to those of an active control design, which employs the H_2/LQG method as control algorithm, those of an ideal semi-active control design, which does not considered the dynamics of control devices, and those of two passive cases in which the MR fluid damper is used. The two passive cases are termed *passive-off* and *passive-on*, which refers to the cases in which the voltage to the MR fluid damper is held at a constant value of $V = 0$ and $V = V_{\max} = 10$ Volts, respectively. In this preliminary study, optimal values of weighting parameters for the proposed semi-active control design and the active control design are determined to be (see (10)) $q_{\mathrm{om}} = 6\times10^{-9}$, $q_{\mathrm{d}} = 6\times10^{3}$. 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 the table for the readers' reference. For the semi-active control strategies, J_{14} and J_{15}, which correspond to the maximum instantaneous power and total power, are not applicable.

Table 2. Maximum evaluation criteria for all the three earthquakes

	Criterion	Dyke et al. (2000)	Ideal active control	Semiactive control			
				Ideal semiactive control	Considering the dynamics of devices		
					Passive-off	Passive-on	Clipped-optimal
Peak responses	J_1 (base shear)	0.45882	0.49922	0.45577	0.44637	0.50248	0.45947
	J_2 (shear at deck level)	1.3784	1.1988	1.1944	1.7960	1.0735	1.2331
	J_3 (base moment)	0.58359	0.44607	0.47615	0.63348	0.65266	0.42782
	J_4 (mom. at deck level)	1.2246	0.86919	0.82813	2.7538	0.59148	0.74371
	J_5 (dev. of cable tension)	0.18609	0.15712	0.17822	0.26859	0.19778	0.16869
	J_6 (deck displacement)	3.5640	2.0181	1.9666	8.4622	0.76009	1.8145
Normed resp.	J_7 (base shear)	0.39830	0.35188	0.34972	0.37832	0.51443	0.36120
	J_8 (shear at deck level)	1.4371	1.0118	1.1443	2.3635	1.1527	1.0841
	J_9 (base moment)	0.45523	0.33038	0.32961	0.80629	0.53672	0.32678
	J_{10} (mom. at deck level)	1.4569	0.85977	0.91366	3.7460	0.60951	0.90266
	J_{11} (dev. of cable tension)	2.7968e-2	1.5465e-2	1.6971e-2	2.6040e-2	2.3562e-2	1.6704e-2
Control strategy	J_{12} (peak control force)	1.7145e-3	1.9608e-3	1.9608e-3	3.2616e-4	1.9608e-3	1.9608e-3
	J_{13} (peak device stroke)	1.9540	1.1065	1.0782	4.6396	0.41674	0.99483
	J_{14} (peak power)	7.3689e-3	9.2050e-3	-	-	-	-
	J_{15} (peak total power)	6.9492e-4	8.6807e-4	-	-	-	-
	J_{16} (no. of devices)	24	24	24	24	24	24
	J_{17} (no. of sensors)	9	9	33	0	0	33
	J_{18} (no. of resources)	30	30	30	30	30	30

As shown in the above table, the semi-active control strategy has nearly the same effectiveness as the active control system for seismic protection of the benchmark cable-stayed bridge model. Note that in this study ideal hydraulic actuators are considered as active control devices, (i.e., actuator dynamics are neglected), which is consistent with the sample controller provided by Dyke *et al.* (2000). Moreover, the performance of the proposed semi-active control system (clipped-optimal control) considering the dynamics of control devices (i.e., MR fluid dampers) is quite similar to that of ideal semi-active control system, which does not consider the dynamics of dampers. Some of the maximum evaluation criteria for the case considering the dynamics of MR fluid dampers are somewhat worse than those in the case of not considering the dynamics (e.g., J_2 (3.1 %) and J_7 (3.2 %)), whereas other criteria for the case considering device dynamics are better than those for the ideal case (e.g., J_3 (11.3 %) and J_6 (8.4 %)). 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., J_1, J_3, and J_7).

Conclusions

In this paper, a semi-active control strategy using MR fluid dampers has been proposed by investigating the ASCE first generation 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 modified Bouc-Wen model is considered as a dynamic model of the MR damper. The parameters of the dynamic model are obtained from the data based on the experimental results of a full-scale MR damper. 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 fully active control system. In addition, 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, therefore, indicate that MR fluid dampers could effectively be used for control of seismically excited cable-stayed bridges.

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