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SEISMIC PROTECTION OF A BENCHMARK CABLE-STAYED BRIDGE USING SMART DAMPING STRATEGIES

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ABSTRACT

This paper presents smart damping strategies for seismic protection of cable-stayed bridges by investigating the first generation benchmark problem for cable-stayed bridges. For this benchmark study, a three-dimensional linearized evaluation bridge model is provided as a *testbed* structure. In this paper, smart dampers (e.g., variable orifice damper, controllable fluid damper, etc.) are considered as supplemental damping devices, and a clipped-optimal control algorithm, shown to perform well in previous studies involving controllable dampers, is employed. Since a smart damper is an energy-dissipative device that cannot add mechanical energy to the structural system, the proposed control strategy guarantees the bounded-input, bounded-output stability of the controlled structure. The numerical simulation results show that the performance of smart damping strategies is quite effective.

KEYWORDS

Benchmark problem, cable-stayed bridge, earthquake, smart damping, seismic protection

INTRODUCTION

In the field of civil engineering, many control algorithms and devices have been investigated over the last two decades to protect structures against natural hazards such as strong earthquakes and high winds. However, comparison of different control strategies directly is generally a challenging task, because standard structures were not considered. This problem can be addressed by employing *testbed* structures, that is, by developing benchmark studies. One goal of such a benchmark study is to direct future research efforts toward the most promising structural control strategies. In recent years, benchmark studies have been actively investigated by the American Society of Civil Engineers (ASCE) Committee on Structural Control and the International Association of Structural Control (IASC). Until recently, however, all of benchmark problems considered has focused on the control of buildings (EESD 1998; IASC 1998; Ohtori et al. 2000).

Because there are a growing number of cable-stayed bridges throughout the world, more research on the seismic protection of such structures is needed. The control of very flexible structures such as cable-stayed bridges is a unique and challenging problem. 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). 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.

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 smart damping strategies for seismic protection of such structures. In this study, smart dampers (e.g., variable orifice damper, variable friction damper, controllable fluid damper, etc.) are considered as supplemental damping devices, and a clipped-optimal control algorithm, shown to perform well in previous studies involving controllable dampers (Dyke et al. 1996; Dyke and Spencer 1997), is employed. Numerical simulation results are 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 2003 in Cape Griardeau, Missouri, USA. 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. 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. Each mode of this evaluation model has 3% of critical damping, which is consistent with assumptions made during the design of bridge.

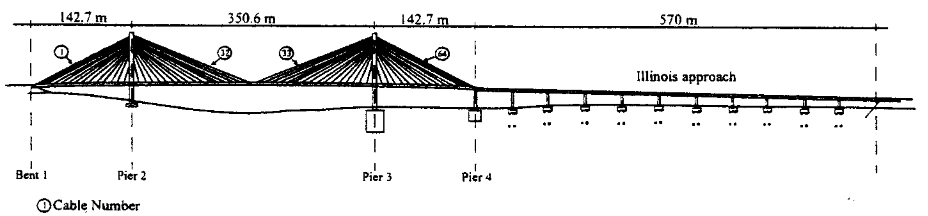

Figure 1: Schematic of the Cape Girardeau Bridge (Dyke et al. 2000)

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 SMART DAMPING STRATEGIES

Sensors and Control Devices

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). In this study, a total of 24 smart dampers are considered, eight between the deck and pier 2, eight between the deck and pier 3, four between the deck and bent 1, and four between the deck and pier 4. Each damper has a capacity of 1000 kN. For this preliminary study, the smart damper is assumed to be "ideal"; i.e., it can generate the desired dissipative forces without considering saturation, delay, and dynamics of the device.

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 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):

$$\dot{\mathbf{x}}_d = \mathbf{A}_d\mathbf{x}_d + \mathbf{B}_d\mathbf{u} - \mathbf{E}_d\ddot{x}_g \tag{1}$$

$$\mathbf{z} = \mathbf{C}_d^z\mathbf{x}_d + \mathbf{D}_d^z\mathbf{u} + \mathbf{F}_d^z\ddot{x}_g \tag{2}$$

$$\mathbf{y}_s = \mathbf{C}_d^y\mathbf{x}_d + \mathbf{D}_d^y\mathbf{u} + \mathbf{F}_d^y\ddot{x}_g + \mathbf{v} \tag{3}$$

where $\mathbf{x}_d$ is the design state vector with a dimension $d = 30$, $\ddot{x}_g$ is the ground acceleration, $\mathbf{u}$ is the control command input, $\mathbf{z}$ is the regulated output vector including shear forces and moments in the towers, deck displacements, and cable tension forces, $\mathbf{y}_s$ is a vector the measured responses including noise, and $\mathbf{v}$ is the measurement noise.

Control Schemes for Smart Damping Strategies

The strategy of a clipped-optimal control algorithm for seismic protection of bridges using smart 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 smart 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. To better inform the controller about the frequency content of the ground motion, a Kanai-Tajimi shaping filter (Soong and Grigoriu 1993) is incorporated into the model of the structure. 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.,

$$J = \lim_{\tau \to \infty} \frac{1}{\tau} E\left[\int_0^\tau \left\{ \mathbf{z}^{\mathrm{T}} \mathbf{Q}\, \mathbf{z} + \mathbf{u}^{\mathrm{T}} \mathbf{R}\, \mathbf{u} \right\} dt \right] \qquad (4)$$

where $\mathbf{R}$ is an identity matrix of order 8, and $\mathbf{Q}$ is the response weighting matrix. Herein, a stochastic response analysis has been performed to determine appropriate values of the weighting parameters. Following the extensive parametric study, two cases are considered:

Case 1: overturning moments (q_{om}) and moments at deck level (q_{md}),

Case 2: overturning moments (q_{om}) and displacements at deck (q_{d}).

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

In this preliminary study, since the device is assumed to be "ideal", the control force can be replaced by the control command. Therefore, the *secondary* control strategy is given by

$$u_{\mathrm{sa},i} = \begin{cases} u_{\mathrm{a},i}, & u_{\mathrm{a},i} \cdot \dot{x}_{\mathrm{dev}} < 0 \\ 0, & \text{otherwise} \end{cases} \qquad (5)$$

where $u_{\mathrm{sa},i}$ is the ith actual control command in Volts, $u_{\mathrm{a},i}$ is the "desired" control command, and $\dot{x}_{\mathrm{dev}}$ is the velocity across the ith damper.

The smart damper control design is depicted in Figure 2.

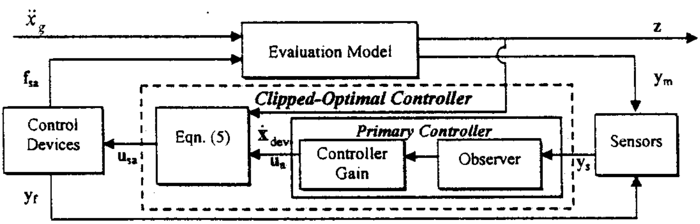

Figure 2: Smart Damper Control Strategy Using Clipped-Optimal Algorithm

NUMERICAL SIMULATION RESULTS

To verify the effectiveness of the proposed control design, a set of simulations is performed for the three earthquakes specified. Then, 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, the same number and location of the sensors/actuators being employed as in the case of the proposed control design. That is, the active control design considered herein is equal to the *primary* controller of the proposed design. In this preliminary study, the appropriate values of weighting parameters for the proposed control design and the active control design are chosen as follows:

- *Case* 1: $q_{\rm om} = 1\times10^{-8}$, $q_{\rm md} = 1\times10^{-8}$,
- *Case* 2: $q_{\rm om} = 1\times10^{-8}$, $q_{\rm d} = 1\times10^{4}$.

Table 1 shows the maximum evaluation criteria for all the three earthquakes. For the smart damping strategies, J_{14} and J_{15} are not considered, because these two criteria cannot be calculated in the proposed design due to assuming an "ideal" smart damper. As seen from Table 1, the performance of both *Case* 1 and *Case* 2 control methods is quite effective. These results verify that smart damping strategies have nearly the same effectiveness as the active control system for seismic protection of the benchmark cable-stayed bridge model.

TABLE 1
MAXIMUM EVALUATION CRITERIA FOR ALL THE THREE EARTHQUAKES

Criterion	Dyke et al. (2000)	Active Control (H_2/LQG)		Smart Damping	
		Case 1	*Case* 2	*Case* 1	*Case* 2
J_1	0.45822	0.46919	0.49434	0.45863	0.46555
J_2	1.3784	1.1641	1.1272	1.2317	1.1865
J_3	0.58359	0.43339	0.42798	0.43837	0.43458
J_4	1.2246	0.92347	0.85594	0.87668	0.85059
J_5	0.18609	0.15556	0.14815	0.16224	0.16206
J_6	3.5640	2.4259	1.8992	2.2948	1.8570
J_7	0.39830	0.36842	0.36008	0.36331	0.35941
J_8	1.4371	1.0186	0.97428	1.1049	1.0918
J_9	0.45523	0.32188	0.30858	0.32852	0.31690
J_{10}	1.4569	0.98763	0.81997	1.0158	0.87031
J_{11}	2.7968e-2	1.5688e-2	1.5072e-2	1.6235e-2	1.5946e-2
J_{12}	1.7145e-3	1.9608e-3	1.9608e-3	1.9608e-3	1.9608e-3
J_{13}	1.9540	1.3301	1.0413	1.2582	1.0181
J_{14}	7.3689e-3	1.0108e-2	9.4646e-3	-	-
J_{15}	6.9492e-4	9.5327e-4	8.9255e-4	-	-
J_{16}	24	24	24	24	24
J_{17}	9	33	33	33	33
J_{18}	30	32	32	32	32

CONCLUSIONS

In this paper, a semi-active control strategy using smart 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 smart dampers as control devices, and the controller has 32 states. A clipped-optimal control algorithm is used to determine the control action for each smart damper. The numerical results demonstrate that the performance of the proposed control design is nearly the same as that of the active control system. In addition, smart damping strategies have many attractive features, such as the bounded-input, bounded-output stability and small energy requirements. The results of this preliminary investigation indicate that smart dampers can effectively be used for control of seismically excited cable-stayed bridges.

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