Benchmark Control Problem for Seismically Excited Cable-Stayed Bridges Using Smart Damping Strategies

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Summary

This paper presents smart damping strategies for seismic protection of cable-stayed bridges by investigating the first generation benchmark problem for cable-stayed bridges [1]. For this benchmark study, a three-dimensional linear 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; seismic load; smart damping; seismic protection

1. 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, it is generally impossible to compare different control strategies directly because the control methods were applied to different structures. This problem can be addressed by employing *testbed* structures, that is, by developing benchmark studies. Benchmark control problems allow researchers to apply various control strategies, such as passive, active, semi-active or a combination thereof, to a specified problem, and to compare results directly in terms of a specified set of performance objectives. One goal of 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 International Association of Structural Control (IASC) and the ASCE Engineering Mechanics Committee [2-3]. Until recently, all of benchmark problems considered have focused on the control of buildings [2-4].

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. [1]. This first generation benchmark control problem for cable-stayed bridges subjected to seismic loads considers a bridge currently under construction in Cape Griardeau, Missouri, USA, which will be completed in 2003. Based on detailed drawings of this cable-stayed bridge, a three-dimensional 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. [1] 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 [5-6], 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. Following an overview of the benchmark problem statement, including discussion of the benchmark bridge model and evaluation criteria, a seismic control system design using smart damping strategies is proposed. Numerical simulation results are then presented to demonstrate the effectiveness of the proposed control strategy.

2. Benchmark Problem Statement

2.1 Benchmark Bridge Model

This benchmark problem considers the cable-stayed bridge shown in *Fig.* 1, which is currently under construction in Cape Griardeau, Missouri, USA. 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 linear evaluation model has been developed to represent the complex behavior of the full-scale benchmark bridge. However, 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 [7]. Since 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.

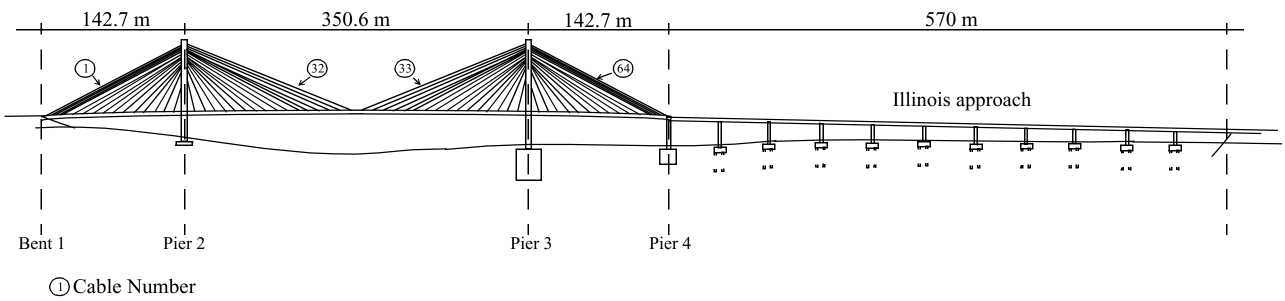

Fig. 1 Schematic of the Cape Girardeau Bridge [1]

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% critical damping, which is consistent with assumptions made during the design of bridge.

2.2 Evaluation Criteria

Eighteen criteria have been defined [1] 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 following first six evaluation criteria consider the ability of the controller to reduce peak responses:

$$J_1 = \max_{\substack{ElCentro\\MexicoCity\\Gebze}} \left\{ \frac{\max_{i,t} |F_{bi}(t)|}{F_{0b}^{\max}} \right\},\ J_2 = \max_{\substack{ElCentro\\MexicoCity\\Gebze}} \left\{ \frac{\max_{i,t} |F_{di}(t)|}{F_{0d}^{\max}} \right\},\ J_3 = \max_{\substack{ElCentro\\MexicoCity\\Gebze}} \left\{ \frac{\max_{i,t} |M_{bi}(t)|}{M_{0b}^{\max}} \right\},$$

$$J_4 = \max_{\substack{ElCentro\\MexicoCity\\Gebze}} \left\{ \frac{\max_{i,t} |M_{di}(t)|}{M_{0d}^{\max}} \right\},\ J_5 = \max_{\substack{ElCentro\\MexicoCity\\Gebze}} \left\{ \max_{i,t} \left| \frac{T_{ai}(t) - T_{0i}}{T_{0i}} \right| \right\},\ J_6 = \max_{\substack{ElCentro\\MexicoCity\\Gebze}} \left\{ \max_{i,t} \left| \frac{x_{bi}(t)}{x_{0b}} \right| \right\}, \quad (1\text{~}6)$$

where $F_{bi}(t)$ is the base shear at the *i*th tower, $F_{0b}^{\max} = \max|F_{0bi}(t)|$ is the maximum uncontrolled base shear, $F_{di}(t)$ is the shear at the deck level in the *i*th tower, $F_{0d}^{\max} = \max|F_{0di}(t)|$ is the maximum uncontrolled shear at the deck level, $M_{bi}(t)$ is the moment at the base of the tower, $M_{0b}^{\max} = \max|M_{0bi}(t)|$ is the maximum uncontrolled moment at the base of the two towers, $M_{di}(t)$ is the moment at the deck level in the *i*th tower, $M_{0d}^{\max} = \max|M_{0di}(t)|$ is the maximum uncontrolled moment at the deck level in the two towers, T_{0i} is the nominal pretension in the *i*th cable, $T_{ai}(t)$ is the actual tension in the cable, and x_{0b} is the maximum of the uncontrolled deck response at these locations.

The second five evaluation criteria consider normed (i.e., *rms*) responses over the entire simulation time as follows:

$$J_7 = \max_{\substack{ElCentro\\MexicoCity\\Gebze}} \left\{ \frac{\max_{i} \|F_{bi}(t)\|}{\|F_{0b}(t)\|} \right\},\ J_8 = \max_{\substack{ElCentro\\MexicoCity\\Gebze}} \left\{ \frac{\max_{i} \|F_{di}(t)\|}{\|F_{0d}(t)\|} \right\},\ J_9 = \max_{\substack{ElCentro\\MexicoCity\\Gebze}} \left\{ \frac{\max_{i} \|M_{bi}(t)\|}{\|M_{0b}(t)\|} \right\},$$

$$J_{10} = \max_{\substack{ElCentro\\MexicoCity\\Gebze}} \left\{ \frac{\max_{i} \|M_{di}(t)\|}{\|M_{0d}(t)\|} \right\},\ J_{11} = \max_{\substack{ElCentro\\MexicoCity\\Gebze}} \left\{ \max_{i} \frac{\|T_{ai}(t) - T_{0i}\|}{T_{0i}} \right\}, \quad (7\text{-}11)$$

where $\|F_{0b}(t)\|$ is the maximum *rms* uncontrolled base shear of the two towers, $\|F_{0d}(t)\|$ is the maximum *rms* uncontrolled shear at the deck level, $\|M_{0b}(t)\|$ is the maximum *rms* uncontrolled overturning moment of the two towers, $\|F_{0d}(t)\|$ is the maximum *rms* uncontrolled moment at the deck level.

The last seven evaluation criteria consider the requirements of each control system itself:

$$J_{12} = \max_{\substack{ElCentro\\MexicoCity\\Gebze}} \left\{ \max_{i,t} \left(\frac{f_i(t)}{W} \right) \right\},\ J_{13} = \max_{\substack{ElCentro\\MexicoCity\\Gebze}} \left\{ \max_{i,t} \left(\frac{|y_i^d(t)|}{x_0^{\max}} \right) \right\},\ J_{14} = \max_{\substack{ElCentro\\MexicoCity\\Gebze}} \left\{ \frac{\max_t \left[\sum_i P_i(t) \right]}{\dot{x}_0^{\max} W} \right\}, \quad (13\text{-}19)$$

$$J_{15} = \max_{\substack{ElCentro\\MexicoCity\\Gebze}} \left\{ \frac{\sum_i \left(\int_0^{t_f} P_i(t) dt \right)}{x_0^{\max} W} \right\},$$

$$J_{16} = number\ of\ control\ devices,$$
$$J_{17} = number\ of\ sensors,$$
$$J_{18} = \dim(\mathbf{x}_k^c),$$

where $f_i(t)$ is the force generated by the *i*th control device over the time history, W = 510,000 kN is the seismic weight of a bridge based on the mass of the superstructure, $y_i^d(t)$ is the stroke of the *i*th control device, $x_0^{\max}$ is the maximum uncontrolled displacement at the top of the towers relative to the ground, $P_i(t)$ is a measure of the instantaneous power required by the *i*th control device, $\dot{x}_0^{\max}$ is the peak uncontrolled velocity at the top of the towers, and $\mathbf{x}_k^c$ is the discrete-time state vector of the control algorithm.

3. Seismic Control System Using Smart Damping Strategies

In this section, a description of the proposed control system using smart damping strategies is provided. Accelerometers, displacement and force transducers are employed as sensors. Smart dampers (e.g., variable orifice dampers, variable friction dampers, controllable fluid dampers, etc.) are used as control devices. A clipped-optimal control algorithm, which has been successfully applied with smart dampers in previous studies [5-6], is employed to determine the control action.

3.1 Sensors and Control Devices

Five accelerometers and four displacement transducers are used for feedback to 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 requires measurement of the control forces applied to the structure, eight force transducers are installed. All sensors, employed in this study, have a constant magnitude and phase [1], and the sensitivity of accelerometers (G_{a}), displacement transducers (G_{d}) and force transducers (G_{f}) are 7/9.81 V/(m/sec^2), 30 V/m and 0.01 V/kN, respectively. Thus, sensors can be modeled as

$$\mathbf{y}_{\mathrm{s}} = \begin{bmatrix} G_{\mathrm{a}}\mathbf{I}_{5\times5} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & G_{\mathrm{d}}\mathbf{I}_{4\times4} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & G_{\mathrm{f}}\mathbf{I}_{8\times8} \end{bmatrix} \mathbf{y}_{\mathrm{m}} + \mathbf{v} \tag{20}$$

where $\mathbf{y}_{\mathrm{s}}$ is a vector of the measured responses, including noise, in Volts, $\mathbf{y}_{\mathrm{m}}$ is a vector of the noise-free responses in physical units, and $\mathbf{v}$ is the measurement noise, which has an *rms* value of 0.003 V.

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 delay and dynamics of the device. The equations describing the forces produced by dampers are

$$\mathbf{f} = \mathbf{K}_{\mathrm{f}}\mathbf{u} = \begin{bmatrix} 2\mathbf{I}_{2\times2} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & 4\mathbf{I}_{4\times4} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & 2\mathbf{I}_{2\times2} \end{bmatrix} \mathbf{D}_{\mathrm{d}}\mathbf{u} \tag{21}$$

$$\mathbf{y}_{\mathrm{f}} = \mathbf{D}_{\mathrm{d}}\mathbf{u} = D_{\mathrm{d}}\mathbf{I}_{8\times8}\mathbf{u} \tag{22}$$

where $\mathbf{f}$ is the force output of devices applied to the structure, $\mathbf{y}_{\mathrm{f}}$ is the force output of devices used for feedback in the control algorithm, D_{d} = 100 kN/V is the gain for the device, and $\mathbf{K}_{\mathrm{f}}$ is a matrix that accounts for the relationship between the input voltage and the desired control force, as well as the number of devices used at each device location, as shown in Eq. (21).

3.2 Control Design Model

Because the evaluation model is too large to handle in the controller, 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 as follows [8]:

$$\dot{\mathbf{x}}_{\mathrm{d}} = \mathbf{A}_{\mathrm{d}}\mathbf{x}_{\mathrm{d}} + \mathbf{B}_{\mathrm{d}}\mathbf{u} + \mathbf{E}_{\mathrm{d}}\ddot{x}_{\mathrm{g}} \tag{23}$$

$$\mathbf{z} = \mathbf{C}_{\mathrm{d}}^{\mathrm{z}}\mathbf{x}_{\mathrm{d}} + \mathbf{D}_{\mathrm{d}}^{\mathrm{z}}\mathbf{u} + \mathbf{F}_{\mathrm{d}}^{\mathrm{z}}\ddot{x}_{\mathrm{g}} \tag{24}$$

$$\mathbf{y}_{\mathrm{s}} = \mathbf{C}_{\mathrm{d}}^{\mathrm{y}}\mathbf{x}_{\mathrm{d}} + \mathbf{D}_{\mathrm{d}}^{\mathrm{y}}\mathbf{u} + \mathbf{F}_{\mathrm{d}}^{\mathrm{y}}\ddot{x}_{\mathrm{g}} + \mathbf{v} \tag{25}$$

where $\mathbf{x}_\mathrm{d}$ is the design state vector with a dimension d = 30, $\ddot{x}_\mathrm{g}$ is the ground acceleration, $\mathbf{u}$ is control command input, $\mathbf{z}$ the regulated output vector including shear forces and moments in the towers, deck displacements, and cable tension forces.

3.3 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 [9-10] is adopted as the *primary* controller. $\ddot{x}_\mathrm{g}$ 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.,

$$J = \lim_{\tau \to \infty} \frac{1}{\tau} E\left[\int_0^\tau \left\{ \mathbf{z}^\mathrm{T} \mathbf{Q}\, \mathbf{z} + \mathbf{u}^\mathrm{T} \mathbf{R}\, \mathbf{u} \right\} dt \right] \tag{26}$$

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. Note that in order to get more reliable results, the evaluation model, not the design model, should be considered in the stochastic response analysis. Two combinations of appropriate weighting parameters are considered as follows:

- *Case* 1: deck displacements (q_d) and overturning moments (q_om),

$$\mathbf{Q}_{\mathrm{d\&om}} = \begin{bmatrix} q_\mathrm{d}\mathbf{I}_{4\times4} & \mathbf{0} \\ \mathbf{0} & q_\mathrm{om}\mathbf{I}_{4\times4} \end{bmatrix} \tag{27}$$

- *Case* 2: deck displacements (q_d) and moments at deck level (q_md)

$$\mathbf{Q}_{\mathrm{d\&md}} = \begin{bmatrix} q_\mathrm{d}\mathbf{I}_{4\times4} & \mathbf{0} \\ \mathbf{0} & q_\mathrm{md}\mathbf{I}_{4\times4} \end{bmatrix} \tag{28}$$

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

For the general smart damping device, the *secondary* control strategy is given by

$$f_{\mathrm{sa},i} = \begin{cases} f_{\mathrm{a},i}, & f_{\mathrm{a},i} \cdot \dot{x}_\mathrm{dev} < 0 \\ 0, & otherwise \end{cases} \tag{29}$$

where $f_{\mathrm{sa},i}$ is the control force of the *i*th smart damper, $f_{\mathrm{a},i}$ is the "desired" control force of the *i*th device, and $\dot{x}_\mathrm{dev}$ is the velocity across the *i*th damper. In this preliminary study, since the device is assumed to be "ideal" (see Eq. (21)), Eq. (29) can be replaced as follows:

$$u_{\mathrm{sa},i} = \begin{cases} u_{\mathrm{a},i}, & u_{\mathrm{a},i} \cdot \dot{x}_\mathrm{dev} < 0 \\ 0, & otherwise \end{cases} \tag{30}$$

where $u_{\mathrm{sa},i}$ is the *i*th actual control command in Volts, $u_{\mathrm{a},i}$ is the "desired" control command.

Since the smart damper is an energy-dissipative device that cannot add mechanical energy to the structural system, special care must be taken in the design of the *primary* controller so that the "desired" control force $f_{a,i}$ is dissipative during the majority of the seismic event. The smart damper control design is depicted in *Fig*. 2.

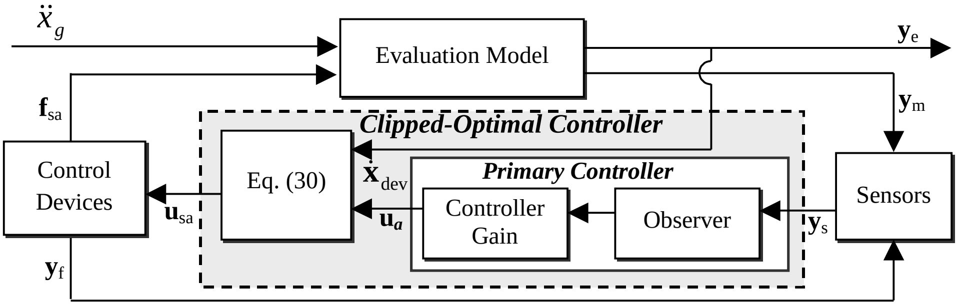

Fig. 2 Smart Damper Control Strategy Using Clipped-Optimal Algorithm

4. 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 the sample active control design in [1], employing the same sensors (5 accelerometers and 4 displacement transducers), control devices (24 "ideal" actuators) and control algorithm (H_2/LQG). In this preliminary study, the optimal values of weighting parameters for the *primary* controller in the proposed design and the active control design are chosen as follows (see Eqs. (27-28)):

- *Case* 1: $q_{\mathrm{d}} = 6.7\times10^{3}$, $q_{\mathrm{om}} = 6.6\times10^{-9}$,
- *Case* 2: $q_{\mathrm{d}} = 6.7\times10^{3}$, $q_{\mathrm{md}} = 1.4\times10^{-8}$.

Tables 1 to 3 show the values of the evaluation criteria in Eqs. (1-19). Here, J_{14} and J_{15}, which correspond to the non-dimensionalized maximum instantaneous power and total power, are not considered because these two criteria cannot be calculated in the proposed design due to assuming an "ideal" smart damper.

As shown in *Tables* 1 to 3, the performance of the proposed control design is quite similar to that of the active control design. In the case of the El Centro earthquake, the performance of both control methods is the most effective (e.g., more than 74% reduction for the maximum overturning moment as compared to the original design). In the case of the Mexico City earthquake, the results of *Case* 1 are slightly better than those of *Case* 2 for both control methods. The stroke of control devices has the largest magnitude in the case of the Gebze earthquake. For the Mexico City and Gebze earthquakes, the deck displacement increases significantly (56%-90% increase for the Mexico City earthquake, and 80%-98% increase for the Gebze earthquake) as compared to the uncontrolled case. 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 Evaluation Criteria for the 1940 El Centro NS Earthquake

Criterion	Active Control (H_2/LQG)		Smart Damping	
	Case 1	*Case* 2	*Case* 1	*Case* 2
J_1	0.27998	0.27520	0.28614	0.30420
J_2	0.82616	0.80058	0.89253	1.0186
J_3	0.26077	0.25410	0.23396	0.22709
J_4	0.58916	0.56530	0.57722	0.57976
J_5	0.15605	0.14162	0.16596	0.16980
J_6	0.99527	1.0978	0.87275	0.96665
J_7	0.19999	0.22345	0.19544	0.21216
J_8	0.77178	0.77588	0.82157	0.89710
J_9	0.18443	0.21938	0.18181	0.21068
J_{10}	0.49962	0.48322	0.52240	0.51888
J_{11}	1.5143e-2	1.3693e-2	1.6652e-2	1.5264e-2

Table 1 Evaluation Criteria for the 1940 El Centro NS Earthquake (Continued)

Criterion	Active Control (H_2/LQG)		Smart Damping	
	Case 1	*Case* 2	*Case* 1	*Case* 2
J_{12}	1.9608e-3	1.9608e-3	1.9608e-3	1.9608e-3
J_{13}	0.65347	0.72078	0.57303	0.63468
J_{16}	24	24	24	24
J_{17}	9	9	17	17
J_{18}	30	30	30	30

Table 2 Evaluation Criteria for the 1985 Mexico City Earthquake

Criterion	Active Control (H_2/LQG)		Smart Damping	
	Case 1	*Case* 2	*Case* 1	*Case* 2
J_1	0.49821	0.60057	0.47224	0.54194
J_2	1.0560	1.1342	1.0152	1.4404
J_3	0.44143	0.48793	0.45914	0.64722
J_4	0.44523	0.44839	0.49605	0.49644
J_5	5.3192e-2	5.1136e-2	5.5034e-2	6.2340e-2
J_6	1.7703	1.8722	1.5611	1.8986
J_7	0.35118	0.40639	0.34784	0.42764
J_8	0.84582	0.88501	0.90155	1.2235
J_9	0.31355	0.40666	0.30739	0.42245
J_{10}	0.68443	0.68490	0.70160	0.75846
J_{11}	5.8113e-3	5.2903e-3	6.3520e-3	6.2077e-3
J_{12}	1.7519e-3	1.6802e-3	1.4802e-3	1.4101e-3
J_{13}	0.89151	0.94846	0.78615	0.95613
J_{16}	24	24	24	24
J_{17}	9	9	17	17
J_{18}	30	30	30	30

Table 3 Evaluation Criteria for the 1999 Gebze NS Earthquake

Criterion	Active Control (H_2/LQG)		Smart Damping	
	Case 1	*Case* 2	*Case* 1	*Case* 2
J_1	0.42695	0.42926	0.41734	0.42829
J_2	1.1968	1.2634	1.2241	1.2762
J_3	0.33110	0.37651	0.32477	0.40932
J_4	0.86460	0.87682	0.86057	0.84455
J_5	9.9678e-2	9.9097e-2	0.10734	0.11365
J_6	1.9781	1.7959	1.9732	1.8620
J_7	0.28229	0.34191	0.27344	0.32638
J_8	1.0063	1.0762	1.1265	1.2540
J_9	0.32664	0.39036	0.32909	0.38228
J_{10}	0.84360	0.78197	0.91361	0.86128
J_{11}	1.0075e-2	9.7870e-3	1.1082e-2	1.0972e-2

Table 3 Evaluation Criteria for the 1999 Gebze NS Earthquake (Continued)

Criterion	Active Control (H_2/LQG)		Smart Damping	
	Case 1	*Case* 2	*Case* 1	*Case* 2
J_{12}	1.9608e-3	1.9608e-3	1.9608e-3	1.9608e-3
J_{13}	1.0845	0.98463	1.0818	1.0209
J_{16}	24	24	24	24
J_{17}	9	9	17	17
J_{18}	30	30	30	30

5. 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 5 accelerometers, 4 displacement transducers and 8 force transducers as sensors, a total of 24 smart dampers as control devices, and the controller has 30 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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