

실제규모의 자기유변 유체 감쇠기를 이용한 사장교의 진동제어

Semiactive Control of Cable-Stayed Bridges Using Full-Scale MR Fluid Dampers

정형조*	박규식**	고만기***	이인원****
Jung, Hyung Jo	Park, Kyu Sik	Ko, Man Gi	Lee, In Won

국문요약

본 논문에서는 미국토목학회(ASCE)의 사장교에 대한 첫번째 벤치마크 문제를 이용하여 제어-구조물 상호작용을 고려한 새로운 반능동 제어 기법을 제안하였다. 이 벤치마크 문제에서는 2003년 완공 예정으로 미국 Missouri 주에 건설 중인 Cape Girardeau 교를 대상 구조물로 고려하였다. Cape Girardeau 교는 New Madrid 지진구역에 위치하고, Mississippi 강을 횡단하는 주요 교량이라는 점 때문에 설계단계에서부터 내진 문제에 대하여 자세하게 고려되었다. 상세 설계 도면을 기반으로 하여 교량의 전체적인 거동 특성을 정확하게 나타낼 수 있는 3차원 모델이 만들어졌고, 사장교의 제어 성능에 관련된 평가 기준이 수립되었다. 본 연구에서는 제어 가능한 유체 감쇠기에 속하는 MR 유체 감쇠기를 제어 장치로 제안하였고, 기존 연구에서 MR 유체 감쇠기를 포함한 구조물의 제어에 효율적이라고 검증된 clipped-optimal 알고리즘을 제어 알고리즘으로 사용하였다. 또한, 실제 규모의 MR 유체 감쇠기 실험 결과를 이용하여 수치해석에 이용할 수 있는 동적 모델을 개발하였다. MR 유체 감쇠기는 제어 가능한 에너지 소산장치이며 구조물에 에너지를 가하지 않기 때문에 제안된 제어 기법은 한정입출력 안정성이 보장된다. 수치해석을 통해, MR 유체 감쇠기를 이용한 반능동 제어 기법이 사장교의 응답 감소에 효과적인 방법임을 증명하였다.

1. 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, semiactive, 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

* 한국과학기술원 토목공학과 연구조교수
** 한국과학기술원 토목공학과 박사과정
*** 공주대학교 토목공학과 교수
**** 한국과학기술원 토목공학과 교수

the International Association of Structural Control (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 semiactive 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.

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 semiactive 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), 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.

2. Benchmark problem statement

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.

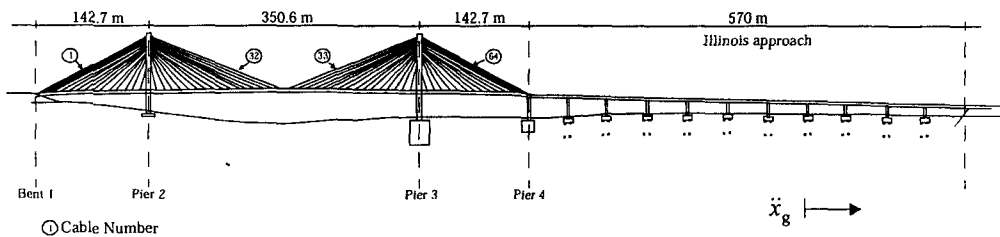


Figure 1. Schematic of the Cape Girardeau bridge (Dyke et al. 2000)

Eighteen evaluation 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. The second five evaluation criteria (J_7 - J_{11}) consider normed (i.e., *rms*) responses over the entire simulation time. The last seven evaluation criteria (J_{12} - J_{18}) consider the requirements of each control system itself.

3. Seismic control system using MR 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), 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

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

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

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

and

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

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

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

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

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

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

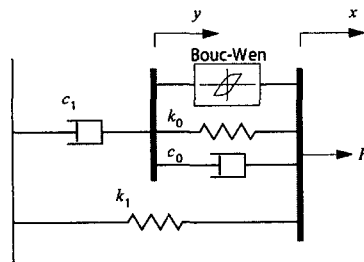


Figure 2. Dynamic model of the MR damper by Spencer *et al.* (1997)

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:

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

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

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

where \mathbf{x}_d is the design state vector with a dimension $d = 30$, $\ddot{\mathbf{x}}_g$ 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.,

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

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:

$$\mathbf{Q}_{\text{om\&d}} = \begin{bmatrix} q_{\text{om}} \mathbf{I}_{4 \times 4} & \mathbf{0} \\ \mathbf{0} & q_{\text{d}} \mathbf{I}_{4 \times 4} \end{bmatrix} \quad (10)$$

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

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

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

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

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.

4. 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 semiactive 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 semiactive control design and the active control design are determined to be (see (10))

$$q_{om} = 6 \times 10^{-9}, q_d = 6 \times 10^3$$

Table 2 shows the maximum evaluation criteria for all the three earthquakes. As shown in the table, the semiactive 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 semiactive control system (clipped-optimal control) considering the dynamics of control devices (i.e., MR fluid dampers) is quite similar to that of ideal semiactive 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 %)).

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

5. Conclusions

In this paper, a semiactive 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, semiactive 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.

Acknowledgements

The authors gratefully acknowledge the support of this research by the National Research Laboratory of Aseismic Control of Structures in Korea, and the National Science Foundation under grant No. CMS 99-00234 (Dr. S. C. Liu, Program Director).

References

1. Dyke, S. J., Spencer, Jr., B. F., Sain, M. K., and Carlson, J. D., "Modeling and control of magnetorheological dampers for seismic response," *Smart Materials and Structures*, 5, 1996. pp. 565-575.
2. Dyke, S. J., Turan, G., Caicedo, J. M., Bergman, L. A., and Hague, S., "Benchmark control problem for seismic response of cable-stayed bridges," <<http://wusceel.cive.wustl.edu/quake/>>, 2000.
3. EESD, "Special issue: benchmark problems," *Earthquake Engineering and Structural Dynamics*, Vol. 27, No. 11, 1998. pp. 1125-1397.
4. International Association on Structural Control (IASC), "Session 10 - benchmark tests of buildings," *Proceedings of the Second World Conference on Structural Control*, Kyoto, Japan, Vol. 2, 1998. pp. 1349-1490.
5. Ohtori, Y., Christensen, R. E., Spencer, Jr., B. F., and Dyke, S. J., "Benchmark control problems for seismically excited nonlinear buildings," <<http://www.nd.edu/~quake/>>, 2000.
6. Spencer, Jr., B. F., Suhardjo, J., and Sain, M. K., "Frequency domain optimal control strategies for aseismic protection," *Journal of Engineering Mechanics*, ASCE, Vol. 120, No. 1, 1994. pp. 135-159.
7. Yang, G., Spencer, Jr., B. F., Carlson, J. D., and Sain, M. K., "Large-scale MR fluid dampers: modeling and dynamic performance considerations," *Engineering Structures*, accepted, 2002.