# Semi-active Control of a Seismically Excited Cable-Stayed Bridge Considering Dynamic Models of MR Fluid Damper

# MR 유체 댐퍼의 동적모델을 고려한 사장교의 반(半)능동제어


정 형 조* 박 규 식** Spencer, B. F., Jr.*** 이 인 원****

Jung, Hyung Jo Park, Kyu Sik Spencer, B. F., Jr. Lee, In Won



## 국문요약

본 논문에서는 미국토목학회(ASCE) 의 사장교에 대한 첫번째 벤치마크 문제를 이용하여 제어-구조물 상호작용을 고려한 새로운 반능동제어 기법을 제안하였다. 이 벤치마크 문제에서는 2003년 완공 예정으로 미국 Missouri주에 건설 중인 Cape Girardeau 교를 대상 구조물로 고려하였다. Cape Girardeau 교는 New Madrid 지진구역에 위치하고, Mississippi 강을 횡단하는 주요 교량이라는 점 때문에 설계단계에서부터 내진 문제를 중요하게 고려하였다. 본 연구에서는 MR 유체 감쇠기를 제어 장치로 제안하였고, clipped-optimal 알고리듬을 제어 알고리듬으로 사용하였다. 또한, 대용량 MR 유체 감쇠기 실험 결과를 이용하여, Bingham 모델, Bouc-Wen 모델, 수정된 Bouc-Wen 모델과 같이 수치해석에 이용할 수 있는 다양한 동적 모델을 개발하였다. MR 유체 감쇠기는 제어가능한 에너지 소산장치이며 구조물에 에너지를 가하지 않기 때문에 제안된 제어기법은 한정입출력 안정성이 보장된다. 수치해석을 통해, MR 유체 감쇠기를 이용한 반능동제어 기법이 사장교의 응답 감소에 효과적인 방법임을 증명하였다.



**주요어** : 벤치마크 사장교 제어 문제, 반능동제어, 대용량 MR 유체 감쇠기, 동적 모델, clipped-optimal 알고리듬



## 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 focuses on a cable-stayed bridge in Cape Girardeau, Missouri, USA, for which construction is expected to be completed in 2003. Seismic considerations were strongly considered in the design of this bridge due to the location of the bridge in the New Madrid seismic zone and its critical role as a principal crossing of the Mississippi River. In this paper, magnetorheological(MR) fluid dampers are proposed as the supplemental damping devices, and a clipped-optimal control algorithm is employed. Several types of dynamic models for MR fluid dampers, such as a Bingham model, a Bouc-Wen model, and a modified Bouc-Wen model, are considered, which are obtained from data based on experimental results for full-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 simulation results show that the performance of the proposed semi-active control strategy using MR fluid dampers is quite effective.



**Key words** : benchmark cable-stayed bridge control problem, semi-active control, full-scale MR fluid damper, dynamic model, clipped-optimal algorithm


## 1. Introduction

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.(1) This first generation benchmark control problem focuses on a bridge currently under construction in Cape Girardeau, Missouri, USA, which will be completed in 2003. This bridge is the Missouri 74-Illinois 146 bridge spanning the Mississippi river designed by the HNTB corporation. Seismic considerations were strongly considered in the design of this bridge due to the location of the bridge in the New Madrid seismic zone and its critical role as a principal crossing of the Mississippi river. 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


* 한국과학기술원 토목공학과, 연구조교수(대표저자 : hjung@mail.kaist.ac.kr)

** 한국과학기술원 토목공학과, 박사과정

*** Linbeck Professor, Dept. of Civil Engineering and Geological Sciences, University of Notre Dame, USA

**** 한국과학기술원 토목공학과, 교수



본 논문에 대한 토의를 2002년 6월 29일까지 학회로 보내 주시면 그 결과를 게재하겠습니다. (논문접수일 : 2002. 3. 4 / 심사종료일 : 2002. 4. 10)

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.[(2)-(5)]

Recently, researchers have studied the first generation benchmark control problem provided by Dyke et al.[(1)] Jung et al.[(6)] proposed a semi-active control strategy for seismic protection of the benchmark cable-stayed bridge. This paper presented an extensive parametric study to obtain the optimal weighting parameters for the ideal semi-active control system design, in which the dynamics of the control devices did not be considered, 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. Koh et al.[(7)] also evaluated the performance and cost effectiveness of the benchmark cable-stayed bridge with semi-active dampers. The semi-active damper system was found to be more cost-effective when the cost due to failure was higher. Moon et al.[(8)] considered the use of MR fluid dampers to control the benchmark cable-stayed bridge. The dynamics of an MR fluid damper was included through use of a simple Bouc-Wen model, and the effect of varying control device configurations were examined.

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 semi-active control strategies using MR fluid dampers for the seismic protection of such structures. In this study, several types of dynamic models for MR dampers, such as a Bingham model[(9)], a Bouc-Wen model[(10),(11)], and a modified Bouc-Wen model[(10)], are considered. The parameters of each dynamic model are optimized by using the data based on the experimental results of a full-scale MR fluid damper. Also, a clipped-optimal control algorithm, shown to perform well in previous studies involving MR fluid dampers[(2),(12)], 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 and 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

For completeness, this section briefly summarizes the benchmark cable-stayed bridge problem, including discussion of the bridge model, ground excitations considered, and evaluation criteria, that was developed under the coordination of the ASCE Task Committee on Structural Control Benchmarks. More details can be found in Dyke et al.[(1)]

### 2.1 Benchmark bridge model

This benchmark problem considers the cable-stayed bridge shown in Fig. 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.[(1)] 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

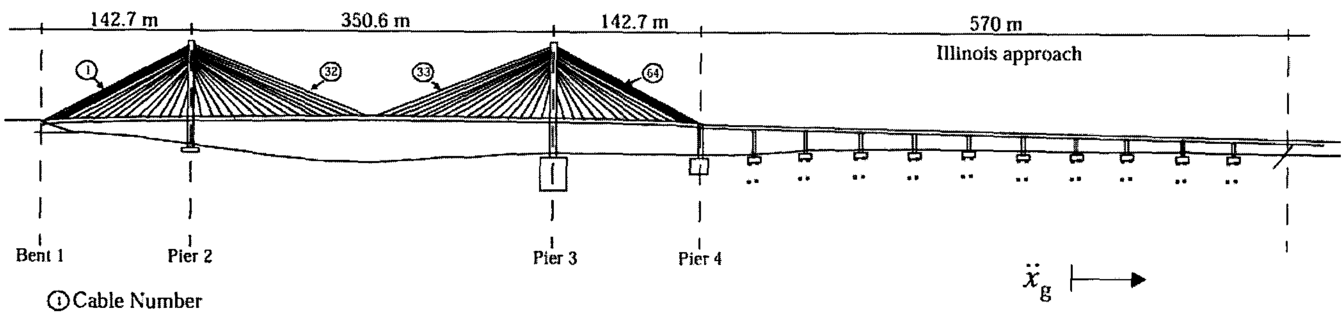



Fig. 1 Schematic of the Cape Girardeau Bridge[(1)]

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 in the longitudinal direction is considered for this first generation benchmark problem.

The finite element model of the bridge(shown in Fig. 2), which is modeled by beam elements, cable elements, and rigid links, has a large number of degrees-of-freedom. 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. In the as-built structure, shock transmission devices are installed at the deck-tower connections. For the benchmark study, these shock transmission devices are removed so as to allow other control devices to be considered. The first ten frequencies of the evaluation bridge model are 0.1618, 0.2666, 0.3723, 0.4545, 0.5015, 0.5650, 0.6187, 0.6486, 0.6965, and 0.7094Hz, which are much lower than those of the bridge model in which the shock transmission devices are present.

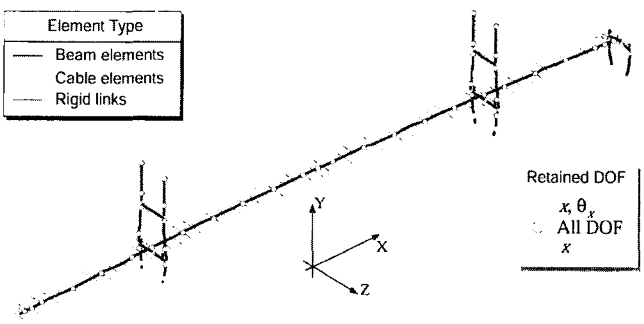



Fig. 2 Finite element model of the Cape Girardeau Bridge[1]

## 2.2 Evaluation criteria

Eighteen criteria have been defined to evaluate the capabilities of each proposed control strategy.[1] 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. More details can be found in Dyke et al.[1]

## 3. 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[2],[12], is employed to determine the control action.

## 3.1 Sensors

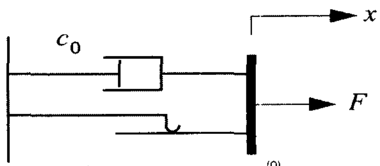
Five accelerometers and four displacement transducers are used for feedback in the control algorithm. Two accelerometers are located at the top of each of the two towers, and one is located on the deck at mid span. Two displacement sensors are placed between the deck and pier 2, and the other two are 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. All sensors employed in this study are assumed to be ideal, having a constant magnitude and phase[6], and the sensitivity of accelerometers ( $G_a$ ), the displacement transducers ( $G_d$ ) and the force transducers ( $G_f$ ) are 7/9.81V/(m/sec$^2$), 30V/m and 0.01V/kN, respectively. Thus, sensors can be modeled as

$$\mathbf{y}_s = \begin{bmatrix} G_a\mathbf{I}_{5\times5} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & G_a\mathbf{I}_{5\times5} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & G_a\mathbf{I}_{5\times5} \end{bmatrix} \mathbf{y}_m + \mathbf{n} = \mathbf{D}_s\mathbf{y}_m + \mathbf{n} \qquad (1)$$

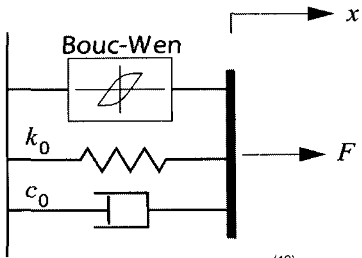
where $\mathbf{y}_s$ is a vector of the measured responses, including noise, in Volts, $\mathbf{y}_m$ is a vector of the noise-free responses in physical units, and $\mathbf{n}$ is the measurement noise, which has an *rms* value of 0.003V.[1]

### 3.2 Control devices

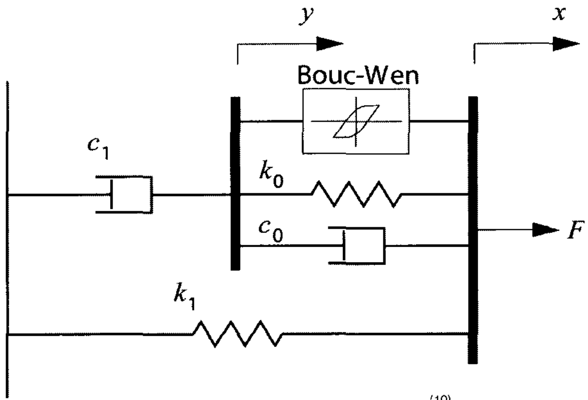
A total of 24 MR fluid dampers are considered as control devices. Each device has a capacity of 1000kN. Four between the deck and pier 2, eight between the deck and pier 3, eight between the deck and bent 1, and four between the deck and pier 4 are placed. To accurately predict the behavior of the controlled structure, an appropriate modeling of MR fluid dampers is essential. Several types of control-oriented dynamic models have been investigated for modeling MR fluid dampers.[9]-[11] Herein, three types of such dynamic models are considered. 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 full-scale(i.e., 20ton) MR fluid dampers.[13]




(a) Bingham model[9]




(b) Bouc-Wen model[10]




(c) Modified Bouc-Wen model[10]

Fig. 3 Dynamic models of the MR fluid damper

#### 3.2.1 Bingham model

The Bingham model consists of a Coulomb friction element in parallel with a viscous damper as shown in Fig. 3(a).[9],[10] The force generated by the MR fluid damper is given by

$$f = f_y \,\mathrm{sgn}(\dot{x}) + c_0\dot{x} \qquad (2)$$

where $f_y$ is the yield force, $c_0$ is the damping coefficient, and $\dot{x}$ is the velocity of the device. This model assumes that in the pre-yield condition, the material is rigid and does not flow.

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.[10] In the Bingham model, therefore, the following relations are considered.

$$f_y = f_{ya} + f_{yb}u, \text{ and } c_0 = c_{0a} + c_{0b}u \qquad (3)$$

#### 3.2.2 Bouc-Wen model

The Bouc-Wen model[10],[11], which is numerically tractable and has been used extensively for modeling hysteretic system, is considered for describing the behavior of the MR damper(see Fig. 3(b)). The force generated by the damper is given by

$$f = \alpha z + c_0\dot{x} \qquad (4)$$

where the evolutionary variable $z$ is governed by

$$z = -\gamma|\dot{x}|z|z|^{n-1} - \beta\dot{x}|z|^n + A\dot{x} \qquad (5)$$

By adjusting the parameters of the model $\gamma$, $\beta$, $n$, and $A$, the degree of linearity in the unloading and the smoothness of the transition from the pre-yield to the post-yield region can be controlled.

Some of the model parameters depend on the command voltage $u$ to the current driver as follows.

$$\alpha = \alpha_a + \alpha_b u, \text{ and } c_0 = c_{0a} + c_{0b}u \qquad (6)$$

#### 3.2.3 Modified Bouc-Wen model

Spencer et al.[10] proposed the modified Bouc-Wen model as shown in Fig. 3(c). 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

$$f = \alpha z + c_0(\dot{x} - \dot{y}) + k_0(x - y) + k_1(x - x_0) = c_1\dot{y} + k_1(x - x_0) \tag{7}$$

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

$$z = -\gamma|\dot{x} - \dot{y}|z|z|^{n-1} - \beta(\dot{x} - \dot{y})|z|^{n} + A(\dot{x} - \dot{y}) \tag{8}$$

and

$$\dot{y} = \frac{1}{c_0 + c_1}\{\alpha z + c_0\dot{x} + k_0(x - y)\} \tag{9}$$

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

$$\alpha = \alpha_a + \alpha_b u,\ c_0 = c_{0a} + c_{0b}u,\ \text{and}\ c_1 = c_{1a} + c_{1b}u \tag{10}$$

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

$$\dot{u} = -\eta(u - v_c) \tag{11}$$

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

A constrained nonlinear optimization was used to obtain the parameters. 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 a 20ton MR fluid damper.[13] In order to obtain the data of a 100ton(i.e., 1000kN) damper considered in this study, the experimental data of the 20ton damper have been linearly scaled up 5 times.

The vector of forces $\mathbf{f}$ produced by the dampers are thus written as

$$\mathbf{f} = \mathbf{K}_f[f_1\ f_2\ \cdots\ f_n]^T \tag{12}$$

where $f_i$ is the force generated by the $i$th damper installed in the structure, and $\mathbf{K}_f$ is a matrix of zeros and ones that accounts for the number of and location of the installed devices.

### 3.3 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.[1] 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.[14]

Table 1 Parameters of mechanical models for the MR damper

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| Bingham model | | | |
| $f_{ya}$ | 100.0 kN | $c_{0a}$ | 82.8 kNsec/m |
| $f_{yb}$ | 75.0 kN/V | $c_{0b}$ | 48.6 kNsec/m/V |
| $\eta$ | 100 sec$^{-1}$ | | |
| Bouc-Wen model | | | |
| $\alpha_a$ | 44.9 kN/m | $\gamma$ | 113.1 m$^{-2}$ |
| $\alpha_b$ | 40.0 kN/m/V | $\beta$ | 113.1 m$^{-2}$ |
| $c_{0a}$ | 72.2 kNsec/m | $A$ | 702.1 |
| $c_{0b}$ | 66.8 kNsec/m/V | $n$ | 2 |
| $\eta$ | 100 sec$^{1}$ | | |
| Modified Bouc-Wen Model | | | |
| $\alpha_a$ | 68.6 kN/m | $k_0$ | 0.012 kN/m |
| $\alpha_b$ | 61.7 kN/m/V | $k_1$ | 0.0028 kN/m |
| $c_{0a}$ | 60.2 kNsec/m | $x_0$ | 0.0 m |
| $c_{0b}$ | 54.2 kNsec/m/V | $\gamma$ | 128.5 m$^{-2}$ |
| $c_{1a}$ | 4395.5 kNsec/m | $\beta$ | 128.5 m$^{-2}$ |
| $c_{1b}$ | 3955.9 kNsec/m/V | $A$ | 386.0 |
| $\eta$ | 100 sec$^{-1}$ | $n$ | 2 |

$$\dot{\mathbf{x}}_d = \mathbf{A}_d\mathbf{x}_d + \mathbf{B}_d\mathbf{f} + \mathbf{E}_d\ddot{x}_g \tag{13}$$

$$\mathbf{z} = \mathbf{C}_d^z\mathbf{x}_d + \mathbf{D}_d^z\mathbf{f} + \mathbf{F}_d^z\ddot{x}_g \tag{14}$$

$$\mathbf{y}_s = \mathbf{D}_s(\mathbf{C}_d^y\mathbf{x}_d + \mathbf{D}_d^y\mathbf{f} + \mathbf{F}_d^y\ddot{x}_g) + \mathbf{n} \tag{15}$$

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, and $\mathbf{z}$ the regulated output vector including shear forces and moments in the towers, deck displacements, and cable tension forces.

### 3.4 Control schemes for MR fluid dampers

The strategy of a clipped-optimal control algorithm[2],[12] 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[15] 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.,

$$J = \lim_{\tau\to\infty}\frac{1}{\tau}E\left[\int_0^{\tau}\left\{\ \mathbf{z}^{\mathrm{T}}\mathbf{Q}\mathbf{z}+\mathbf{f}^{\mathrm{T}}\mathbf{R}\mathbf{f}\right\}\ dt\right] \tag{16}$$

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[6], the following combination of weighting parameters is considered.

$$\mathbf{Q}_{\mathrm{om\&d}} = \begin{bmatrix} q_{\mathrm{om}}\mathbf{I}_{4\times4} & \mathbf{0} \\ \mathbf{0} & q_{\mathrm{d}}\mathbf{I}_{4\times4}\end{bmatrix} \tag{17}$$

where $q_{\mathrm{om}}$ and $q_{\mathrm{d}}$ 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

$$\mathbf{f}_c = L^{-1}\left\{-\mathbf{K}_c(s)L\begin{Bmatrix}\mathbf{y}_m\\ \mathbf{y}_f\end{Bmatrix}\right\} \tag{18}$$

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

$$v_i = V_{\max}H[(f_{ci}-f_i)f_i] \tag{19}$$

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. A block diagram of this semi-active control system is shown in Fig. 4. In the block diagram, the dependence of the MR damper forces on the structural responses is indicated by the link feeding back the vectors $\mathbf{x}$ and $\dot{\mathbf{x}}$ which contain the displacements of the devices and velocities at the attachment points of the MR fluid dampers.

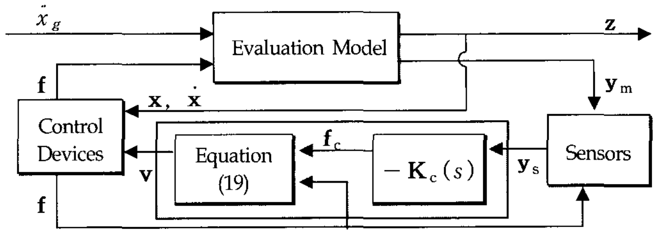


Fig. 4 Semi-active control strategy using clipped-optimal algorithm

## 4. Numerical simulation results

To verify the effectiveness of the proposed control design, a set of simulations is performed for the three earthquakes specified in the benchmark problem statement. In the simulation studies, the digitally implemented controller has a sampling time of $T$=0.002sec, which is set equal to the integration time step of the simulation. Simulation results for the proposed control design are compared to those of an ideal 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 $q_{om} = 6\times10^{-9}$, $q_d = 6\times10^{3}$.[17]

Table 2 shows the values of the 18 evaluation criteria. While the controller presented in Dyke et al.[1] 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 strategies, $J_{14}$ and $J_{15}$, which correspond to the non-dimensionalized maximum instantaneous power and total power, are not applicable. Note that in each case tension in the stay cables remained within the recommended region of allowable values, and peak values of the force, stroke, and velocity of the control devices are feasible.[1] The time-history responses of the controlled bridge are compared to those of the uncontrolled bridge for the El Centro, Mexico City, and Gebze

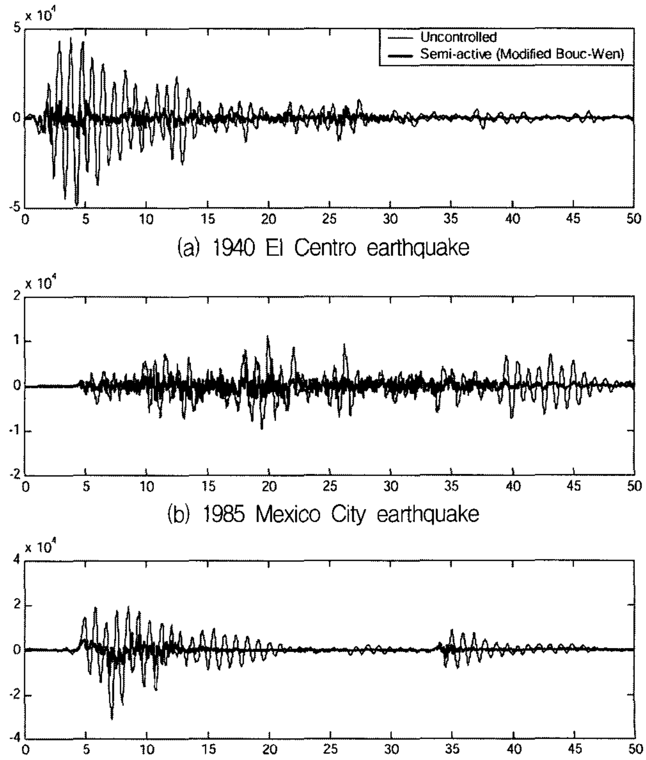
Table 2 Maximum evaluation criteria for all the three earthquakes

| Criterion | Dyke et al. (2000) | Ideal active control ($H_2$/LQG) | Semi-active control | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Ideal semi-active control | Considering the dynamics of the control devices | | | | | | | | |
| | | | | Bingham model | | | Bouc-Wen model | | | Modified Bouc-Wen model | | |
| | | | | Passive-off | Passive-on | Clipped-optimal | Passive-off | Passive-on | Clipped-optimal | Passive-off | Passive-on | Clipped-optimal |
| $J_1$ - peak base shear | 0.458 | 0.499 | 0.456 | 0.448 | 0.589 | 0.472 | 0.452 | 0.551 | 0.486 | 0.446 | 0.535 | 0.474 |
| $J_2$ - peak shear at deck level | 1.378 | 1.199 | 1.194 | 1.761 | 2.342 | 1.181 | 1.903 | 1.153 | 1.246 | 1.896 | 1.018 | 1.234 |
| $J_3$ - peak overturning mom. | 0.584 | 0.446 | 0.476 | 0.615 | 0.501 | 0.434 | 0.664 | 0.644 | 0.439 | 0.662 | 0.575 | 0.432 |
| $J_4$ - peak mom. at deck level | 1.225 | 0.869 | 0.828 | 2.645 | 0.626 | 0.735 | 2.966 | 0.589 | 0.774 | 2.928 | 0.591 | 0.765 |
| $J_5$ - peak deviation of cable tension | 0.186 | 0.157 | 0.178 | 0.261 | 0.211 | 0.175 | 0.281 | 0.190 | 0.168 | 0.279 | 0.188 | 0.167 |
| $J_6$ - peak deck displacement | 3.564 | 2.018 | 1.967 | 8.152 | 1.059 | 1.764 | 9.000 | 0.829 | 1.881 | 8.937 | 0.865 | 1.840 |
| $J_7$ - normed base shear | 0.398 | 0.352 | 0.350 | 0.380 | 0.484 | 0.362 | 0.393 | 0.555 | 0.366 | 0.378 | 0.456 | 0.360 |
| $J_8$ - normed shear at deck level | 1.437 | 1.012 | 1.144 | 2.290 | 3.764 | 1.146 | 2.549 | 1.223 | 1.115 | 2.521 | 0.931 | 1.087 |
| $J_9$ - normed overturning mom. | 0.455 | 0.330 | 0.330 | 0.770 | 0.385 | 0.342 | 0.884 | 0.612 | 0.337 | 0.872 | 0.471 | 0.328 |
| $J_{10}$ - normed mom. at deck level | 1.457 | 0.860 | 0.914 | 3.567 | 0.862 | 1.050 | 4.149 | 1.228 | 0.992 | 4.067 | 0.654 | 0.909 |
| $J_{11}$ - normed dev. of cable tension | 2.797e-2 | 1.546e-2 | 1.697e-2 | 2.531e-2 | 2.134e-2 | 1.747e-2 | 2.703e-2 | 2.275e-2 | 1.662e-2 | 2.660e-2 | 2.101e-2 | 1.652e-2 |
| $J_{12}$ - peak control force | 1.714e-3 | 1.961e-3 | 1.961e-3 | 3.185e-4 | 1.961e-3 | 1.961e-3 | 2.691e-4 | 1.961e-3 | 1.961e-3 | 2.553e-4 | 1.961e-3 | 1.961e-3 |
| $J_{13}$ - peak stroke | 1.954 | 1.106 | 1.078 | 4.470 | 0.580 | 0.967 | 4.934 | 0.454 | 1.031 | 4.900 | 0.474 | 1.009 |
| $J_{14}$ - peak power | 7.369e-3 | 9.205e-3 | - | - | - | - | - | - | - | - | - | - |
| $J_{15}$ - peak total power | 6.949e-4 | 8.681e-4 | - | - | - | - | - | - | - | - | - | - |
| $J_{16}$ - no. of control devices | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 24 |
| $J_{17}$ - no. of sensors | 9 | 9 | 33 | 0 | 0 | 33 | 0 | 0 | 33 | 0 | 0 | 33 |
| $J_{18}$ - no. of resources | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 |

earthquakes in Fig. 5. In this figure, it is shown that the controller is able to achieve a significant reduction in the base shear forces as compared to the uncontrolled system.

The performance of the clipped-optimal control system is generally similar to that of the ideal active control system as shown in the table. 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. 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.[1]

As shown in the table, the performance of the proposed semi-active control system 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 control devices. 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., $J_1$ - peak base shear at deck level(3.8%) and $J_2$ - shear at deck level(3.2%)), whereas other criteria for the case considering device dynamics are better than those for the ideal case (e.g., $J_3$ - peak overturning moment(9.2%) and $J_6$ - peak deck displacement(6.5%)). Since the proposed semi-active control




(a) 1940 El Centro earthquake

(b) 1985 Mexico City earthquake

(c) 1999 Gebze earthquake

Fig. 5 Uncontrolled and controlled base shear forces devices still act as passive-type viscous dampers when the calculated semi-active control force is zero, this behavior of the damper could affect the performance of the proposed control system in a positive way and may also be one of the reasons that some of the evaluation criteria for the case considering the dynamics of the control devices can be better than those in the ideal case, although including the dynamics of control devices would generally worsen the achievable results.

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., $J_1$ - peak base shear, and $J_7$ - normed base shear).

Note that the three dynamic models of MR dampers considered in this study generally give the similar results, as shown in Table 2. In the case of the 1985 Mexico City earthquake, however, the normed moments at deck level ($J_8$) of the passive-on system using the Bingham model are quite different from those of the other two models(e.g., 3.764 vs 1.223 and 0.924). If the integration time step of the simulation in the case of the Bingham model is reduced, the results are closer to those in the cases of the other two models. On the other hand, the smaller integration time step results in the longer simulation time. Therefore, the Bouc-Wen model and the modified Bouc-Wen model are generally more computationally tractable than the Bingham model.

## 5. 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. Various dynamic models of MR fluid dampers, such as the Bingham model, the Bouc-Wen model, and the modified Bouc-Wen model, are considered. The parameters of each dynamic model are optimized by using the data based on the experimental results of a full-scale MR fluid damper. As seen from numerical results, the Bouc-Wen model and the modified Bouc-Wen model are more appropriate than the Bingham model in this preliminary study. A clipped-optimal control algorithm is used to determine the control action for each MR fluid 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, 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.

## Acknowledgements

The authors gratefully acknowledge the support of this research by the 1999 Korea Research Foundation Grant, the National Research Laboratory for 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., 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.
2. 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*, Vol. 5, 1996, pp. 565-575.
3. Jansen, L. M. and Dyke, S. J., "Semiactive control strategies for MR dampers: comparative study," *Journal of Engineering Mechanics*, ASCE, Vol. 126, No. 8, 2000, pp. 795-803.
4. Spencer, Jr., B. F., Johnson, E. A., and Ramallo, J. C., "'Smart' isolation for seismic control," *JSME International Journal*, Vol. 43, No. 3, 2000, pp. 704-711.
5. Yoshioka, H., Ramallo, J., and Spencer, Jr., B. F., "'Smart' base isolation strategies employing magnetorheological dampers," *Journal of Engineering Mechanics*, ASCE, 2001 (accepted).
6. Jung, H. J., Spencer, Jr., B. F., and Lee, I. W., "Benchmark control problem for seismically excited cable-stayed bridges using smart damping strategies," *IABSE Conference on Cable-Supported Bridges*, Seoul, Korea, Serial 84, 2001, pp. 256-257.
7. Koh, H. M., Park, W., Park, K. S., Ok, S. Y., and Hahm, D., "Performance evaluation and cost effectiveness of semi-active vibration control system for cable-stayed bridges under earthquake excitation," *IABSE Conference on Cable-Supported Bridges*, Seoul, Korea, 2001, pp. 258-259.
8. Moon, S. J., Bergman, L. A., and Voulgaris, P. G.,

"Application of magnetorheological dampers to control of a cable-stayed bridge subjected to seismic excitation," *Journal of Structural Engineering*, ASCE, 2001(submitted).

9. Stanway, R., Sproston, J. L., and Stevens, N. G., "Non-linear modeling of an electro-rheological vibration damper," *Journal of Electrostatics*, Vol. 20, 1987, pp. 167-184.
10. Spencer, Jr., B. F., Dyke, S. J., Sain, M. K., and Carlson, J. D., "Phenomenological model of a magnetorheological damper," *Journal of Engineering Mechanics*, ASCE, Vol. 123, No. 3, 1997, pp. 230-238.
11. Wen, Y. K., "Method of random vibration of hysteretic systems," *Journal of Engineering Mechanics Division*, ASCE, Vol. 102, EM2, 1976, pp. 249-263.
12. Dyke, S. J., Spencer, Jr., B. F., Sain, M. K., and Carlson, J. D., "An experimental study of MR dampers for seismic protection," *Smart Materials and Stuctures: Special Issue on Large Civil Structures*, 1997.
13. 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*, Vol. 30, No. 3, 2002, pp. 309-323.
14. Laub, A. J., Health, M. T., Paige, C. C., and Ward, R. C., "Computation of system balancing transformations and other applications of simultaneous diagonalization algorithms," *IEEE Transaction on Automatic Control*, AC-32, 1987, pp. 17-32.
15. 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.