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Vibration Suppression of Stay Cable Using MR Damper-based Control Systems

Hyung-Jo Jung[1], Ji-Eun Jang[2], Woon Jeong[3] and In-Won Lee[4]

[1]*Department of Civil and Environmental Engineering, Sejong University, Seoul 143-747, Korea*
[2]*Department of Civil and Environmental Engineering, KAIST, Daejeon 305-701, Korea*
[3]*Hyundai Institute of Construction Technology, Yongin 449-716, Korea*
[4]*Department of Civil and Environmental Engineering, KAIST, Daejeon 305-701, Korea*
hjung@sejong.ac.kr, jejang@kaist.ac.kr, maskwj@hdec.co.kr, iwlee@kaist.ac.kr

ABSTRACT

In this paper, the efficacy of the MR damper-based control systems for vibration suppression of stay cables has been experimentally investigated. The performance of the several control strategies for the semiactive control system, such as the clipped-optimal control, the Lyapunov stability theory-based control, the maximum energy dissipation and the modulated homogeneous friction, has been compared with that of the passive-type control systems employing an MR damper (i.e., the *passive-off* and the *passive-on* types). To do this, the full-scale stay cable, which is the same as used for the in-service cable-stayed bridge in Korea, is considered. The acceleration and the displacement of the stay cable as well as the damping force of the MR damper are measured. The velocity of the cable at the damper location, which is needed for some control algorithms, is obtained by differentiating the measured displacement. The damping ratios of the cable system employing MR dampers, which can be estimated by the Hilbert transform-based identification method, show the effectiveness of each control strategy considered.

INTRODUCTION

A cable-stayed bridge has become a popular type of bridges throughout the world because of its aesthetic shape, structural efficiency, and economical construction. However, such a structure might be vulnerable to dynamic loads such as earthquakes and strong winds due to its flexibility, low structural damping, and so on. Especially, long steel stay cables, such as are widely used in cable-stayed bridges and other cable structures, are highly susceptible to vibration caused by wind, rain and support motion due to their large flexibility, relatively small mass and extremely low inherent damping. The cable vibration can result in reduction of cable and connection life due to premature failure and/or breakdown of corrosion protection as well as the risk of losing public confidence in such structures.

A number of methods, such as tying multiple cables together, aerodynamic cable surface

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[1] Assistant Professor
[2] Graduate Student
[3] Researcher
[4] Professor

modification, and passive and active axial and transverse cable control, have been proposed and/or implemented to suppress cable vibrations, though each method has its limitations. Tying cables together deteriorates the aesthetics of the cable-stayed bridge and changing the surface of the cable is impractical for retrofitting applications and may increase motion during high winds. Discrete passive viscous dampers attached perpendicular to the cables have been used on lots of bridges. It has been, however, demonstrated that the damper attachment location should be typically restricted to be within 5% of the cable length from the cable anchorage. On the other hand, an active transverse control method for mitigating the cable vibration has not been implemented in spite of its prominent performance, because it requires significant power sources beyond practical limits for the given number of cables and the isolated locations where controllers are placed.

Recently, several studies have demonstrated that semiactive dampers such as magnetorheological (MR) dampers may provide levels of damping far superior to their passive counterparts as well as can potentially achieve performance levels nearly the same as comparable active devices with few of the detractions. Johnson et al. (2000) analytically verified the efficacy of a semiactive damper in the case of stay cable neglecting sag, whereas Johnson et al. (2003) showed the similar numerical results in the case of flat-sag cables. Christenson (2001) experimentally verified the performance of an MR damper in mitigating cable responses by using a medium-scale cable. Ni et al. (2002) and Ko et al. (2002) carried out field comparative tests of cable vibration control using MR dampers. This is the world's first time implementation of MR-based smart damping technology in civil engineering structures.

In this paper, the effectiveness of MR dampers in mitigating responses of the real-scaled cable is experimentally investigated. In the experiment, an inclined flat-sag real-scaled cable, which is used in the in-service cable-stayed bridge in Korea, is considered. Two MR dampers are attached transverse to the cable near the bottom support to reduce cable vibration. The environmental excitation is a sinusoidal point load produced by a cable exciting system attached to the cable. The semiactive control systems consist of the controller with semiactive control algorithms, experimental sensors and MR dampers. The several semiactive control algorithms, such as the control strategy based on the Lyapunov stability theory, the clipped optimal controller, the maximum energy dissipation algorithm and the modulated homogeneous friction algorithm, are adopted and evaluated for the vibration control of stay cables. The performance of the control strategies for the semiactive control system is compared with that of the passive-type control systems employing an MR damper (i.e., the *passive-off* and the *passive-on* types).

EXPERIMENTAL SETUP FOR SEMIACTIVE CONTROL OF CABLE VIBRATION

A schematic of the experimental setup used in this study is shown in Fig. 1. The components of the experiment include the flat-sag cable, shaker, MR dampers, digital controller and spectrum analyzer. In the figure, F_s is the shaker force, F_d is the damper force, V is the voltage input to MR dampers, v_d and $\ddot{v}_d$ is the displacement and acceleration of the cable at the damper location, respectively, and v_e is the displacement of the cable at the evaluation point.

Stay Cable

The flat-sag cable used in the experiment is a PVC covered high-tension cable. The real-scaled cable experiment setup is shown in Fig. 2. The cross section and properties of the cable are demonstrated in Fig. 3 and Table 1. As shown in the figure, the cable is comprised of 7 strands, 5.73 cm in diameter. The cable is attached at one end to a base plate secured to the floor and attached at the other end to a wall plate attached to a sufficiently thick shear wall. In the table, L is the length of the cable, m is the cable mass per unit length, E is the modulus of elasticity, EI and EA are the flexural and axial rigidity, respectively, T is the cable tension, ς is the modal damping ratio, ω_0 is the first natural frequency of cable and θ is the inclination angle.

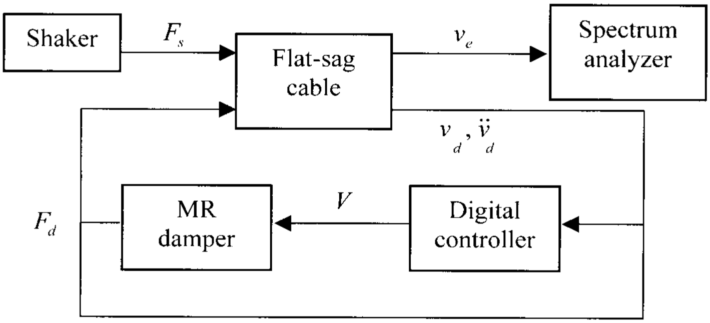

Fig. 1. Schematic of the experimental setup (Christenson 2001)

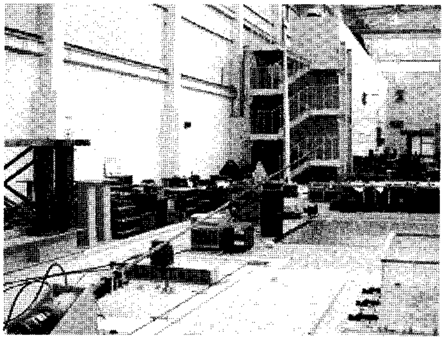

Fig. 2. Real-scaled stay cable experimental setup

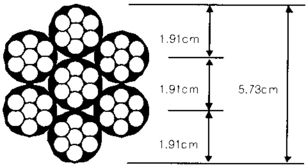

Fig. 3. Cross section of the cable

Table 1. Cable characteristics

Parameter	Value	Parameter	Value
L	44.7m	m	0.090 kN/m
E	1.89×10^8 kN/m^2	EI	3.79×10^5 kNm^2
θ	8.37°	EA	77.36 kN
T	500 kN	ς	$\varsigma_1 = 0.0015$
ω_0	2.45Hz		$\varsigma_{i\geq1} = 0.0005$

Magnetorheological (MR) Dampers

The semiactive damper used in the experiment is a MR controllable friction damper (Model No.: RD-1097-01) from Lord Corporation (see Fig. 4). The two dampers are attached transversely to the cable at the location of 1.34m (3% of the cable length) from the bottom supports as shown in Fig. 5. This damper has a maximum force level of approximately ± 100 N and the maximum voltage we can apply is 1.4 volts because of heat damage at the current more than 0.5 amp.

Fig. 4. Magnetorheological (MR) damper

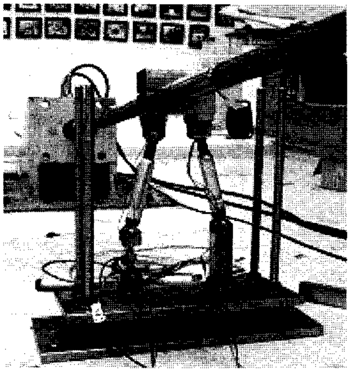

Fig. 5. Installation of MR dampers

Cable Exciting System

The cable exciting system consists of the hardware shown in Fig. 6 and the software governing the hardware, which was developed by Kim et al. (2003). The exciter can generate the harmonic exciting force perpendicular to longitudinal cable direction by rotating two identical masses in opposite direction respectively as shown in Fig. 7. The harmonic loading transmitted to the cable by the cable exciting system is

$$F(t) = \overline{m}e\overline{\omega}^2 \sin \overline{\omega} t$$

where $\overline{m}$ is a mass of the two rotating masses attached, e is the radius of rotation and $\overline{\omega}$ is the frequency of the rotating mass.

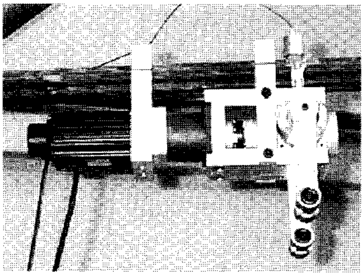

Fig. 6. Cable exciting system

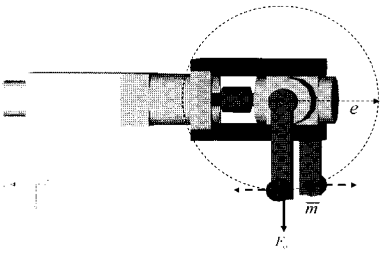

Fig. 7. Schematics of exciting system

Digital Controller

The controller is constructed by the Matlab real-time workshop executed in real-time using MS Visual C++. The measurements of responses are acquired from the displacement and acceleration sensors at the damper location and converted into the digital data by the NI DAQCard-6062E. The semiactive controller computes the value of the voltage, which is applied to the devices, from the cable responses and current damper force, since it is not possible to directly command the MR damper to generate a specific force.

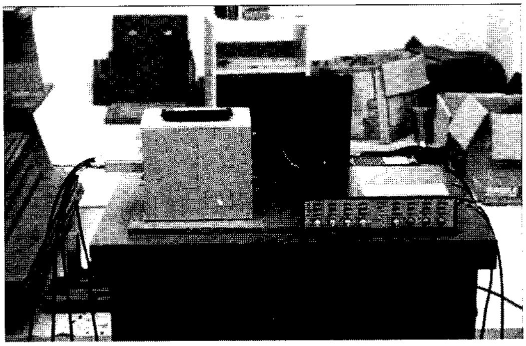

Fig. 8. Digital controller

CABLE MODEL FOR SEMIACTIVE CONTROL SYSTEM

In this study, the experiment is carried out on the real-scaled stay cable as shown in Fig. 2, which has small sag (within 0.1 % sag-to-span ratio with tension of 500 kN) (Kim et al. 2003). With small sag, the motion of the cable may be modeled by the motion of a taut string (Irvine 1981). Therefore, the transverse motion of the cable with a damper attached transverse to the cable is described as shown in Fig. 9.

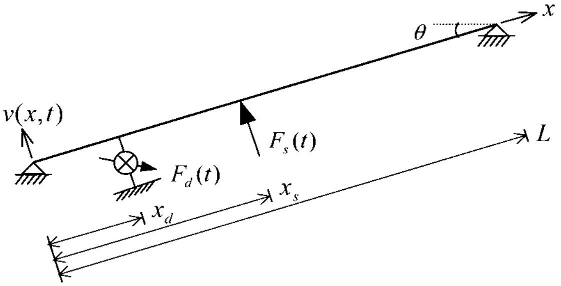

Fig. 9. Taut cable model

The motion of the taut cable in the linear range is described by the following partial differential equation,

$$m\ddot{v}(x,t) + c\dot{v}(x,t) - Tv''(x,t) = F_s(t)\delta(x - x_s) + F_d(t)\delta(x - x_d) \tag{1}$$

where $v(x,t)$ is the transverse deflection of the cable, c is the viscous damping per unit length and x_d and x_s are the locations of the damper and shaker.

Assuming that the transverse deflection may be approximated using a finite series

$$v(x,t) = \sum_{j=1}^{m} q_j(t)\phi_j(x) \tag{2}$$

with the generalized displacements, $q_j(t)$ and a set of shape functions, $\phi_j(x)$ that are

$$\phi_1(x)=\begin{cases} x/x_d & 0\le x\le x_d \\ (L-x)/(L-x_d) & x_d\le x\le L \end{cases} \tag{3a}$$

$$\phi_2(x)=\begin{cases} x/x_s & 0\le x\le x_s \\ (L-x)/(L-x_s) & x_s\le x\le L \end{cases} \tag{3b}$$

$$\phi_{j+2}(x)=\sin\pi jx \tag{3c}$$

We can get the equation of motion written in matrix form, using a standard Galerkin approach,

$$M\ddot{q}(t)+C\dot{q}(t)+Kq(t)=\varphi_s F_s(t)+\varphi_d F_d(t) \tag{4}$$

where M is the mass matrix, C is the damping matrix, K is the stiffness matrix, and φ_d and φ_s are the damper and shaker load vectors, respectively.

This equation can be written in state-space form as

$$\dot{z}=Az+BF_d+GF_s \tag{5}$$

where z is state vector, and

$$A=\begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix},\quad B=\begin{bmatrix} 0 \\ M^{-1}\varphi_d \end{bmatrix},\quad G=\begin{bmatrix} 0 \\ M^{-1}\varphi_s \end{bmatrix}$$

SEMIACTIVE CONTROL ALGORITHMS FOR CABLE DAMPING EXPERIMENT

Various approaches have been proposed for the control of semiactive devices. In this study, four control algorithms are adopted: the control algorithm based on the Lyapuov stability theory, the maximum energy dissipation algorithm, the clipped-optimal control algorithm, and the modulated homogeneous friction algorithm. In this section, each algorithm is briefly explained. More detailed information can be found in Jansen and Dyke (2000).

Control Algorithm Based on Lyapunov Stability Theory

According to the Lyapunov stability theory, the state is stable in the sense of Lyapunov when the rate of change of the Lyapunov function is negative semidefinite. Leitmann (1994) applied the Lyapunov's approach for the design of a semiactive controller. In this approach, the control law which will minimize the rate of change of the Lyapunov function is connected to control voltage input to semiactive devices as

$$v=V_{\max}H((-z)^T PBF_d) \tag{6}$$

where $V_{\max}$ is the maximum voltage input to MR dampers (i.e., 1.4 volts), and P is the real, symmetric, positive definite matrix satisfying the following Lyapunov equation

$$A^TP+PA^T=-Q_P$$

for a positive semidefinite matrix Q_P, and $H(\cdot)$ is the heaviside step function.

Maximum Energy Dissipation Algorithm

In the maximum energy dissipation algorithm, the Lyapunov function was chosen to represent the total vibratory energy and determine the control voltage as follows:

$$v = V_{\max} H(-\dot{v}_d F_d) \qquad (7)$$

The maximum energy dissipation control law requires only local measurements and command the maximum control voltage when the relative velocity at damper location and the measured damper force dissipate energy.

Clipped-optimal Control Algorithm

The clipped-optimal control algorithm consists of two parts of controller. The primary controller is the LQG control design which gives the optimal control force, $F_{d_{ci}}$, that minimizes the cost function as

$$J = \lim_{T \to \infty} E\left[\frac{1}{T}\int_0^T (z^T Q z + R F_d{}^2) dt\right] \qquad (8)$$

where Q and R are the response and control weighting matrices, respectively.

The secondary controller, which accounts for the characteristics of MR dampers that can only exert dissipative forces, is given by

$$v = V_{\max} H(\{F_{d_{ci}} - F_d\} F_d) \qquad (8)$$

The control law means that when the force produced by the damper is smaller than the desired optimal force and the two forces have the same direction, the controller will command the maximum voltage to control devices.

Modulated Homogeneous Friction Algorithm

The modulated homogeneous friction algorithm increases the slip force with the increasing damper deformation by increasing the contact force through feedback of the damper deformation to improve the energy dissipation process of semiactive dampers (Inaudi 1997). In this approach, at every local extreme deformation of the device the desired control force level, or control voltage input to dampers is renewed as following equations

$$v = V_{\max} H(F_{d_n} - |F_d|) \qquad (10)$$

$$F_{d_n} = g_n [P[v_d(t)]] \qquad (11)$$

where g_n is the positive gain and the operator $P[\cdot]$ is defined as the most recent local extreme deformation of the device.

EXPERIMENTAL RESULTS

To evaluate the performance of the semiactive control systems for cable vibration, the free vibration test is conducted with the stay cable which the two MR dampers controlled by each semiactive control algorithm are attached to. The cable is forced by the sinusoidal loading produced by the cable exciting system with the resonance frequency until the cable response reaches the sufficient vibration level for the free vibration test. The damping ratios of the cable system employing MR dampers are calculated to show the effectiveness of each control strategy considered. The damping ratios are dependent on the vibration amplitude, which represents the nonlinear characteristic of the stay cable. The Hilbert transform-based identification method is used to obtain the amplitude-dependent damping ratios of the cable by using the displacement measured at the location of 10.2 from the bottom support (Ko et al. 2002).

Passive-mode MR Damper

Before implementing semiactive control systems, MR dampers are passively operated with the different magnitudes of voltage inputs to find the optimal passive-mode case for control of cable vibration. To do this, the control voltage is incremented from 0 volts to 1.4 volts including the *passive-off* (i.e., $v = 0$ volts) and *passive-on* (i.e., $v = 1.4$ volts) cases.

As shown in Fig. 10, all the passively operated cases show the better performance than the uncontrolled case. While the damping ratio in the uncontrolled case is less than 0.1%, the ratio in the *passive-on* case with the amplitude of 5 mm is almost ten times (i.e., about 0.65%). According to the experimental results, the optimal passive-mode MR damper-based control system is the *passive-on* case. As the voltage input increases, the damping ratios also increases as well as the variation of damping ratio is appreciable, that is, the nonlinear behavior of the cable is more clearly observed.

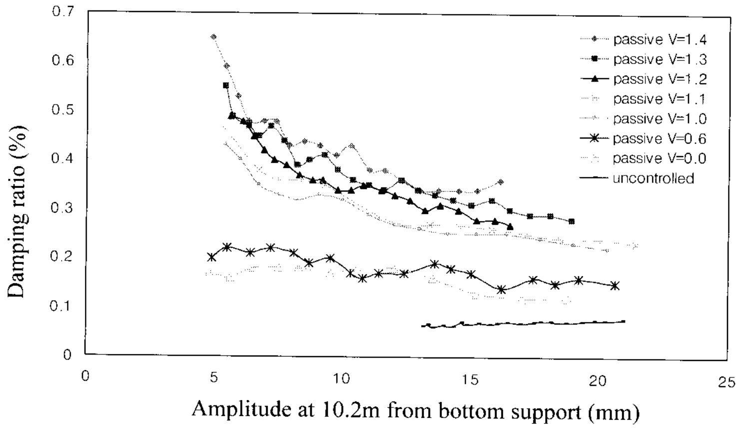

Fig. 10. Damping ratios of stay cable with passively operated MR dampers

Semiactive-mode MR Damper

All the semiactive control systems considered in the experiment have the bang-bang type (i.e., *on-off* type) controller, that is, the voltage input to MR dampers is either 0 volts or 1.4 volts, which is already expressed in the previous section. To make the well-performed controller, the optimal parameters for each controller should be obtained. In the case of the control algorithm based on the Lyapunov stability theory, the several experimental tests are carried out by varying the values in Q_p because of no standard method for selecting Q_p, The resulting Q_p is the matrix which has nonzero values in the first row of the matrix. In the case of the maximum energy dissipation algorithm, there is no need to find any parameters. In the case of the clipped-optimal control algorithm, after the parametric study, the following appropriate weighting parameters are obtained:

$$Q = \begin{bmatrix} \frac{1}{2}M & 0 & 0 \\ 0 & \frac{1}{2}M & 0 \\ 0 & 0 & 0 \end{bmatrix} \text{ and } R = 10^{-11}.$$

In the case of the modulated homogeneous friction algorithm, $g_n = 80{,}000\text{N/m}$ is selected after several experimental tests.

As shown in Fig. 11, all the semiactive controllers have the larger amplitude-dependent damping ratios than the *passive-off* cases. The overall performance of the control algorithm based on the Lyapunov stability theory is slightly better than other semiactive control strategies in this experiment. The *passive-on* case, however, shows the comparable result with the semiactive controllers as shown in the figure. This is because the capacity of the MR damper may not be proper to the real-scaled stay cable used in the experiment. That is, the maximum capacity of the MR damper has too small to effectively run the semiactive controllers for mitigating the vibration of the real-scaled cable. In addition, there might be a few additional reasons such as the ignorance of the sag effect in the cable model for the controller design.

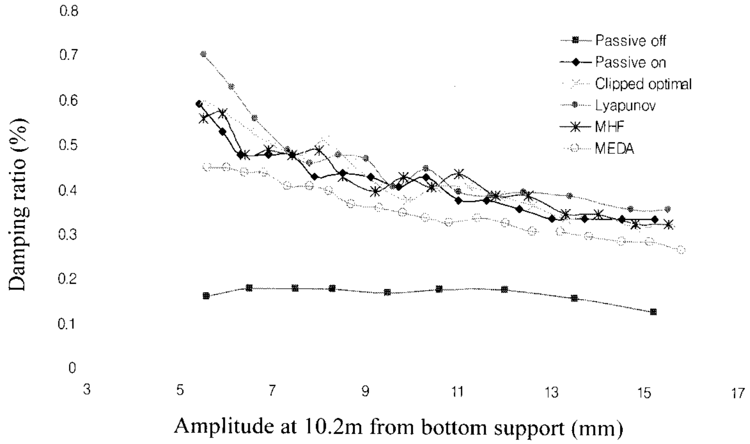

Fig. 11. Damping ratios of stay cable with semiactive MR dampers

CONCLUSIONS

The efficacy of the MR damper-based control systems for vibration suppression of stay cables has been experimentally investigated by using the 44.7 m real-scaled cable used in the in-service cable-stayed bridge in Korea. The performance of the several control strategies for the semiactive control system, such as the clipped-optimal control, the Lyapunov stability theory-based control, the maximum energy dissipation and the modulated homogeneous friction, has been compared with that of the passive-type control systems employing an MR damper (i.e., the *passive-off* and the *passive-on* types). It is verified from the experimental results that all the semiactive control cases show the larger damping ratios than the *passive-off* as well as uncontrolled cases, whereas the *passive-on* case has the similar performance to the semiactive control cases. The reasons why the effectiveness of the semiactive control systems is not clearly revealed in the experiment might be the discordance between the capacity of the MR damper and the size of the real-scaled cable, the ignorance of the sag effect, etc. To more clearly verify the superiority of semiactive-type dampers over passive-type dampers, the additional experiments by using MR dampers with the larger capacity as well as by considering the sag effect should be carried out.

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