TIME DELAY STUDY ON THE SEMI-ACTIVE CONTROL WITH A MAGNETORHEOLOGICAL DAMPER

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ABSTRACT :

The semi-active control with the advantages of both passive control and active control has been shown to be a promising strategy in mitigating seismic responses for isolated structures. A Magnetorheological (MR) damper is one of the smart semi-active devices which have been developed and studied recently. The damping force exerted from MR dampers can be regulated easily by changing the current input. Although the past researches have revealed that MR dampers in semi-active control systems are capable of mitigating seismic hazard, analytically and experimentally, it is inevitable that time delay may decrease the control performance of the semi-active control system.
The time-delay effect of an isolated bridge under semi-active control with a MR damper controlled by sliding mode control is studied in this paper. A target structure is analyzed under a typical near-field ground motion recorded in the Chi-Chi earthquake to evaluate effect of the time delay and the time delay compensation method. The numerical analytical results reveal that the time-delay deteriorates the control performance. A time-delay compensation method based on Newmark's integration method is adopted to mitigate such an effect. Through numerical simulation the compensation method shows a satisfactory performance of decreasing the time-delay effect in the semi-active control system by using a MR damper with the sliding mode control.

KEYWORDS: Time Delay, Semi-Active Control, Isolated Bridge, Magnetorheological Damper, Sliding Mode Control

1. INTRODUCTION

Semi-active control has been investigated popularly to mitigate the seismic responses of civil engineering structures because of having the advantages of both passive control and active control. A Magnetorheological (MR) damper is one of the smart semi-active devices which have been developed and studied recently. The damping force exerted from MR dampers can be regulated easily by changing the current input. In the past studies, MR dampers has been shown to effectively decrease the seismic responses of isolated bridges (e.g., Ruangrassamee and Kawashima 2001; Sahasrabudhe and Nagarajaiah 2005).
Since semi-active control system need proceeding time to feedback the structural responses and calculate the demanded control force by the used control algorithm, the effect of time delay is inevitable. Time delay may reduce the control performance or further cause the instability of the structure under control system. To decrease the influence of time delay, several compensation methods have been proposed (e.g., Abdel-Mooty and Roorda 1991; Agrawal *et al*. 1993, 2000; Pu 1998; Lee and Kawashima 2007). Among the proposed time delay compensation method, the compensation method based on Newmark's integration method proposed by Lee and Kawashima (2007) shows its superiority in semi-active control system. In the writers' previous experimental study on a MR damper, time delay is detected in the semi-active control system. Therefore this study is aimed to investigate the effect of the time delay compensation based on Newmark's integration method on the semi-active control system with a MR damper.
An isolated bridge under semi-active control with a MR damper controlled by sliding mode control is studied. The input excitation is a typical near-field ground motion recorded at Sun-Moon Lake in the 1999 Taiwan Chi-Chi earthquake. Through numerical simulation, the time delay compensation method based on Newmark's integration method demonstrates a satisfactory performance of decreasing the time-delay effect.

2. MAGNETOREOLOGICAL DAMPER

A Magnetorheological (MR) damper is one of the smart semi-active devices which have been developed and studied recently. MR fluids consist of micro-sized magnetic particles, such as iron particles, suspended in hydrocarbon or silicon oil. When a current is applied to change a magnetic field in the MR fluid, the dispersed particles form chains and the MR fluid alters the phase between viscous fluid and semi-solid to regulate the damping force. In this study, the property of a MR damper, RD-1005-3, produced by Lord Corporation is used in analysis.

2.1. Cyclic Test

In order to identify the property of the MR damper, cyclic tests are conducted under harmonic excitations of 0.5 Hz, 1 Hz and 2 Hz with applied current varying from 0 mA to 1000 mA by an servo-hydraulic actuator. The force-displacement and force-velocity responses of the MR damper are displayed in Figure 1.

2.2. MR Damper Model

Considering the practical implementation, two types of MR damper models are used in this study, shown in Figure 2. The simple MR damper model consisting of friction damping force and viscous damping force, which are linear functions of the applied current, is used to calculate the current (Ruangrassame and Kawashima, 2001). The damping force V generated by the MR damper is given by

$$V(t) = f_m(t) + c_m(t)\dot{x}_m(t) \tag{2.1}$$

where $\dot{x}_m$ is the relative velocity of the piston of the MR damper; f_m and c_m are assumed as the forms of

$$f_m(t) = f_{m1} + f_{m2}I(t)\,;\;\; c_m(t) = c_{m1} + c_{m2}I(t) \tag{2.2}$$

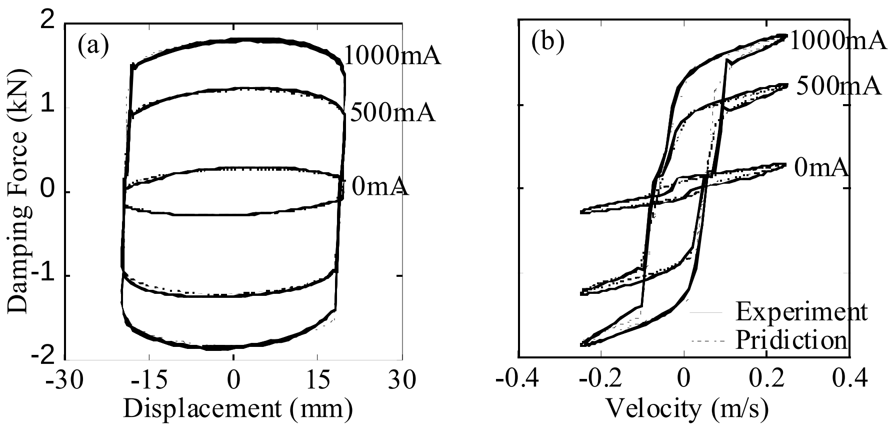

Figure 1 Comparison between experimentally-obtained and predicted responses vs. damping force under 2Hz sinusoidal excitation with an amplitude of 20 mm: (a) displacement, (b) velocity

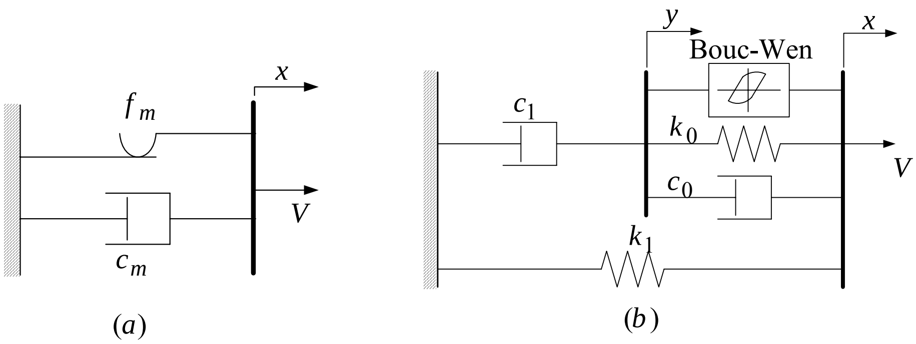

Figure 2 MR damper models: (a) simple model (b) complete model

where I is the applied current; the friction damping force and viscous damping coefficients of the MR damper with respect to current are shown in Figure 3. The parameters f_{mi} and c_{mi} can be obtained by the least square method.

Since the actual behavior of the MR damper exhibits hysteretic loop at small velocity, the complete model consisting of friction damping force, viscous damping force and Bouc-Wen hysteresis model proposed by Spencer *et al*. (1997) is used in analysis to simulate more accurately. It is of the form

$$\begin{aligned} V_{MR} &= \alpha z + c_0(\dot{x} - \dot{y}) + k_0(x - y) + k_1(x - x_0) \\ &= c_1\dot{y} + k_1(x - x_0) \end{aligned} \tag{2.3}$$

where

$$\dot{z} = -\gamma|\dot{x} - \dot{y}|z|z|^{n-1} - \beta(\dot{x} - \dot{y})|z|^n + A(\dot{x} - \dot{y}) \tag{2.4}$$

$$\dot{y} = \frac{1}{c_0 + c_1}\{\alpha z + c_0\dot{x} + k_0(x - y)\} \tag{2.5}$$

in which α, c_0, and c_1 are assumed to be the functions of current as (Yang *et al*. 2002)

$$\alpha(I) = -\alpha_a I^3 + \alpha_b I^2 + \alpha_c I + \alpha_d \tag{2.6}$$

$$c_0(I) = -c_{0a} I^2 + c_{0b} I + c_{0c} \tag{2.7}$$

$$c_1(I) = c_{1a} I^2 + c_{1b} I - c_{1c} \tag{2.8}$$

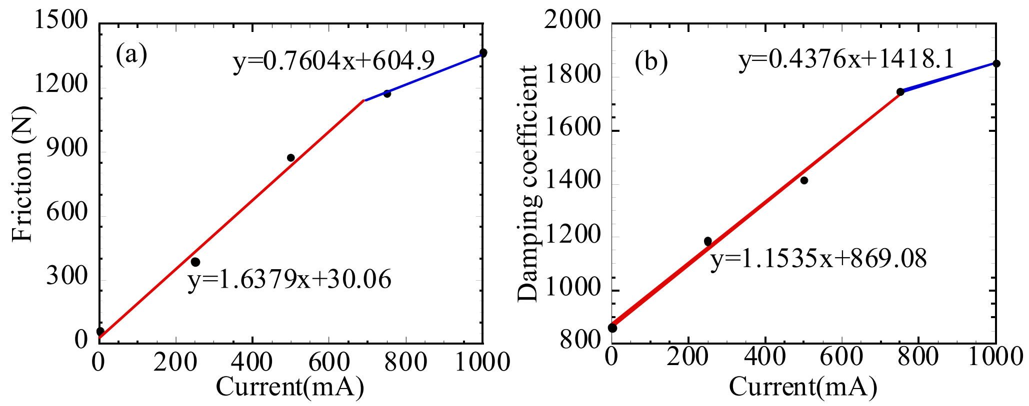

Figure 3 (a) Friction damping force and (b) viscous damping coefficient of the simple MR damper model

By a constrained nonlinear optimization subprogram of MATLAB, the parameters in Eqns. (2.6) through (2.8) can be obtained and the optimized parameters are given in Table 1. Figure 1 also shows the comparison between the experimental data and predicted results. It is found that the numerical model of the MR damper is satisfactory.

3. CONTROL ALGORITHM

The modified sliding mode control algorithm proposed by Lee (2005) is used to calculate the demanded control force herein. Assume a lump-mass shear-type structure is subjected the one-dimensional ground acceleration $\ddot{x}_g$, the equations of motion are given by

$$\mathbf{M}\ddot{\mathbf{X}}(t)+\mathbf{C}\dot{\mathbf{X}}(t)+F[\mathbf{X}(t)] = \mathbf{HU}(t)+\boldsymbol{\eta}\ddot{x}_g(t) \tag{3.1}$$

in which $\mathbf{X}(t)=\left[x_1,x_2,\ldots,x_n\right]^T$ is an n-vector with $x_j(t)$ being the displacement of the jth mass; $\mathbf{M}$ and $\mathbf{C}$ are $(n\times n)$ mass and damping matrices, respectively, where linear viscous damping is assumed for the bridge; $\mathbf{F}[\mathbf{X}(t)]$ is an n-vector denoting the nonlinear restoring force that is assumed to be a function of $\mathbf{X}(t)$; $\mathbf{H}$ is a $(n\times r)$ matrix denoting the location of r controllers; and $\boldsymbol{\eta}$ is an n-vector denoting the influence of the earthquake excitation. The equations of motion by Eqn. (3.1) can be written in a state space formulation as follows:

$$\dot{\mathbf{Z}}(t) = \mathbf{g}[\mathbf{Z}(t)]+\mathbf{BU}(t)+\mathbf{E}(t) \tag{3.2}$$

where $\mathbf{Z}(t)=\left[\mathbf{X}(t) \quad \dot{\mathbf{X}}(t)\right]^T$ is a $2n$ state vector; $\mathbf{g}\left[\mathbf{Z}(t)\right]$ is a $2n$ vector which is a nonlinear function of the state vector $\mathbf{Z}(t)$; $\mathbf{B}$ is a $(2n\times r)$ control force location matrix, and $\mathbf{E}$ is a $2n$ earthquake ground excitation vector, respectively, defined as follows:

$$\mathbf{g}[\mathbf{Z}(t)]=\begin{bmatrix}\dot{\mathbf{X}}(t)\\ -\mathbf{M}^{-1}[\mathbf{C}\dot{\mathbf{X}}(t)+\mathbf{F}[\mathbf{X}(t)]]\end{bmatrix};\quad \mathbf{B}=\begin{bmatrix}\mathbf{0}\\ \mathbf{M}^{-1}\mathbf{H}\end{bmatrix};\quad \mathbf{E}(t)=\begin{bmatrix}\mathbf{0}\\ \mathbf{M}^{-1}\boldsymbol{\eta}\end{bmatrix}\ddot{x}_g(t) \tag{3.3}$$

In sliding mode control, the aim of the control force is to drive the response trajectory toward the sliding surface, where the motion on the sliding surface defined by $\mathbf{S}=\mathbf{0}$ is stable, and then to maintain it on the sliding surface. Define the sliding surface $\mathbf{S}$ as a linear function of state vector $\mathbf{Z}$ such that

$$\mathbf{S} = \mathbf{PZ}(t) \tag{3.4}$$

Table 1 Parameters for the complete model of the MR damper

Parameter	Value	Parameter	Value
γ , β	36 cm^{-2}	α_c	1182 N/A
A	15	α_d	85 N
k_0	10 N/cm	c_{0a}	4 N s/A^2m
k_1	10 N/cm	c_{0b}	13.914 N s/Am
n	5	c_{0c}	8.56 N s/m
x_0	0.1 cm	c_{1a}	10046 N s/A^2m
α_a	2729 N/A^3	c_{1b}	10046 N s/Am
α_b	3319 N/A^2	c_{1c}	28017 N s/m

The sliding surface can be determined using the pole assignment method or the LQR method (Yang 1995). To design the controller, the Lyapunov function $V = \mathbf{S}^T\dot{\mathbf{S}}/2$ is considered. The sufficient condition for the sliding mode to occur is given by

$$\dot{V} = \mathbf{S}^T\dot{\mathbf{S}} \leq 0 \tag{3.5}$$

Substituting Eqn. (3.4) in Eqn. (3.5), taking the derivative and using the state equations of motion by Eqn. (3.2), an estimated recursive controller in form of discrete time, which is free of chattering effect, is written as

$$\mathbf{U}(t+\psi) = \mathbf{U}(t) - (\mathbf{PB})^{-1}\mathbf{P}\dot{\mathbf{Z}}(t) - \boldsymbol{\delta}\boldsymbol{\lambda}^T(t) \tag{3.6}$$

where ψ is sampling time; $\boldsymbol{\lambda} = \mathbf{S}^T\mathbf{PB}$; $\boldsymbol{\delta}$ is a ($r \times r$) diagonal positive-definite matrix with diagonal entries $\delta_1, \delta_2, ..., \delta_r$.

4. TIME DELAY EFFECT AND COMPENSATION METHOD

4.1. Time Delay Effect

Time delay is inevitable in active and semi-active control systems. Data acquisition, filtering, computing control force, control device achieving the required control force etc. are the reasons to cause the time delay. The time delay may reduce the control performance or result the instability of the controlled structure further. In the semi-active control, MR damper is expected to provide the demanded control force by Eqn. (3.6). Equating the demanded control force by Eqn. (3.6) and the exerting damping force from the MR damper by Eqn. (2.1) yields the demanded current. However, the above-mentioned time delay may occur in the semi-active control system. In this study, the effect of current delay caused by time delay is considered and a compensation method is used below.

4.2. Time Delay Compensation Method

The integration compensation method, proposed by Lee and Kawashima (2007), forecasting the response of the system based on Newmark's integration method is used in this research. On the assumption of the variation of acceleration over a time delay τ, the incremental equation by Eqn. (3.1) can be expressed as

$$\bar{\mathbf{K}}_{t-\tau}\Delta\mathbf{X}_{t-\tau} = \Delta\bar{\mathbf{P}}_{t-\tau} \tag{4.1}$$

where

$$\bar{\mathbf{K}}_{t-\tau} = \mathbf{K} + \frac{\gamma}{\beta\tau}\mathbf{C} + \frac{1}{\beta\tau^2}\mathbf{M} \tag{4.2}$$

$$\Delta\bar{\mathbf{P}}_{t-\tau} = \boldsymbol{\eta}\left(\Delta\ddot{x}_g\right)_{t-\tau} + \mathbf{H}\Delta\mathbf{U}_{t-\tau} + \left[\frac{1}{\beta\tau}\mathbf{M} + \frac{\gamma}{\beta}\mathbf{C}\right]\dot{\mathbf{X}}(t-\tau) + \left[\frac{1}{2\beta}\mathbf{M} + \tau\left(\frac{\gamma}{2\beta}-1\right)\mathbf{C}\right]\ddot{\mathbf{X}}(t-\tau) \tag{4.3}$$

in which $\Delta\mathbf{X}_{t-\tau} \equiv \mathbf{X}_t - \mathbf{X}_\tau$ is the incremental displacement and subscript t and $t-\tau$ denote the displacement at time t and $t-\tau$, respectively. $\left(\Delta\ddot{x}_g\right)_{t-\tau} \equiv \left(\ddot{x}_g\right)_t - \left(\ddot{x}_g\right)_\tau$ and $\Delta\mathbf{U}_{t-\tau} \equiv \mathbf{U}_t - \mathbf{U}_\tau$ are the incremental ground motion and control force, respectively; the parameters β and γ define the variation of acceleration over a time delay τ. Once $\Delta\mathbf{X}_{t-\tau}$ is computed from Eqn. (4.1), the incremental velocity $\Delta\dot{\mathbf{X}}_{t-\tau}$ and acceleration $\Delta\ddot{\mathbf{X}}_{t-\tau}$ can be obtained from

$$\Delta\dot{\mathbf{X}}_{t-\tau} = \frac{\gamma}{\beta\tau}\Delta\mathbf{X}_{t-\tau} - \frac{\gamma}{\beta}\dot{\mathbf{X}}_{t-\tau} + \tau\left(1-\frac{\gamma}{\beta}\right)\ddot{\mathbf{X}}_{t-\tau} \tag{4.4}$$

$$\Delta\ddot{\mathbf{X}}_{t-\tau} = \frac{\gamma}{\beta\tau^2}\Delta\mathbf{X}_{t-\tau} - \frac{\gamma}{\beta\tau}\dot{\mathbf{X}}_{t-\tau} - \frac{\gamma}{2\beta}\ddot{\mathbf{X}}_{t-\tau} \tag{4.5}$$

Because the ground acceleration $\ddot{x}_g$ and demanded control force $\mathbf{U}$ at time t are unknown, they are assumed to remain constant during the interval of time delay τ in this method. By the forecasted responses, the demanded control force and current can be predicted by the Eqn. (3.6) and Eqn. (2.1), respectively.

5. NUMERICAL SIMULATION AND RESULTS

5.1. Target Structure

For a typical continuous isolated bridge, it can be idealized as a two degree-of-freedom lump-mass system, as shown in Figure 4. A MR damper is set between the deck and column as a semi-active control device. To compromise the size of the MR damper used in this research, a small structure system is designed with $m_d = 200$ kg, $m_c = 85$ kg, $k_b = 28000$ N/m, and $k_c = 45500$ N/m is analyzed. The damping ratios of the system with the MR damper are assumed 4% for both modes.

5.2. Analytical Results

A typical near-field ground motion recorded at Sun-Moon Lake in 1999 Taiwan Chi-Chi earthquake is used in analysis. The ground motion is scaled down to 30%, as shown in Figure 5. Assuming that the current delay caused by the time delay is 100 ms and that the sampling time is 10 ms, Figures 6 and 7 show the comparison of the control damping force, applied current and deck displacements, respectively, of the target structure

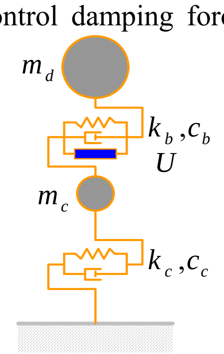

Figure 4 Two-degree-of-freedom lump-mass system

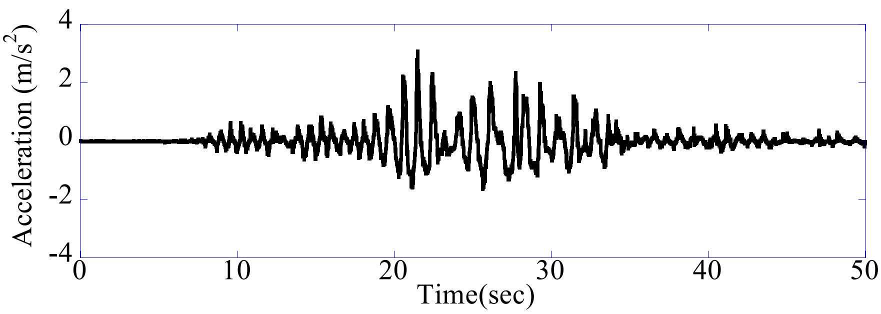

Figure 5 30% of Sun-Moon Lake ground motion

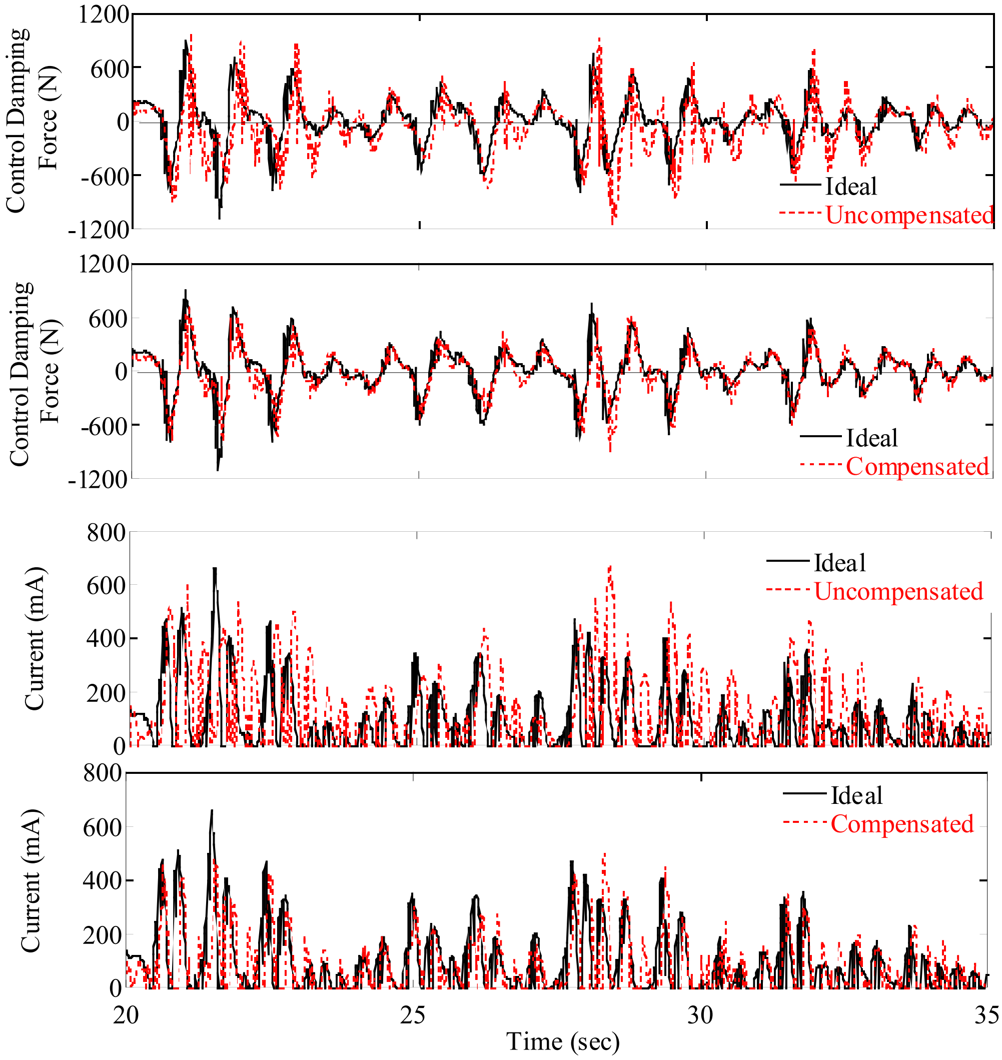

Figure 6 Comparison of the control damping force and current on the 100 ms time-delayed system with and without compensation

subjected to 30% of Sun-Moon Lake ground motion under semi-active control without time delay compensation and with time delay compensation method. As observed from Figure 6, the trend of control force of the MR damper of the time-delayed system with compensation is closer to the ideal system and the current also reveals the similar result. As shown in Figure 7, the less discrepancy occurs in the seismic response between the ideal system and the time-delayed system with compensation. It also can be found that the time-delayed system with compensation has the peak deck displacement of 32 cm, which is less than 42 cm in the time-delayed system without compensation but larger than 28 cm of the ideal system. In general the results show that the control force, current and seismic responses have good agreement under the system with time-delay compensation. Therefore, the used compensation method can effectively mitigate the deterioration of performance due to time delay in the semi-active control system with a MR damper.

6. CONCLUSIONS

The time-delay effect of an isolated bridge under semi-active control with a MR damper controlled by sliding mode control is studied in this paper. A target structure is analyzed under a typical near-field ground motion

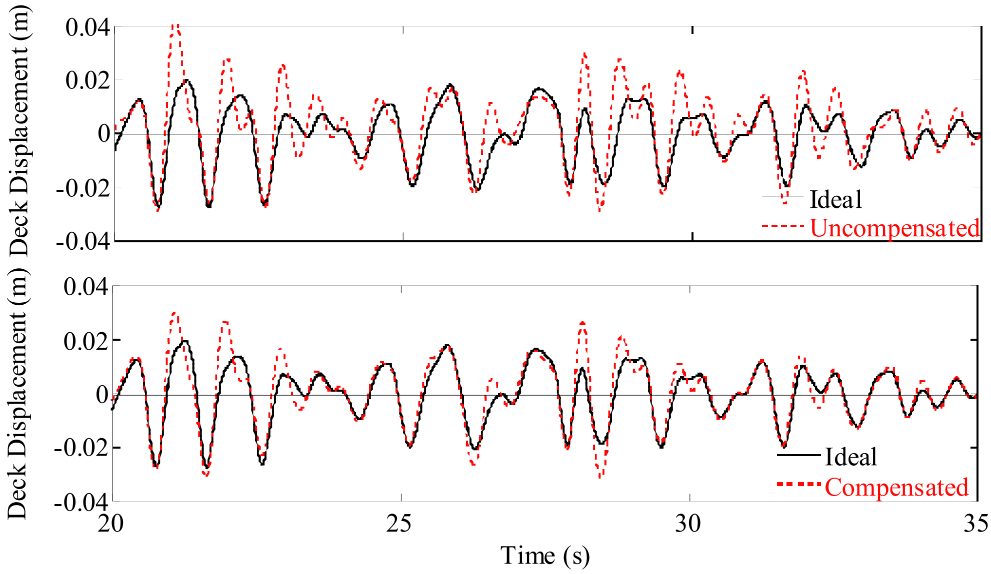

Figure 7 Comparison of the deck displacement on the 100 ms time delayed system with and without compensation

recorded at Sun-Moon lake in the 1999 Taiwan Chi-Chi earthquake to evaluate effect of the time delay and the time delay compensation method. The numerical analytical results reveal that the time-delay deteriorates the control performance. A time-delay compensation method based on Newmark's integration method is adopted to mitigate such an effect. Through numerical simulation the compensation method shows a satisfactory performance of decreasing the time-delay effect in the semi-active control system by using a MR damper with the sliding mode control.

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