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Time delay study for semi-active control of coupled adjacent structures using MR damper

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Abstract. The pounding phenomenon in adjacent structures happens in severing earthquakes that can cause great damages. Connecting neighboring structures with active and semi-active control devices is an effective method to avoid mutual colliding between neighboring buildings. One of the most important issues in control systems is applying online control force. There will be a time delay if the prose of producing control force does not perform on time. This paper proposed a time-delay compensation method in coupled structures control, with semi-active Magnetorheological (MR) damper. This method based on Newmark's integration is adopted to mitigate the time-delay effect. In this study, Lyapunov's direct approach is employed to compute demanded voltage for MR dampers. Using Lyapunov's direct algorithm guarantees the system stability to design a controller based on feedback. Because of the strong nonlinearity of MR dampers, the equation of motion of coupled structures becomes an involved equation, and it is impossible to solve it with the common time step methods. In present paper modified Newmark-Beta integration based on the instantaneous optimal control algorithm, used to solve the involved equation. In this method, the response of a coupled system estimated base on optimal control force. Two MDOF structures with different degrees of freedom are finally considered as a numeric example. The numerical results show, the Newmark compensation is an efficient method to decrease the negative effect of time delay in coupled systems; furthermore, instantaneous optimal control algorithm can estimate the response of structures suitable.

Keywords: coupled structures control; time delay; Newmark compensation; magneto rheological damper

1. Introduction

The pounding phenomenon in adjacent structures happens in intensive earthquakes that can cause great damages. For improving the seismic behavior of neighboring structures, linking them to each other has been investigated in recent decades. The possibilities of using passive, active, and semi-active control devices as an energy dissipating tool has been practical. Installation this equipment between near structures can avoid pounding effect and reduce structures damages. Different configuration of connection between adjacent structures, have been studied by many researchers. First of them, Klein *et al*. (1972) presented the concept of connecting two tall buildings; subsequent researches have been focused on the type of links, extensively (Seung *et al*.

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2800). A hinged link to connect two adjacent buildings studied by Westermo (1989), this connection was able to prevent interaction pounding and reduce the response of both of structures, but it is found that this system causes changes in properties of unconnected buildings and makes torsional response. Zhang and Xu (1999) investigated the effectiveness of viscoelastic dampers as a connection device between adjacent structures. Semi-active coupling system of a building includes of a main building and a podium structure, using variable friction dampers studied by Ng and Xu (2007). The result of their study showed that semi-active friction damper is efficient for reducing seismic responses of both buildings. A comparative study done by Zhu *et al*. (2011), the viscoelastic damper (VED) and viscous fluid damper (VFD) are considered as connectors. The result of their study showed the similarity effect of VFD and VED in the coupled system. Application of Maxwell model for fluid dampers as a link between two structures, studied by Zhang and Xu (2000), it is observed that fluid dampers are more effective than other links.

In most of the former researches on coupled structural systems, dampers with linear behavior used as connecting devices. While, Ni *et al*. (2001) showed, using nonlinear hysteretic dampers for coupled systems is more useful and can be efficient in decreasing seismic response and increasing control performance, even if they were placed in few floors. Qu *et al*. (2001) pointed out that the MR damper as a nonlinear connecting device is appropriate to reduce the pounding between two adjacent buildings during an earthquake. Seung-Yong Ok *et al*. (2008) proposed an optimal design method for nonlinear hysteretic MR dampers that connected two adjacent building. In this study MR damper is considered as a passive device with a constant voltage. The voltage and number of dampers is optimized base on genetic algorithm. Bharti *et al*. (2010) studied the effectiveness of MR damper for seismic response mitigation of adjacent multistory buildings under the coupled building control scheme. Based on the results of this study it has been observed that the MR damper is an effective device to control the response of both the buildings for a wide range of ground motion.

To protect civil engineering structures from environmental hazards, a realistic solution, including passive, active and semi-active control strategies has been introduced. Recently, semi-active devises, combing the best features of both passive and active controls, attract much attention (Housner *et al.* 1997). The choice of a suitable control algorithm is one of the challenging aspects of the semi-active control strategy, so some semi-active control strategies have been suggested. Leitmann (1994) used Lyapunov's direct approach for the design of a semi-active controller. McClamroch *et al.* (1995) applied a similar approach to develop bang-bang control strategy for using an ER damper. Dyke *et al.* (1996) presented the clipped linear optimal control law that has been shown effective for MR damper.

MR damper is one of the strongest semi-active devices. Nonlinear dependent relation between damper control force, floors displacement and velocity does not allow to solve governing equation of motion. So analyzing the structure response is impossible with the common methods. There are a few new methods to estimate the response of structure with MR damper; for example, Seung-Yong *et al*. (2008) presented a stochastic linearization method that could predict the response of the system. Ying *et al*. (2004) used reduced-order model and a non-linear stochastic optimal control method for analyzing the coupled system. Lee *et al*. (2011) used continuous sliding mode control to predict optimum control force. According to their method, the response of structure was estimated and MR damper control force computed. In the present study modified Newmark-Beta method base on the instantaneous optimal control algorithm is used to estimate the response of the coupled system with MR damper, for the first time.

One of the most important problems in control systems is applying online control force. There are various components such as sensors, filters, controllers, etc. in smart systems of civil engineering structures. Some process lead to time delay in a practical active or semi-active system like Gathering information from sensors at different locations, filtering and processing them for computing control force suitably, and producing demanded control force by control equipment. Time delay may decrease the control systems efficiency or unstable the active control systems; according to these concepts, it is obvious that the effect of time delay must be compensated. To investigate the effect of time delay on a control system, many researchers have been introduced different compensation methods, Harmonic compensation method for linear systems under semi-active control proposed by Symans and Constantinou (1995). In this method, the effect of time delay is investigated in variable dampers. The structure responses are considered as an un-damped free vibration mode between the time when the responses are sensed and the time when the command force is applied. Agrawal and Yang (2000) recommend the recursive response method for the active controlled linear system. In recursive method, the effect of time delay changes the state space's parameters. They compared five methods for the compensation of fixed time-delay. These methods include the recursive response, state-augmented compensation, controllability based stabilization, the Smith predictor and the Pade approximation method. The result of their study showed the recursive method is more efficient than other methods. Xu and Shen (2003) proposed intelligent bi-state control for the Structure with MR damper; this method can compensate time delay effect in the semi-active control system. Xu *et al*. (2003) suggested an on-line real-time control based on neural network to control of structures with MR dampers. This method strongly considers the time-delay problem and can remove an inherent time-delay problem lies in the traditional method efficiently. Cha *et al*. (2013) studied time delay effects on large-scale MR dampers in different algorithm, applying this method reduces structure responses. Zhao-Dong Xu *et al*. (2008) proposed neuro-fuzzy control strategy. In this strategy, the neural-network technique is used to solve time-delay problem and the fuzzy controller is adopted to determine the control current of MR dampers quickly and accurately. Lee and Kawashima (2007) proposed a time-delay compensation method based on the Newmark's integration. This method used to reduce the effect of time delay in semi-active control of nonlinear isolated bridges equipped with viscose damper. Advantages of this approach in comparison rather than other methods have been shown throughout this study. Also Newmark's compensation method is used by Chen and Lee (2008) in nonlinear isolated bridges with MR dampers controlled by sliding mode. This compensation method showed a satisfactory performance of decreasing the time-delay effect in the semi-active MR damper. In both mentioned studies, Newmark's compensation method has been used in a bridge with only two degrees of freedom. For the first time, Newmark's compensation method in MDOF building structures is used in present paper.

2. Modeling of adjacent coupled buildings with MR dampers

Two adjacent buildings with n_1 and n_2 stories are considered in this paper. Each building assumed as linear elastic and shear type with lateral degrees of freedom at their floor levels. These buildings are connected with hysteresis semi-active MR dampers (see Fig. 1). So, the total degrees of freedom of the coupled system would be $N=n_1+n_2$. The governing equation of motion of this system is express

$$\begin{bmatrix} M_1 & 0 \\ 0 & M_2 \end{bmatrix}\begin{Bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{Bmatrix} + \begin{bmatrix} C_1 & 0 \\ 0 & C_2 \end{bmatrix}\begin{Bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{Bmatrix} + \begin{bmatrix} K_1 & 0 \\ 0 & K_2 \end{bmatrix}\begin{Bmatrix} x_1 \\ x_2 \end{Bmatrix} + \begin{Bmatrix} -f_d \\ 0 \\ f_d \end{Bmatrix} = -\begin{bmatrix} M_1 & 0 \\ 0 & M_2 \end{bmatrix}.\eta.\ddot{x}_g \tag{1}$$

Subscript 1 and 2 pointed out to tall and short structures with n_1 and n_2 degrees of freedom, respectively; x_1, $\dot{x}_1$ and $\ddot{x}_1$ are $n_1 \times 1$ displacement, velocity, and acceleration vectors, respectively; M_1, C_1 and K_1 denote to $n_1 \times n_1$ mass, damping and stiffness matrixes, respectively; Similarity, these parameters can identify for short structure; f_d is $r \times 1$ MR dampers control force vector that is computed base on modify Bouc-Wen model. Also r is the number of dampers; $\ddot{x}_g$ is the earthquake ground acceleration; η is an earthquake influence coefficient vector. The Eq. (1) can be rewritten as

$$M\ddot{x}(t) + C\dot{x}(t) + Kx(t) = -M.\eta.\ddot{x}_g + L\,F_{MR} \tag{2}$$

Where $x(t)=\{x_1 \quad x_2\}^T$, $\dot{x}(t)=\{\dot{x}_1 \quad \dot{x}_2\}^T$, $\ddot{x}(t)=\{\ddot{x}_1 \quad \ddot{x}_2\}^T$ are $N \times 1$ displacement, velocity, and acceleration vectors, respectively; M, C and K are $N \times N$ mass, damping and stiffness matrixes, respectively; L is the matrix denoting the location of controllers. F_{MR} is the vector consisting of

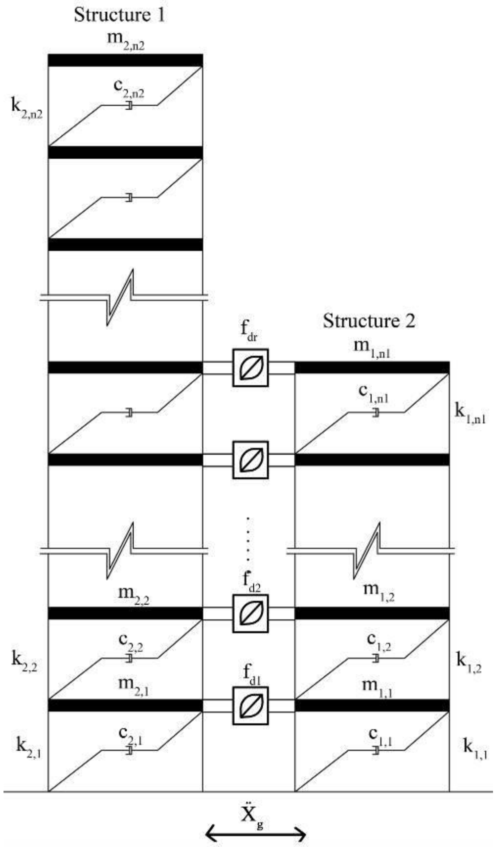


Fig. 1 Coupled structures control with MR damper

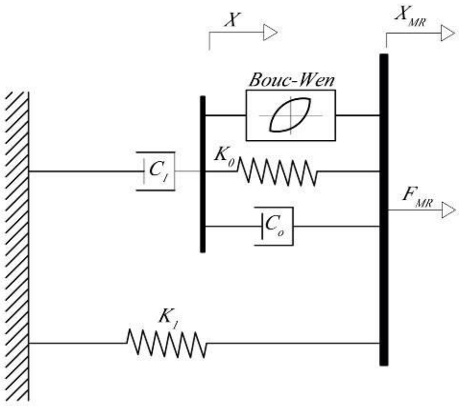


Fig. 2 Modified Bouc-Wen model

forces in the MR dampers. The relationship between control force and velocity can be express base on modify Bouc-Wen model as follow (Spencer *et al*. 1996). Also mechanical modify Bouc-Wen model showed in Fig. 2.

$$f_d = c_1\dot{e} + k_1(u_{MR} - x_0) \tag{3}$$

where the evolutionary variable y is governed by

$$\dot{y} = -\gamma|v_{MR} - \dot{e}|(y)|y|^{(n-1)} - \beta(v_{MR} - \dot{e})|y|^{(n)} + A_{MR}(v_{MR} - \dot{e}) \tag{4}$$

and e can gain by

$$\dot{e} = \left\{\frac{1}{c_0 + c_1}\right\}\{\alpha_0 y + c_0 v_{MR} + k_0(u_{MR} - e)\} \tag{5}$$

where c_0 is the viscous damping coefficient at large velocities; viscous damping coefficient at low velocities is c_1; α_0 is the evolutionary coefficient; u_{MR} and v_{MR} are relative displacement and velocity between connected floors; The shape of the hysteresis loops depended on γ, β and A_{MR} parameters; k_1 related to damper force that is accumulator stiffness; k_0 control damper force in large velocities; x_0 associated with k_0.

The coefficients c_0, c_1 and α_0 determined by command voltage, as follow

$$c_0 = c_{0a} + c_{0b}u \tag{A.6}$$

$$c_1 = c_{1a} + c_{1b}u \tag{B.6}$$

$$\alpha_0 = \alpha_{0a} + \alpha_{0b}u \tag{C.6}$$

where, u is given as output of first order filter

$$\dot{u} = -\mu(u - v) \tag{7}$$

v can be determined by control algorithm. It is proved in previous study that choosing an appropriate algorithm, increase the performance of semi-active control system, using a MR damper as connecting device in coupled system is able to reduce structures response, if the control algorithm is properly selected. In this study, Lyapunov's direct approach is employed and can be determined by fallow equation

$$v = v_{max} H(-Z^T P_L B f_d) \tag{8}$$

where, *H*(.) is Heaviside step function. When *H*(.) is greater than zero, voltage applied to the damper should be v_{max}; otherwise, the command voltage is set to zero. *Z* is the state space vector and *B* matrix is one of the state space parameters, P_L is real, symmetric, positive definite matrix and is chosen as a unit matrix (Spencer *et al*. 1997).

3. Optimal estimation of responses

As observed from Eqs. (3)-(8), computing MR damper control force depended on piston's displacement and velocity, on the other hand, the Eq. (1) shows that calculating displacement and velocity is not independent of control force, too. So it is not feasible to determine control force and structures responses, for the next discrete time step, simultaneously. Because of the strong nonlinear behavior of MR dampers that emerged in Bouc-Wen model, the equation of motion of coupled structures becomes an involved equation and it is impossible to solve it with common time stepping methods (Lee *et al*. 2011). In present paper, the instantaneous optimal control algorithm based on Newmark-Beta integration proposed by Chang and Yang (1994), used to solving the involved equation without considering an especial control device interaction. In this method the response of the coupled system estimated base on optimal control force. The Eq. (2) during the time interval $(i)\Delta t$ to $(i-1)\Delta t$ is able to solve base on follow equations

$$M\Delta\ddot{x}(t) + C\Delta\dot{x}(t) + K\Delta x(t) = \Delta P(t) \tag{A.9}$$

$$\Delta\ddot{x}(t) = \ddot{x}_i - \ddot{x}_{i-1} \tag{B.9}$$

$$\Delta\dot{x}(t) = \dot{x}_i - \dot{x}_{i-1} \tag{C.9}$$

$$\Delta x(t) = x_i - x_{i-1} \tag{D.9}$$

$$\Delta P(t) = P_i - P_{i-1} \tag{E.9}$$

$$P_i = -M.\eta.\ddot{x}_{gi} + LU_i \tag{F.9}$$

$$P_{i-1} = -M.\eta.\ddot{x}_{gi-1} + LU_{i-1} \tag{G.9}$$

where the U_i is the optimal control force in *i*-th step. The response of coupled system can be obtained by follow equation using Newmark-Beta method

$$x_i = \Delta x_i + x_{i-1} \tag{A.10}$$

$$\dot{x}_i = (1 - s_5)\dot{x}_{i-1} - s_6\ddot{x}_{i-1} + s_4\Delta x_i \tag{B.10}$$

$$\ddot{x}_i = (1 - s_3)\ddot{x}_{i-1} - s_2\dot{x}_{i-1} + s_1\Delta x_i \tag{C.10}$$

$$\Delta x_i = K^{*-1}\Delta F_i \tag{D.10}$$

$$K^* = K + s_1 M + s_4 C \tag{E.10}$$

$$\Delta F_i = (P_i - P_{i-1}) + M(s_2 \dot{x}_{i-1} + s_3 \ddot{x}_{i-1}) + C(s_5 \dot{x}_{i-1} + s_6 \ddot{x}_{i-1}) \tag{F.10}$$

i denoted to time number step. s_1, s_2, s_3, s_4, s_5 and s_6 coefficients defined as

$$s_1 = \frac{1}{\delta(\Delta t)^2}; s_2 = \frac{1}{\delta \Delta t}; s_3 = \frac{1}{2\delta}; \tag{A.11}$$

$$s_4 = \frac{\lambda}{\delta \Delta t}; s_5 = \frac{\lambda}{\delta}; s_6 = \Delta t\left(\frac{\lambda}{2\delta} - 1\right) \tag{B.11}$$

where δ, λ are Newmark's parameters (Chopra 1995). Optimal control force Computed by an instantaneous performance index that included structure responses at each time step *i*, different feedback of system states can be used in this index. It is proved that using displacement; velocity and acceleration feedback in performance index is more efficient, simultaneous. Instantaneous performance index proposed by Chang and Yang (1994) defined as follow

$$J_i = \frac{1}{2}(x_i^T Q_x x_i + \dot{x}_i^T Q_{\dot{x}} \dot{x}_i + \ddot{x}_i^T Q_{\ddot{x}} \ddot{x}_i + U_i^T R U_i) \tag{12}$$

R is $r \times r$ positive definite matrix related to demanded control force. Q_x, $Q_{\dot{x}}$ and $Q_{\ddot{x}}$ are $N \times N$ positive semi-definite weighting matrices corresponding to the displacement, velocity and acceleration feedback, respectively. In the instantaneous optimal control, at each time step *i*, the control force U_i is computed by minimizing the performance index J_i as bellow

$$U_i = -R^{-1} L^T K^{*-T} (Q_x x_i + s_4 Q_{\dot{x}} \dot{x}_i + s_1 Q_{\ddot{x}} \ddot{x}_i) \tag{13}$$

So, the optimal control force included displacement, velocity an acceleration terms in each time. The equation of motion can be rewritten as bellow

$$(M + M_{opt})\Delta\ddot{x}(t) + (C + C_{opt})\Delta\dot{x}(t) + (K + K_{opt})\Delta x(t) = -M.\eta.\ddot{x}_g \tag{A.14}$$

$$M_{opt} = s_1 H R^{-1} L^T K^{*-T} Q_x \tag{B.14}$$

$$C_{opt} = s_4 H R^{-1} L^T K^{*-T} Q_{\dot{x}} \tag{C.14}$$

$$K_{opt} = H R^{-1} L^T K^{*-T} Q_{\dot{x}} \tag{D.14}$$

M_{opt}, C_{opt} and K_{opt} are constant parameters, where Superscript ($-T$) is used to show the inverse transpose of matrix. So the response of structure can be estimated by this method and using optimal control force U_i. Estimated responses lead to calculate MR damper voltage and control force in Eq. (8) and (4), and as a result Eq. (2) can be solved.

4. Newmark compensation method for time delay

A control system is an ideal system, if all control procedures perform continues. But consuming time for measuring responses, calculating and applying control force is inevitable. Consider τ as a time delay in control process, the real control force that applied to the structure at time t is $U(t-\tau)$, so the equation of motion can be modified as bellow (Kawashima *et al*. 2007)

$$M\ddot{x}(t) + C\dot{x}(t) + Kx(t) = -M.\eta.\ddot{x}_g + LU(t-\tau) \tag{15}$$

In this method Δt ($\Delta t=(i)-(i-1)$) would replace with the value of time delay τ. Therefor the Eqs. (10)-(11) would change to

$$\Delta x_{t-\tau} = K^{*-1}\Delta F_{t-\tau} \tag{A.16}$$

$$K^* = K + s_1 M + s_4 C \tag{B.16}$$

$$\Delta F_{t-\tau} = \eta(\Delta\ddot{x}_g)_{t-\tau} + L\Delta U_{t-2\tau} + M(s_2\dot{x}(t-\tau) + s_3\ddot{x}(t-\tau)) + C(s_5\dot{x}(t-\tau) + s_6\ddot{x}(t-\tau)) \tag{C.16}$$

$$\Delta x_{t-\tau} = x_t - x_{t-\tau} \tag{D.16}$$

$$(\Delta\ddot{x}_g)_{t-\tau} = (\ddot{x}_g)_t - (\ddot{x}_g)_{t-\tau} \tag{E.16}$$

$$\Delta U_{t-2\tau} = U_{t-\tau} - U_{t-2\tau} \tag{F.16}$$

Once x_t is computed from Eq. (D.16), the velocity $\dot{x}_t$ and acceleration $\ddot{x}_t$ can be obtained from

$$\dot{x}_t = (1-s_5)\dot{x}(t-\tau) - s_6\ddot{x}(t-\tau) + s_4\Delta x_{t-\tau} \tag{G.16}$$

$$\ddot{x}_t = (1-s_3)\ddot{x}(t-\tau) - s_2\dot{x}(t-\tau) + s_1\Delta x_{t-\tau} \tag{H.16}$$

$$s_1 = \frac{1}{\delta(\tau)^2};\ s_2 = \frac{1}{\delta\tau};\ s_3 = \frac{1}{2\delta}; \tag{I.16}$$

$$s_4 = \frac{\lambda}{\delta\tau};\ s_5 = \frac{\lambda}{\delta};\ s_6 = \Delta t\left(\frac{\lambda}{2\delta} - 1\right) \tag{J.16}$$

For producing new acceleration, the values of seismic excitation in each step must be interpolated from available ground motion records.

5. Numerical study and results

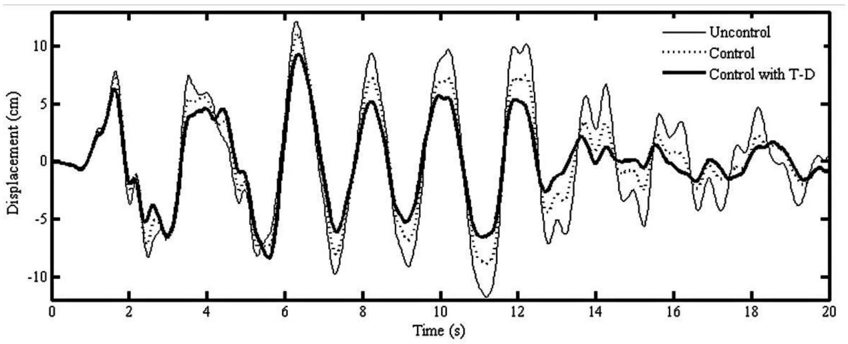
To study the effect of time delay on controlled coupled system, two structures with ten and twenty stories are considered. These buildings are connected by MR dampers. The values of Bouc-Wen parameters are: μ=195 s-1, $c_{1a}c$=8106.2 KN s m-1, c_{1b}=7807.9 KN s/m V, c_{0a}=50.3 KN s/m, c_{0b}=48.7 KN s/m V, k_0=0.0054 KN/m, k_1=0.0087 KN/m, α_{0a}=8.7 KN/m, α_{0b}=6.4 KN/m V, γ, β=496 m^{-2}, A_{MR}=810.5, x_0=0.18 m, n=2. The mass and stiffness of the two buildings in each floor are the same and equal with 800 ton and 1.4×10^8 KN/m, respectively. The damping ratio to each mode is supposed 5%. The fundamental time period of building 1 (tall building) and building 2 (short building) is 1.9 sec and 1sec, respectively. The coupled system is subjected by two groups of near field (El-Centro, 1940, Kobe, 1995, Northridge, 1994) and far field (Loma Prieta, 1989, Tabas, 1978, Morgan hill, 1984) unidirectional ground motion records. The efficient of Newmark's compensation method in dispelling the negative effect of time delay is evaluated under three values of 2 ms, 40 ms and 60 ms. The weighting matrixes and R computed by trial and error, where R=10^{-8} $[I]_{10\times 10}$ and

$$Q_x = [Q_{x\,ij}]_{30\times 30} = \tfrac{1}{2}\begin{cases} j & i = j \\ 0 & i \neq j \end{cases} \tag{17}$$

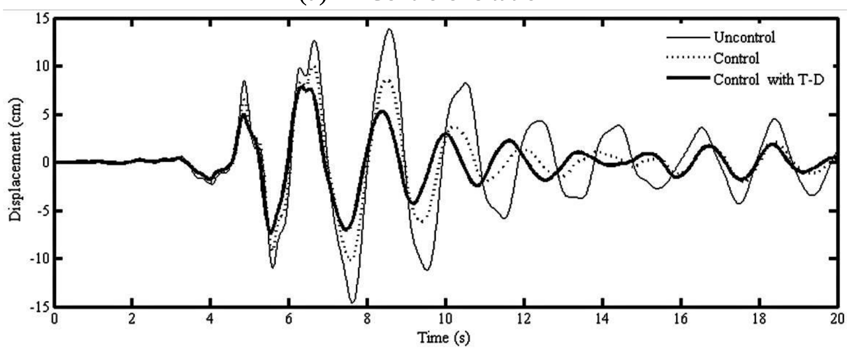
$$Q_{\dot{x}} = [Q_{\dot{x}i\,j}]_{30\times 30} = \begin{cases} j & i = j \\ 0 & i \neq j \end{cases} \tag{18}$$

Also $Q_{\ddot{x}}$ is 30×30 identity matrix. (j is the number of story, j=1,2,.....,30).

The effect of Newmark's integration method in compensation 40 ms time delay is shown in bellow pictures. Three strategies are compared in each figure (un-control single structure (is shown Uncontrol in the figures), coupled control structures (is shown Control) and the coupled control structures with considering time delay (is shown Control with T-D)). Figs. 3 and 4 are noted top floor displacement of building 2 and 1, respectively. It is obvious that connecting two structures decrease the displacement during excitations. As proved in mentioned studies, linking two adjacent structures by MR dampers is an appropriate method, it is able to avoid pounding by reducing structures extra movement. Also using Newmark compensation method in coupled system, decrease the negative effect of time delay and cause reduction in top floor displacements. So time delay would not satisfy the control structures purpose and considering it, is inevitable in semi-active MR damper.

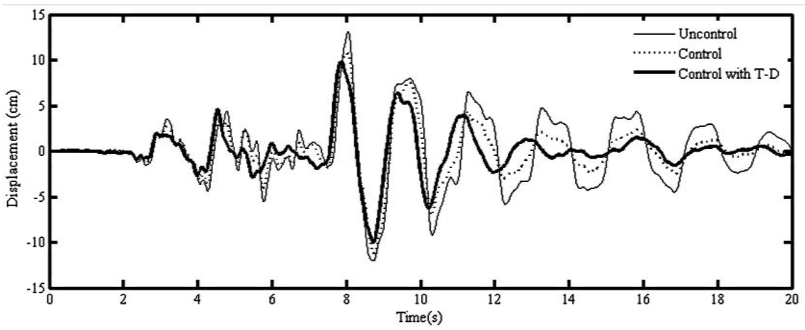


(a) El-Centro excitation



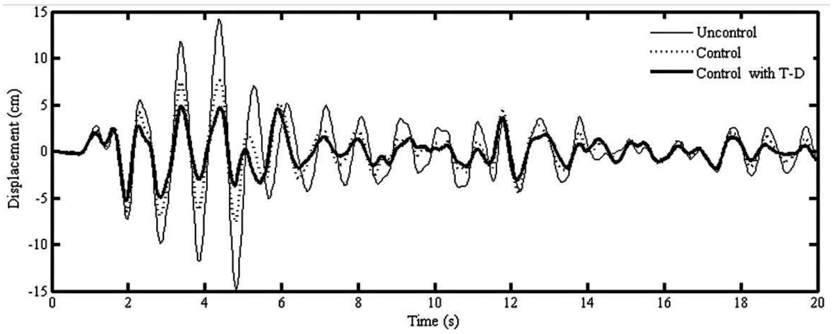
(b) Kobe excitation

Fig. 3 Time history displacement response of top floor (structure 2, for 40 ms T-D)

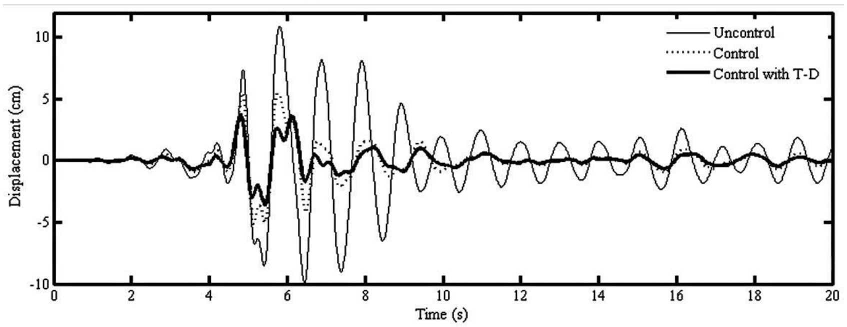


(c) Northridge excitation

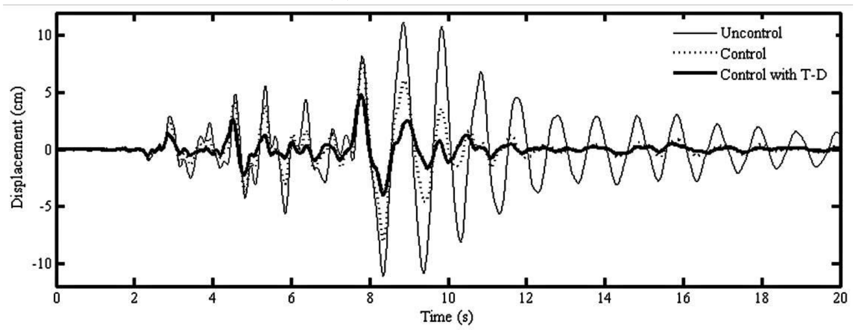
Fig. 3 Continued



(a) El-Centro excitation

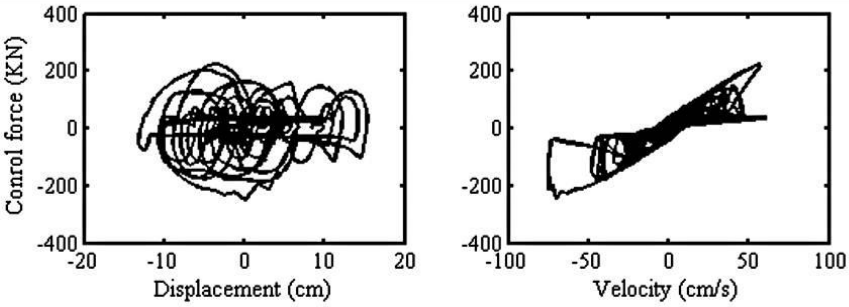


(b) Kobe excitation

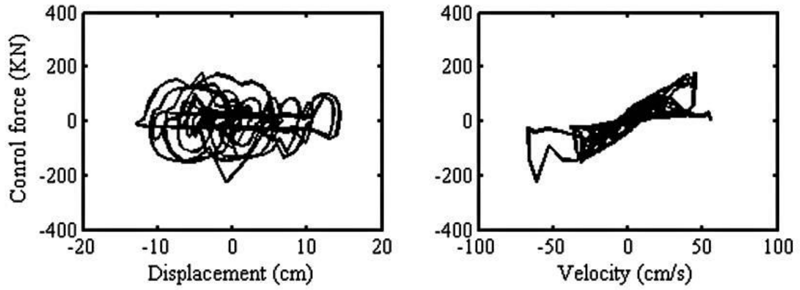


(c) Northridge excitation

Fig. 4 Time history displacement response of top floor (structure 1, for 40 ms T-D)

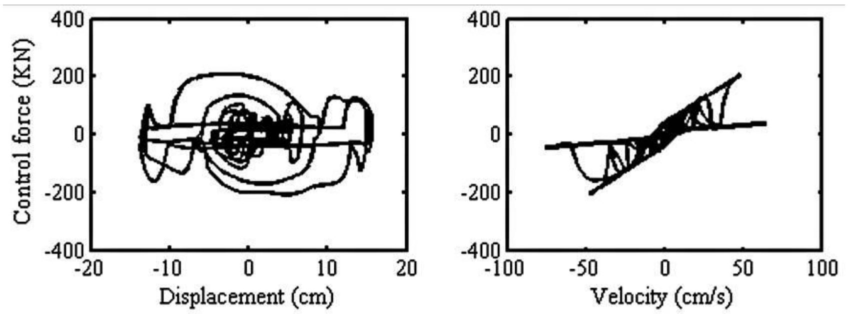


(a) Without time delay

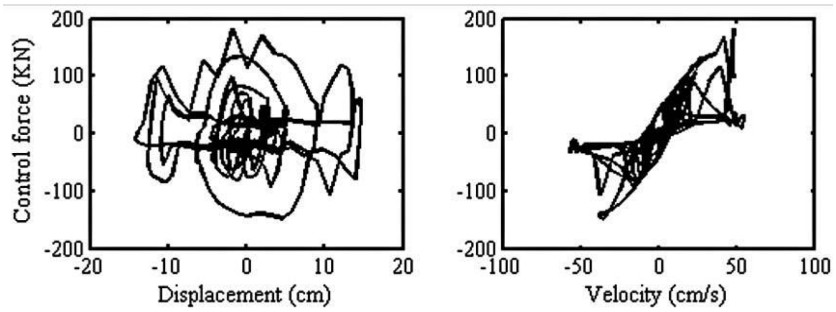


(b) With 40 ms time delay

Fig. 5 MR damper Loop behavior (10-th story) under El-Centro excitation

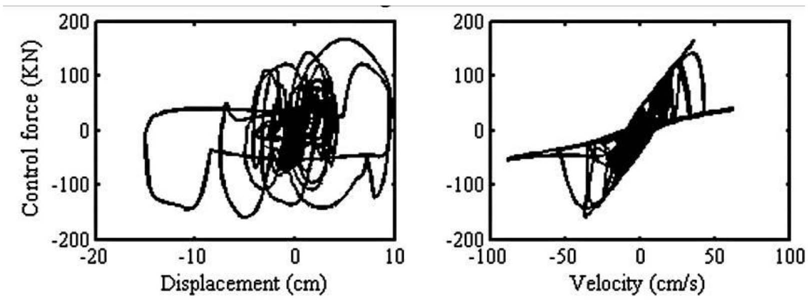


(a) Without time delay

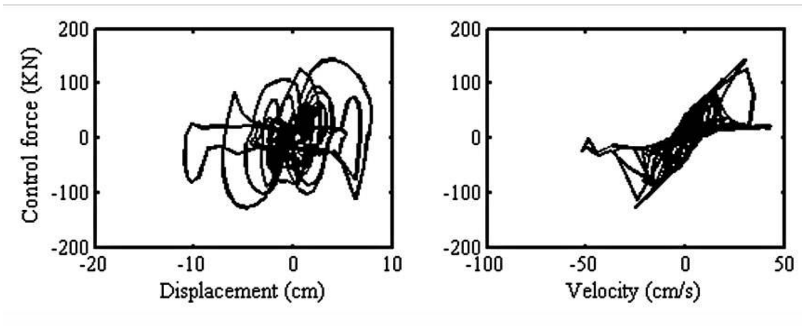


(b) With 40 ms time delay

Fig. 6 MR damper Loop behavior (10-th story) under Kobe excitation.



(a) Without time delay



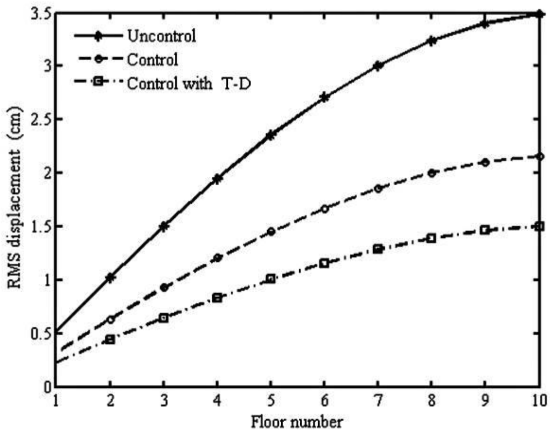
(b) With 40 ms time delay

Fig. 7 MR damper Loop behavior (10-th story) under Northridge excitation

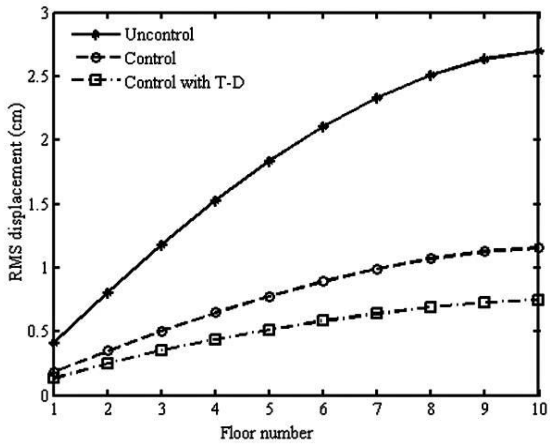
Nonlinear behavior of MR damper is shown in hysteresis loops in Figs. 5-7. It is clear that the value of control force reduces, when the effect of time delay is considered. The reduction of tenth damper control forces are 7%, 9%, and 23% for El-Centro, Kobe, and Northridge excitation, respectively. Also reduction in damper displacement and velocity can be seen in these figures. Since the behavior of MR damper in low velocity, has been shown correctly in Figs. 5-7, it is proved that the optimal control algorithm is an efficient method to forecast the response of structures.

For assessment the effect of connecting adjacent structures and compensation time delay method in all floors of structures, performance indexes, that it is known RMS (root mean square) in structural control literature, are studied. Figs. 8 and 9 are showing variation of displacement and control force performance indexes of short building vs. number of floor. Performance indexes reduction in all floors, can demonstrate the effective of connecting adjacent structures and considering time delay.

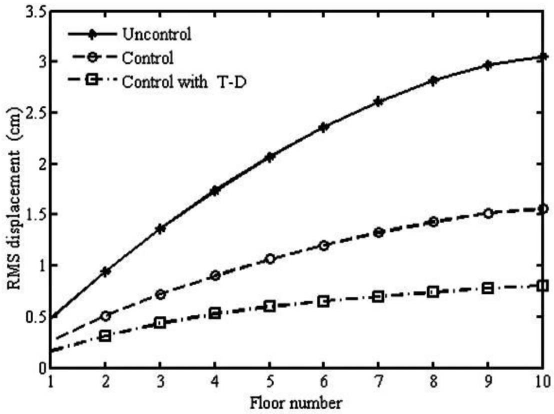
The summary of results is demonstrated in Tables 1-6. The outputs of responses of two structures under two groups of excitation and three various time delay (2, 40, and 60 ms) are compared. It is noted that Newmark compensation method is more applicable in smaller time delay, because there is an inherent limitation in basic Newmark-Beta method for estimating response of structure. Newmark- Beta method is used in two special cases that are well-known linear acceleration and average acceleration methods. Newmark-Beta method stability is depended on structure fundamental period, the value of time step, and δ, λ parameters. Average acceleration case (λ=1/2 and δ=1/4) is stable for any time step, but in large time steps, method accuracy in responses estimation reduces. While stability of linear acceleration case (λ=1/2 and δ=1/6)



(a) El-Centro excitation

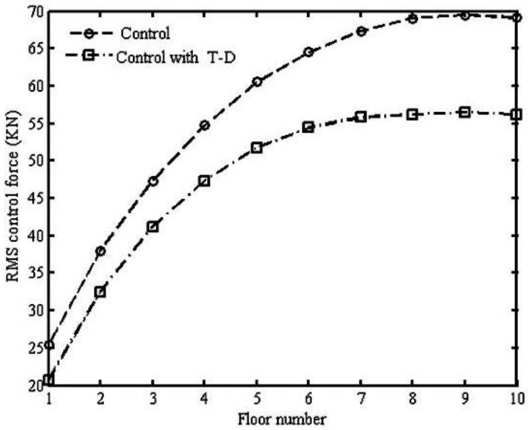


(b) Kobe excitation

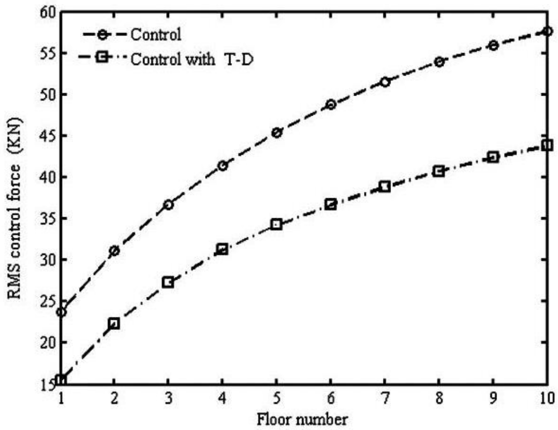


(c) Northridge excitation

Fig. 8 RMS of Displacement (structure 2)

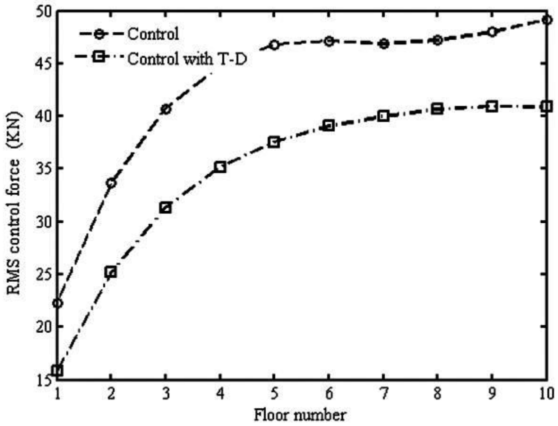


(a) El-Centro excitation



(b) Kobe excitation

Fig. 9 RMS of Control force



(c) Northridge excitation

Fig. 9 Continued

Table 1 Summary of results under El-Centro excitation

Parameters	structure 1					Structure 2				
	Ucn [a]	Cn [b]	Control with T-D[c]			Ucn	Cn	Control with T-D		
			2 ms	40 ms	60 ms			2 ms	40 ms	60 ms
Peak displacement (cm)	14.2	8.1	2.5	5	5.2	12.5	11	7	9	11
Peak control force (KN)	-	190	220	175	155	-	-	-	-	-
Peak base shear	3.86	2.35	1. 1	1.61	1.6	2.67	2.43	1.5	1.91	2
Peak acceleration	0.98	0.65	0.4	0.61	0.65	0.55	0.45	0.35	0.45	0.38

Table 2 Summary of results under Kobe excitation

Parameters	structure 1					structure 2				
	Ucn [a]	Cn [b]	Control with T-D [c]			Ucn	Cn	Control with T-D		
			2 ms	40 ms	60 ms			2 ms	40 ms	60 ms
Peak displacement (cm)	10.9	5.8	2.59	3.9	3.2	14.0	9.5	7.5	8.5	8.5
Peak control force (KN)	-	155	165	141	120	-	-	-	-	-
Peak base shear	3.3	1.54	1.02	1.44	1.5	3.1	2.1	2.0	2.0	2.2
Peak acceleration	0.78	0.63	0.60	0.8	0.4	0.7	0.5	0.39	0.55	0.41

depends on time step and it is forbidden to exceed of a certain limit. Since the method stability and accuracy depends on the value of time step, it is impossible to ignore the method Inherent limitation.

So increasing time delay in Newmark compensation method causes a defect in process control and increases some outputs up to un-control responses i.e., acceleration response. Using Newmark compensation method in the coupled system is appropriate in values of time delay in range of linear acceleration method. This method is not able to compensated large time delay.

The results show that application of connecting adjacent structures idea causes more reduction

Table 3 Summary of results under Northridge excitation

Parameters	structure 1					structure 2				
	Ucn [a]	Cn [b]	Control with T-D [c]			Ucn	Cn	Control with T-D		
			2 ms	40 ms	60 ms			2 ms	40 ms	60 ms
Peak displacement (cm)	11	7.9	3.2	4.8	5.0	7.5	6.0	5.0	5.5	5.9
Peak control force (KN)	-	160	150	123	110	-	-	-	-	-
Peak base shear	3.1	2.1	1.0	1.6	2.0	2.47	1.85	0.95	1.4	1.5
Peak acceleration	0.72	0.50	0.53	0.40	0.50	0.50	0.45	0.40	0.36	0.50

[a] Un-controlled; [b] Controlled; [c] Controlled with Time delay consideration

Table 4 Summary of results under Loma Prieta excitation

Parameters	structure 1					structure 2				
	Ucn [a]	Cn [b]	Control with T-D [c]			Ucn	Cn	Control with T-D		
			2 ms	40 ms	60 ms			2 ms	40 ms	60 ms
Peak displacement (cm)	12.5	10.0	2.0	3.5	5	3.1	2	0.5	1	1.8
Peak control force (KN)	-	290	50	60	75	-	-	-	-	-
Peak base shear	3.5	3.0	0.5	0.8	1.0	0.7	0.6	0.2	0.25	0.25
Peak acceleration	0.58	0.5	0.3	0.1	0.15	0.14	0.11	0.09	0.02	0.10

Table 5 Summary of results under Tabas excitation

Parameters	structure 1					structure 2				
	Ucn [a]	Cn [b]	Control with T-D [c]			Ucn	Cn	Control with T-D		
			2 ms	40 ms	60 ms			2 ms	40 ms	60 ms
Peak displacement (cm)	1.3	1	0.3	0.5	0.7	0.7	0.6	0.4	0.5	0.6
Peak control force (KN)	-	30	10	15	20	-	-	-	-	-
Peak base shear	0.35	0.2	0.15	0.18	0.25	0.25	0.23	0.21	0.25	0.25
Peak acceleration	0.15	0.1	0.05	0.05	0.1	0.1	0.09	0.05	0.05	0.04

Table 6 Summary of results under Morgan Hill excitation

Parameters	structure 1					structure 2				
	Ucn [a]	Cn [b]	Control with T-D [c]			Ucn	Cn	Control with T-D		
			2ms	40ms	60ms			2ms	40ms	60ms
Peak displacement (cm)	2.5	1	0.5	0.8	1	2.5	2.3	0.8	1.5	2
Peak control force (KN)	-	80	60	45	60	-	-	-	-	-
Peak base shear	0.7	0.5	0.2	0.25	0.4	0.3	0.25	0.1	0.27	0.25
Peak acceleration	0.15	0.1	0.08	0.05	0.1	0.05	0.04	0.05	0.05	0.06

[a] Un-controlled; b Controlled; [c] Controlled with Time delay consideration

in shorter structure responses; also this technic is more efficient under far field excitations. The values of base shear and acceleration responses normalized base on the weight of each floor and g (g=9.81 m /s^2).

6. Conclusions

In this study, two main points are investigated. First, Because of strong nonlinear behavior of MR damper, it is impossible to gain the structure's response with common time step methods. For resolving this problem, instantaneous optimal control algorithm is used to calculate a demand control force, rewrite the equation of motion and estimate responses of the coupled system at time *t*. with these information, MR damper's control force and voltage are obtained. Second, time delay is an inseparable part of semi-active and active control process, so considering this phenomenon lead to a realistic control performance. In this study, Newmark compensation method is employed to decrease the effect of time delay. Two structures with separate mode considered to evaluate the ability of mentioned methods. Three values of time delay are compensated by Newmark compensation method. Main results obtained base on this numerical study can be written as fallow:

- Coupling adjacent building with control devices is an efficient technic to decrease the response of structures and can be avoided mutual pounding.
- MR damper is an appropriate control device in coupled system and is able to increase seismic performance of two structures.
- Coupled system technic is more effective for shorter structure.
- Instantaneous optimal control algorithm is able to estimate response of structure rightly, because nonlinear behavior of MR damper is shown properly.
- The effect of time delay is inevitable and must be considered in semi-active MR dampers.
- Newmark method can compensate the effect of time delay well and increase control performance of coupled system. Appropriate improvement in performance indexes can prove this.
- The value of control force will reduce, when time delay compensates. This reduction causes lower energy consumption in control process.
- Because of an Inherent limitation in time step Newmark-Beta method, there is a limitation in compensating time delay by Newmark compensation method, so large time delays can't compensate in this method.

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