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Structural Vibration Control Using Semiactive Tuned Mass Damper

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ABSTRACT

The main purpose of this study is to show the sufficient control performance of semiactive tuned mass damper and to identify a suitable control method for semiactive tuned mass damper in structural vibration control. In this study, four control algorithms are considered: displacement based groundhook (DBG), velocity based groundhook (VBG), clipped optimal, maximum energy dissipation (MEDA). For semiactive tuned mass damper, MR damper is considered as a controllable damping device, and the command voltage is calculated by the control algorithms. Each of the control theory is applied to the three story shear building excited by earthquake load. The performance of each algorithm is compared with the conventional tuned mass damper model using evaluation criteria. Also, to check the robustness of the semiactive tuned mass damper, stiffness uncertainties are applied to the system. The result indicates that semiactive tuned mass damper shows control efficiency, especially with uncertainty. And DBG and clipped optimal algorithm perform the best among the considered control policies.

INTRODUCTION

Many seismic design methods and construction technologies have been developed and investigated over the years to reduce the seismic responses of buildings, bridges and potentially vulnerable structures. As a method of vibration control, the inclusion of mechanical damper can be a way. Tuned mass damper (TMD) has been found to be effective in reducing the response of structures subjected to dynamic loads. In the classical work on the dynamic vibration absorber, Den Hartog (1956) derived expressions for the optimum damping ratio for an undamped mass subjected to harmonic excitation. Randall *et al.*

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(1981) and Warburton and Ayorinde (1980) further tabulated and developed design charts for the optimum parameters for specified mass ratios and different primary system damping. Warburton (1982) presented optimal parameters for tuned mass dampers under random excitations idealized by white noise. Soong *et al* (1998) carried out parametric study on the case that primary system has inherent damping and investigated the detuning effects. Several studies have confirmed that the effectiveness of semiactive tuned mass dampers, and shown that performances of tuned mass dampers were further improved by making them semiactive. Those studies were mostly intended for applications in winds or earthquake engineering. Abe and Igusa (1996) developed an analytical theory for optimal control algorithms for semiactive absorbers. Hidaka *et al* (1995) performed one of a few experiments of variable damping dynamic absorbers. They investigated the performance of a variable damping dynamic absorber using ER fluid. Agrawal and Yang (2000) proposed device-specific, semiactive algorithms for protection of seismic excited structures subjected to near field earthquake ground motions. Pinkaew and Fujino (2001) studied the the control effectiveness of a semiactive tuned mass damper with variable damping under harmonic excitation. They investigated the response of a SDOF structure coupled with a semiactive tuned mass damper by employing the numerical technique and the optimal control theory. Koo *et al* (2003) adopted groundhook theory as a semiactive damping control algorithm. They provide a numerical investigation on a two-degree-of-freedom numerical model in which the primary structure is coupled with a tuned mass damper. The numerical investigation considers four semiactive control methods to regulate damping in the semiactive tuned mass damper. Loh *et al* (2005) proposed a new semiactive control device which uses a variable damping device and MR damper. Controllable damping device is installed in the place of actuator of ATMD and evaluate the performance under earthquake load.

SEMIACTIVE TUNED MASS DAMPER

The equation of motion of semiactive TMD

The proposed semiactive tuned mass damper system replaces the passive damping element with a controllable damping elements. Figure 1 shows the proposed semiactive tuned mass damper. The equation of motion that describes the dynamic of this system is

$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix}\begin{Bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{Bmatrix} + \begin{bmatrix} c_1 + -c_2(t) & - -c_2(t) \\ -c_2(t) & -c_2(t) \end{bmatrix}\begin{Bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{Bmatrix} + \begin{bmatrix} k_1 + k_2 & -k_2 \\ -k_2 & k_2 \end{bmatrix}\begin{Bmatrix} x_1 \\ x_2 \end{Bmatrix} = -\ddot{x}_g \begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \tag{1}$$

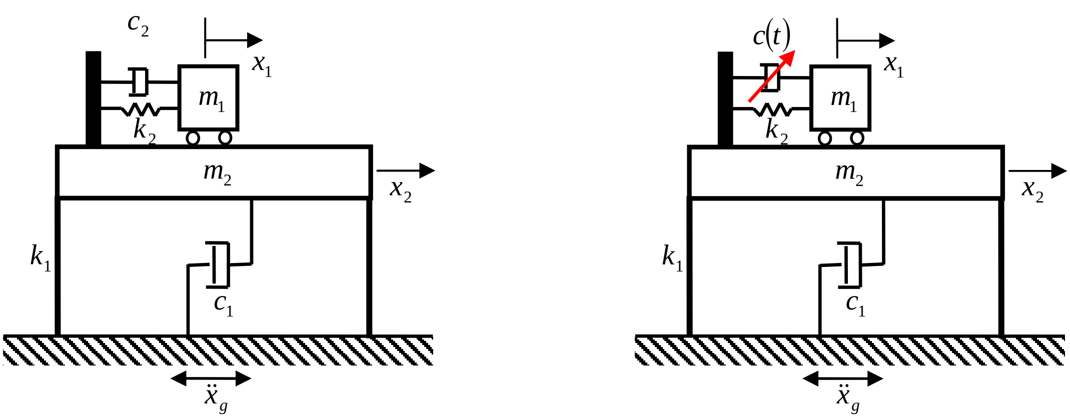


Fig. 1. SDOF system with TMD and semiactive TMD

The damping constants $c(t)$ varies with time by the suitable control algorithms. In the conventional tuned mass damper system, the damper force dose not vary when the velocity of mass damper is constant. On the other hand, in the semiactive tuned mass damper system, the controllable damper offers variable damping force. This controllable damper, which provides a wide dynamic force range, improves the dynamic performance of the semiactive tuned mass damper with proper control algorithms

The controllable damping device

The MR dampers are semiactive devices that use MR fluids to construct a versatile damping force. Because the strength of the magnetic field controls the yield stress of the fluid, devices utilizing MR fluids are expected to be applicable for a wide range of situations. The essential characteristic of MR fluid is their ability to reversivly change from a free-flowing, linear viscous fluid to a semisolid with a controllable yield strength in milliseconds when exposed to a magnetic field. When a magnetic field is applied to the fluids, particle chains form, and the fluid becomes a semisolid and exhibits viscoplastic behavior. Transition to rheological equilibrium can be achieved in a few milliseconds, allowing construction of devices with high bandwidth. The MR fluid can be readily controlled with a low voltage, current-driven supply.

The controllable damping device considered in this study is MR fluid damper. Spencer *et al* (1996) proposed a phenomenological model to describe the behavior of prototype MR damper. This model is based on a Bouc-Wen hysteresis model and named modified Bouc-Wen model. The simple mechanical idealization of MR damper is depicted in figure 2. The applied force f predicted by this model is given by the flowing 7 equation.

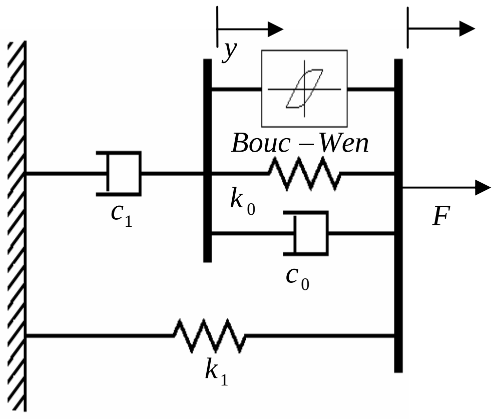


Fig 2. Modified Bouc-Wen Model

$$f = c_1 \dot{y} + k_1 (x - x_0) \tag{2}$$

$$\dot{z} = -\gamma |\dot{x} - \dot{y}| z |z|^{n-1} - \beta (\dot{x} - \dot{y}) |z|^n + A(\dot{x} - \dot{y}) \tag{3}$$

$$\dot{y} = \frac{1}{(c_0 + c_1)} \{ \alpha z + c_0 \dot{x} + k_0 (x - y) \} \tag{4}$$

$$\alpha = \alpha_a + \alpha_b u \tag{5}$$

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

$$c_0 = c_{0a} + c_{0b} u \tag{7}$$

$$\dot{u} = -\eta (u - v) \tag{8}$$

Here, the accumulator stiffness is represented by k_1, the viscous damping observed at larger velocities by c_0. A dashpot represented by c_1, is included in the model to introduce the nonlinear roll-off, k_0 is present to control the stiffness at large velocities, and x_0 is the initial displacement of spring k_1 associated with the nominal damper force due to the accumulator. γ , β and A are hysteresis parameters.

CONTROL ALGORITHMS

Various approaches have been proposed for the control of semiactive devices. Since the response of the semiactive device is dependent on deformation of the device as well as the command input, it is not possible to commend directly to generate a specified damper force. Instead, the value of the voltage applied to the current driver is changed to increase or decrease the damper force. Based on this observation, semiactive control algorithms are designed to produce the command voltage input.

Control algorithms based on groundhook

Koo (2003) proposed the four semiactive control logics based on the groundhook theory, and two control algorithms (on-off VBG and on-off DBG) are considered in this study. As the semiactive controllable damper used in this study is MR fluid damper, the semiactive control algorithms are designed to produce the command voltage input. The control logics are

velocity based on-off groundhook control (on-off VBG)

$$\begin{aligned} v_1(v_1 - v_2) \geq 0 \quad V = V_{max} \\ v_1(v_1 - v_2) < 0 \quad V = V_{min} \end{aligned} \tag{9}$$

displacement based on-off groundhook control (on-off VBG)

$$\begin{aligned} x_1(v_1 - v_2) \geq 0 \quad V = V_{max} \\ x_1(v_1 - v_2) < 0 \quad V = V_{min} \end{aligned} \tag{10}$$

Where, v_1 and v_2 are the velocity of primary structure and tuned mass damper, and x_1 is displacement of primary structure. These control algorithms are designed using the relative motion between the primary structure and tuned mass damper.

Clipped optimal algorithm

The clipped optimal control algorithm proposed by Dyke *et al*. (1996) is the one that has been shown to be effective for use with the MR damper. This algorithm consists of two parts of controller. The primary controller is the LQR control design which gives the optimal control force, $F_{d\,ci}$, that minimizes the cost function. This controller uses force proportional to an estimate of the state of the system using feedback gain that minimizes the cost function

$$J = \lim_{T\to\infty} E\left[\frac{1}{T}\int_0^T (z^T Q z + R F_{d_{ci}}{}^2) dt\right] \tag{11}$$

Optimal control force $F_{d\,ci}$ is given by equation $F_{d\,ci} = -L\,z$ and the feedback gain L is given by the equation,

$$L = (R + D_Z{}^T Q D_Z)^{-1}(B^T P_c + D_Z{}^T Q C_Z) \tag{12}$$

where, P_c satisfies the algebraic Riccati equation

$$A^T P_c + P_c A - (P_c B + C_Z{}^T Q D_Z)(R + D_Z{}^T Q D_Z)^{-1}(B^T P_c + D_Z{}^T Q C_Z) = -C_Z{}^T Q C_Z \tag{13}$$

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

$$V = V_{\max} H(\{F_{d\,ci} - F_d\} F_d) \tag{14}$$

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.

Maximum energy dissipation algorithm (MEDA)

Maximum Energy Dissipation (MED) algorithm is presented as a variation of the decentralized bang-bang approach proposed by McClamroch and Gavin (1995). In the maximum energy dissipation algorithm, the Lyapunov function was chosen to represent the relative total vibratory energy in the system as (Jansen and Dyke, 2000)

$$K = \frac{1}{2}\eta^T K \eta + \frac{1}{2}\dot{\eta}^T M \dot{\eta} \tag{15}$$

From the Lyapunov theory, the control law for semiactive controller is obtained as

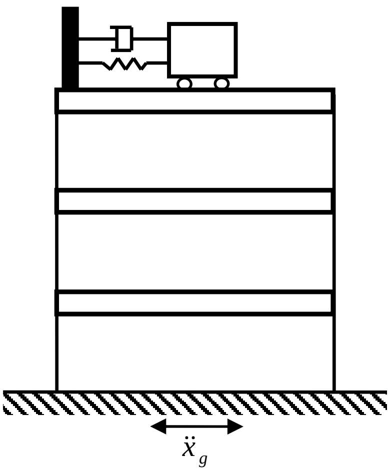
$$V = V_{\max} H(-\dot{\eta}\, \varphi F_d) \tag{16}$$

This control algorithm commands the maximum control voltage when the system dissipates energy.

NUMERICAL EXAMPLE

Numerical model

The model for the numerical analysis is 3 story shear building, and a semiactive tuned mass damper is installed at third floor. In the numerical model shown in figure 3, the mass and stiffness of each floor are 1500 kg and 2.1×10^6 N/m, and 1% modal damping of each mode. For the optimal tuning of the mass damper, the close form solutions which Den Hartog (1956) introduced were considered in the case of passive tuned mass damper system.



$$\mathbf{M} = \begin{bmatrix} 1500 & 0 & 0 \\ 0 & 1500 & 0 \\ 0 & 0 & 1500 \end{bmatrix} kg$$

$$\mathbf{K} = \begin{bmatrix} 4.2 & -2.1 & 0 \\ -2.1 & 4.2 & -2.1 \\ 0 & -2.1 & 2.1 \end{bmatrix} 10^6 \ \text{N/m}$$

$\mathbf{C}$ = 1% modal damping

$m_{TMD} = 150\, kg$

$k_{TMD} = 3.64\times10^4\ N/m$

Fig. 3. Three story shear building with semiactive TMD

In simulation, the model of the structure is subjected to the two earthquakes, El Centro earthquake (N-S component, 1940), Hachinohe earthquake (N-S component, 1968). Because the shear building system is a scaled mode, the amplitude of the earthquakes is scaled to 30% of the full-scale earthquake.

The linear viscous damper which has a constant damping coefficient is considered in the conventional tuned mass damper, and in the case of semiactive tuned mass damper, MR fluid damper is installed for the semiactive control of the model. In this MR damper model, command voltage has two values ($V_{min} = 0$ volts and $V_{max} = 2.25$ volts) in the case of semiactive control. The maximum force and stroke of this MR damper are 1500N and 2.5 cm.

The various control algorithms are evaluated using a set of evaluation criteria . The first evaluation criterion J_1 is a measure of the normalized maximum floor displacement. The second evaluation criterion J_2 is a measure of the normalized maximum interstory drift, and the third evaluation criterion J_3 is a measure of the normalized peak floor acceleration.

Control performance

Figure 4 and table 1 ~2 show the normalized maximum displacement, interstory drift and acceleration (evaluation criteria J_1, J_2 and J_3) of the cases using MR dampers of passive off mode, passive on mode and four semiactive control algorithms under two earthquakes. And these values are compared with conventional tuned mass damper case.

Table 1. Numerical results under El Centro earthquake

Evaluation Criteria	TMD	passive off	passive on	DBG	VBG	clipped optimal	MEDA
J_1	0.384	0.388	0.498	0.361	0.391	**0.359**	0.391
J_2	0.373	0.371	0.515	0.332	0.343	**0.331**	0.343
J_3	0.448	0.466	0.498	0.439	0.438	**0.434**	0.438

Table 2. Numerical results under Hachinohe earthquake

Evaluation Criteria	TMD	passive off	passive on	DBG	VBG	clipped optimal	MEDA
J_1	0.349	0.363	0.505	**0.348**	0.401	0.361	0.401
J_2	0.347	0.351	0.487	**0.318**	0.391	0.337	0.391
J_3	0.381	0.408	0.466	0.357	0.367	**0.354**	0.367

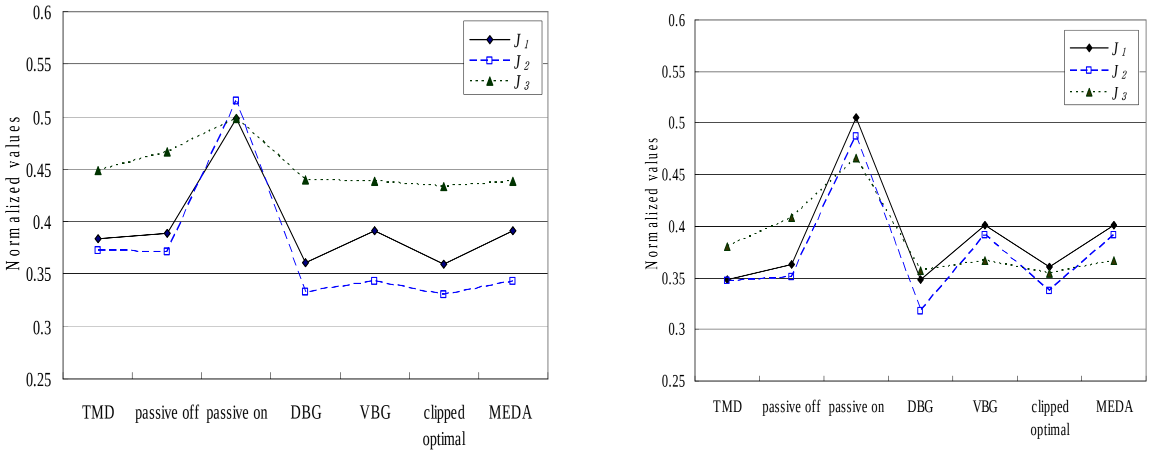


Fig. 4. Numerical results under (a) El Centro and (b) Hachinohe earthquake

As shown in figure 4, DBG and clipped optimal control algorithm are most efficient for all criteria while passive on mode of MR damper shows the worst performance. In the case of passive on mode, excessive MR damper force is applied to the mass damper so that energy dissipation effect of the mass damper is reduced. When command voltage of MR damper is calculated by the control algorithm, the overall control performance is increased considerably compared with the uncontrolled case. But compared with the conventional TMD, the efficiency of semiactive TMD is not so high. Even the DBG and clipped optimal case, improvement of control performance is not bigger than 5% , compared with TMD.

Robustness with respect to stiffness uncertainty

The stiffness matrix of shear building model has uncertainties by amount of δ, and the tuned mass damper is simulated with the parameters designed for the nominal model. The resulting stiffness matrix of shear building which has stiffness uncertainties is calculated as

$$\hat{\mathbf{K}} = \mathbf{K}(1+\delta) \tag{17}$$

Where, $\mathbf{K}$ is the nominal stiffness matrix of the building, which is used for the design of optimal tuned mass damper, δ is the uncertainty amount, and $\hat{\mathbf{K}}$ is the stiffness matrix with uncertainty. The stiffness uncertainties of -15%, -10%, -5%, +5%, +10%, and +15% are considered in this study.

Figure 5 ~ 7 shows the evaluation criteria with the stiffness uncertainty under two earthquakes. As shown in the figures, in general, the control performance of tuned mass damper decreases with the increase of uncertainty of stiffness matrix. When there is no uncertainty in the primary system, the difference of control performance between the conventional TMD and semiactive TMD is very small, as shown in the figure 4. But, as the uncertainty increases, the response reduction ratio with semiactive TMD is larger than conventional TMD. Overall control performance of semiactive TMD is better than conventional TMD with the uncertainty. Especially DBG and clipped optimal control theory shows the better efficiency than conventional TMD and other control algorithms. In the case of 10% stiffness uncertainty under Hachinohe earthquake, DBG control algorithm reduce the maximum interstory drift by 20% over the conventional TMD. With the increase of uncertainty, DBG and clipped optimal algorithms reduce the response by 10% ~20% over the conventional TMD. But under the Hachinohe earthquake, VBG and MEDA method show worse control performance than TMD and other algorithms with positive stiffness uncertainty. It's because of the excessive command voltage produced by the controller. However, this result shows that semiactive TMD controlled by aptitude algorithm has sufficient robustness under the stiffness uncertainty.

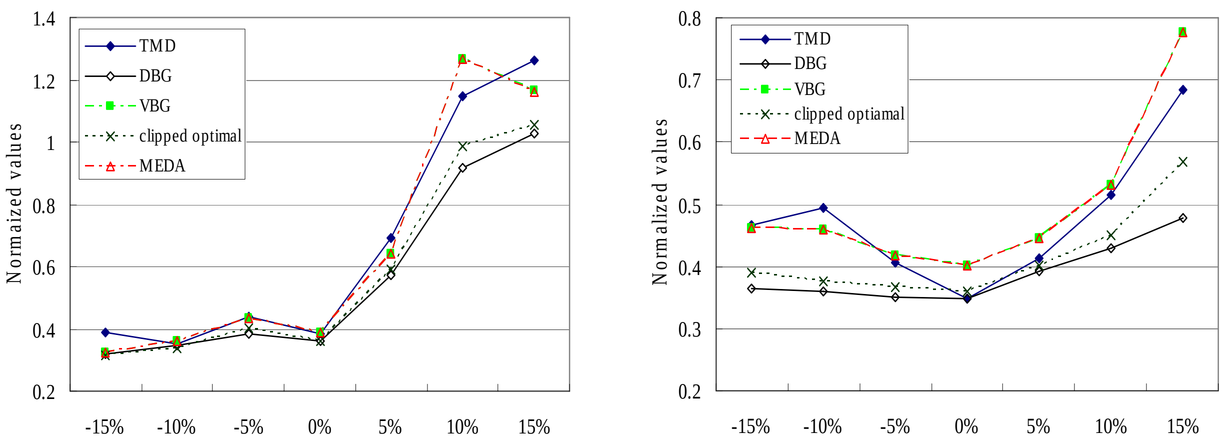


Fig. 5. J_1 with stiffness uncertainty under EL Centro and Hachinohe earthquake

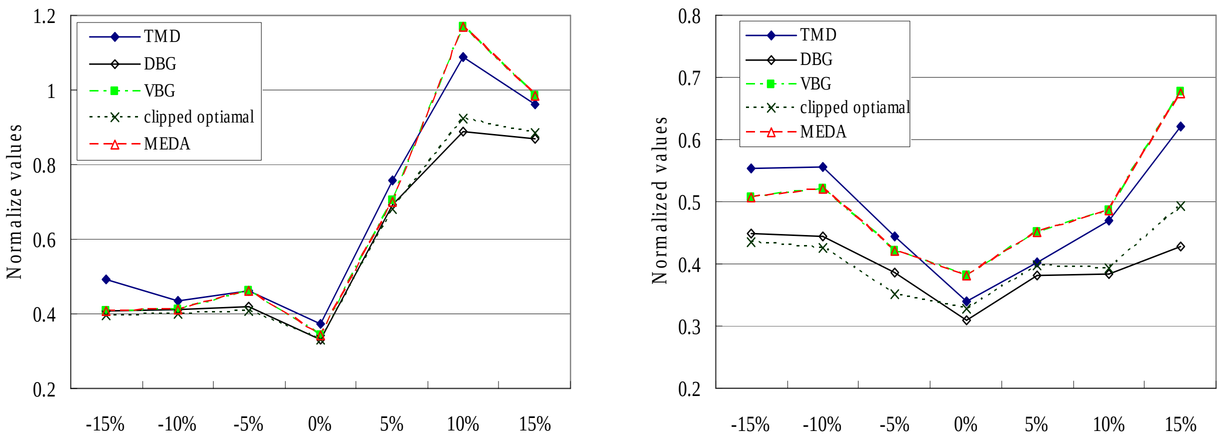


Fig. 6. J_2 with stiffness uncertainty under EL Centro and Hachinohe earthquake

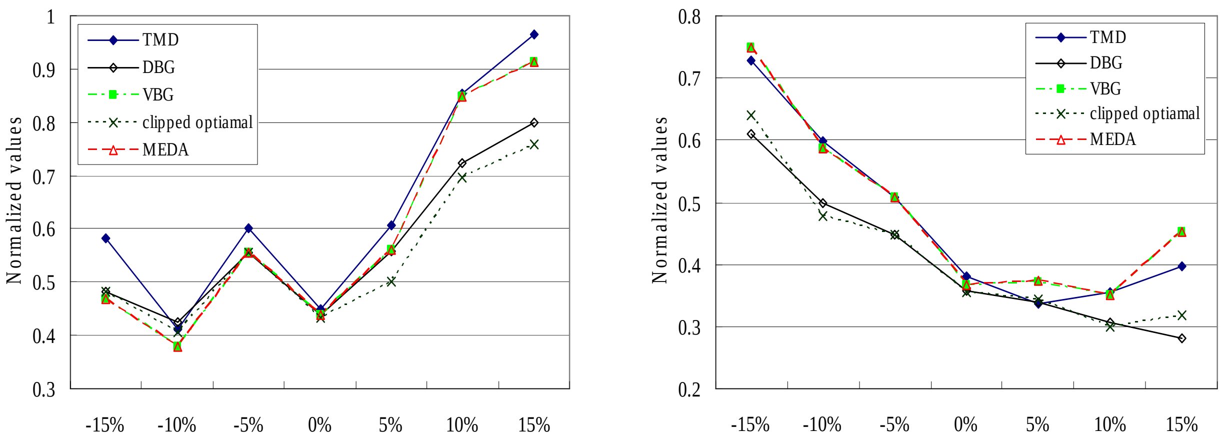


Fig. 7. J_3 with stiffness uncertainty under EL Centro and Hachinohe earthquake

CONCLUSIONS

In this study, four control algorithms are evaluated to identify a suitable control method for semiactive TMD in structural application. The numerical result indicates that efficiency of semiactive TMD is better than conventional TMD, especially under the uncertainty of primary system. Among the four control algorithms, DBG and clipped optimal algorithm show the best performance under the earthquake load. The result implies semiactive tuned mass damper controlled by optimal control algorithm can improve the control efficiency.

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