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DESIGN OF SEMI-ACTIVE TUNED MASS DAMPER FOR CONTROLLING SEISMICALLY INDUCED RESPONSES OF ELASTIC AND INELASTIC STRUCTURES

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Abstract

In this study, the performance of a passive tuned mass damper (TMD) and a semi-active TMD (STMD) was evaluated in terms of seismic response control of elastic and inelastic structures under seismic loads. First, elastic displacement spectra were obtained for the damped structures with a passive TMD and with a STMD proposed in this study. The displacement spectra confirm that STMD provides much better control performance than passive TMD in spite of having less stroke. Also, the robustness of the TMD was evaluated by off-tuning the frequency of the TMD to that of the structure. Finally, numerical analyses were conducted for an inelastic structure of which hysteresis was described by Bouc-Wen model and the results indicated that the performance of the passive TMD of which design parameters were optimized for a elastic structure considerably deteriorated when the hysteretic portion of the structural responses increased, while the STMD showed about 15-40% more response reduction than the TMD.

1. INTRODUCTION

Tuned mass damper (TMD) is one of the most traditional passive mass type dampers and it consists of mass, spring, and viscous damping devices [1]. Since TMD is effective in reducing the stationary first modal response, it is conventionally utilized in the field of wind engineering. Recently, the seismic application of TMD and tuned liquid damper (TLD) is investigated through analytical and experimental studies. Tsai and Lin numerically obtained a regression equation for optimal parameters of damped structures under stationary base excitation load and showed that optimal tuning frequency ratio decreases and optimal damping ratio increases with increasing structural damping [2]. Setareh designed a semi-active TMD (STMD) which can modulate its viscosity of the damper and verified the excellence of the STMD over TMD in terming of controlling a structure subject to sinusoidal base excitation [3]. Setareh applied so called ‘ground hook’ control algorithm in which the force transferred through the viscous damper to the structure adds structural damping. Kim et al. proposed a STMD of which damping plays a role similar to the restoring force of the structure by adopting magneto-reological (MR) damper [4]. The results from these studies were obtained by using not real earthquake load but sinusoidal or white noise excitation.

Kaynia et al. presented that TMD was not as effective as expected in seismic application by conducting the numerical analysis using 48 ground accelerations [5]. Sadek et al. briefly reviewed the previous studies on seismic application of TMD and demonstrated through statistical analysis using 52 ground motions measured in the western parts of the United States that TMD could control earthquake-induced responses if the parameters of TMD were set up for the structure-TMD system to have identical damping ratio in the first two complex modes by modifying the process by Villaverde [6]. As Sadek et al. mentioned in their study, however, the existence of the structural damping considerably impairs the efficiency of the passive TMD and larger mass ratio is required to maintain the performance of TMD. Also, previous studies on seismic applications of TMD were mostly focused on the elastic structures. However, because most structures show inelastic behaviors under earthquake and then structural damping increases, in order to verify that TMD is effective in the seismic application, the performance of TMD should be evaluated by considering the inelastic behavior.

In this study, the performances of the passive TMD and STMD are investigated in terms of seismic response control of elastic and inelastic structures. First, elastic displacement response spectra are obtained for the damped structures controlled by passive TMD and by STMD of which stiffness and viscosity are modulated to switch from maximum value to minimum one. Also, the robustness of TMD is evaluated by off-tuning the frequency of TMD to that of the structure. Finally, the effect of TMD and STMD are evaluated for an inelastic structure of which hysteretic characteristics are considered by adopting Bouc-Wen model.

2. EQUATION OF MOTION

The hysteretic characteristics of an inelastic structure can be described by using well known Bouc-Wen model [13]. The governing equation of the inelastic structure with TMD is

$$\begin{bmatrix} m_s & 0 \\ 0 & m_t \end{bmatrix}\begin{bmatrix} \ddot{x}_s \\ \ddot{x}_t \end{bmatrix}+\begin{bmatrix} c_s+c_t & -c_t \\ -c_t & c_t \end{bmatrix}\begin{bmatrix} \dot{x}_s \\ \dot{x}_t \end{bmatrix}+\begin{bmatrix} \alpha k_s+k_t & -k_t \\ -k_t & k_t \end{bmatrix}\begin{bmatrix} x_s \\ x_t \end{bmatrix}=\begin{bmatrix} -(1-\alpha)k_s D_y \\ 0 \end{bmatrix}\eta-\begin{bmatrix} m_s \\ m_t \end{bmatrix}\ddot{x}_g \quad (1)$$

where m_s, c_s, and k_s denote, respectively, the mass, damping, and initial stiffness of the structure, and m_t, c_t, and k_t denote, respectively, the mass, damping, and stiffness of TMD. x_s and x_t, are, respectively, the relative displacements of the structure and TMD to the ground and $\ddot{x}_g$ is ground acceleration. α denotes the ratio of post-yielding stiffness to the initial one and D_y is yielding displacement. $\alpha=1$ means that the structure behaves elastically. η is an non-dimensional variable adopted for describing hysteresis and it is governed by following differential equation.

$$D_y\dot{\eta}+\gamma|\dot{x}_s||\eta|\eta^{n-1}+\beta\dot{x}_s\eta^{n-1}-A\dot{x}_s=0 \quad (2)$$

where γ, β, n and A are parameters associated with the magnitude, shape and the smoothness of the hysteretic curve. Whittaker et al. described the bi-linear behavior using Bouc-Wen model with γ =0.5, β =0.5, n =5, and A =1 [7]. The parameters presented by Whittaker et al. are used in this study. The mass, stiffness and damping of TMD were determined based on following equation.

$$m_t = \mu m_s\,,\; k_t = f_r^2 \omega_1^2 m_t\,,\; c_t = 2\xi_t \sqrt{m_t k_t} \tag{3}$$

where μ is the ratio of TMD mass to the effective modal mass of the structure, f_r is the tuning frequency ratio, ω_1 is the first modal radial frequency of the structure, and ξ_t is the damping ratio of TMD.

Passive TMD is designed to keep f_r and ξ_t constant, and accordingly the stiffness and damping do not change during its maintenance. Many researches have been conducted to find optimal values of f_r and ξ_t, which are known to be dependent on the mass ratio, structural damping, type of excitation, and the optimization criteria. Sadek et al. presented regression equations for determining the optimal f_r and ξ_t based on numerical eigenvalue analysis of the damped structure with TMD and showed that mean response spectrum for 52 ground accelerations can be reduced over all structural periods by using passive TMD. Since the study by Sadek et al. considered both the effect of structural damping and seismic loads, which is in accordance with the purpose of this study, the following tuning frequency ratio and damping ratio presented by Sadek et al. are used in the design of passive TMD in this study.

$$f_r = \frac{1}{1+\mu}\left(1 - \xi_s \sqrt{\frac{\mu}{1+\mu}}\right) \qquad \xi_t = \frac{\xi_s}{1+\mu} + \sqrt{\frac{\mu}{1+\mu}} \tag{4}$$

where ξ_s is the structural damping. With increasing ξ_s, f_r decreases while ξ_t increases.

3. CONTROL ALGORITHM FOR STMD

Passive TMD mitigates mainly the vibration energy corresponding to the tuning frequency. Rana and Soong investigated the performance of multiple TMDs of which masses are tuned to different modes and verified that multiple TMDs designed in that manner were not effective in structural control because masses tuned to higher modes excited the first mode responses [8]. This fact indicates that passive TMD has a limitation that TMD should be designed to tune a fundamental frequency and the structural response should be governed by the tuned mode.

Active TMD (ATMD) adopting additional excitation system and STMD were proposed in order to improve the performance of the passive TMD by controlling the force of TMD transferred to the structure, and the performance of ATMD or STMD is known to be better than the passive TMD. ATMD, however, requires additional power supply, computer for computing control force, sensors for measuring structural responses, and signal processing system, which makes the application of ATMD impractical. Although also STMD requires supplemental devices for controlling the stiffness or damping and measuring structural responses, STMD is stable and economical because STMD does not utilize exciter requiring large power supply. Accordingly, this study is focused on the application of STMD to seismic engineering and carried out performance comparison of STMD to that of passive TMD.

When α =1, the first row of the Eq.(1) can be expressed as follows by transposing TMD generated force to the right side.

$$m_s \ddot{x}_s + c_s \dot{x}_s + k_s x_s = -m_s \ddot{x}_g + c_t(\dot{x}_t - \dot{x}_s) + k_t(x_t - x_s) \tag{5}$$

Eq. (5) indicates that TMD generates the damping and restoring forces which result, respectively, from the velocity and displacement of TMD relative to the TMD installed floor. The derivative of the structural conservatory energy to time is

$$
\begin{aligned}
dE/dt &= d(0.5m_s\dot{x}_s^2 + 0.5k_s x_s^2)/dt = m_s\dot{x}_s\ddot{x}_s + k_s x_s\dot{x}_s \\
&= -c_s\dot{x}_s^2 - m_s\ddot{x}_g\dot{x}_s + c_t\dot{x}_s(\dot{x}_t - \dot{x}_s) + k_t\dot{x}_s(x_t - x_s)
\end{aligned} \tag{6}
$$

Eq. (6) shows that the conservatory energy increases when the sign of the displacement or velocity of TMD relative to TMD installed floor is identical to the velocity of TMD installed floor, and vice versa.

Most previous studies on STMD considered only damping term as variable or controllable while stiffness remained unchanged because viscosity can be easily modulated by adopting MR damper of which viscosity varies in milli-second according to the applied magnetic field [4]. Yamada and Kobori proposed an active variable stiffness (AVS) system using a Chevron brace-beam connection detail in which the connection state can be controlled between '*connected*' and '*disconnected*' [9]. However, this detail cannot be directly applied to the design of STMD and a mechanism should be developed so that the spring stiffness of STMD or the connection state of the spring to the structure can be controlled. In this study, considering that stiffness of the spring is difficult to be controlled in real time to have arbitrary value, it is assumed that both the stiffness of the spring and damping can have maximum and minimum values simply by changing the connection states of the elements which have stiffness and viscosity.

A control algorithm is designed to make the STMD transfer maximum force to the structure through the spring and damper when they play a role of decreasing conservatory structural energy and otherwise the minimum one. This control algorithm is

$$
c_t = \begin{cases} c_{\max} & \dot{x}_s(\dot{x}_t - \dot{x}_s) \le 0 \\ c_{\min} & otherwise \end{cases} \qquad k_t = \begin{cases} k_{\max} & \dot{x}_s(x_t - x_s) \le 0 \\ k_{\min} & otherwise \end{cases} \tag{7}
$$

where $c_{\max}$, $c_{\min}$, $k_{\max}$ and $k_{\min}$ are, respectively, maximum viscosity, minimum viscosity, maximum stiffness and minimum stiffness.

4. NUMERICAL EXAMPLE

4.1 Elastic Structures

In this section, numerical analyses of mass normalized elastic SDOF systems with TMD and STMD are performed using 20 accelerations measured in rock sites [10]. All the results for elastic structures are obtained by averaging the peak responses induced by 20 accelerations.

4.1.1 Displacement response spectra of SDOF systems with passive TMD

Fig. 1 shows the displacement response spectra of structures installed with passive TMD of which tuning frequency ratio and damping ratio are determined by using Eq.(4). The structural damping ratios of 2% and 5% are considered and the response spectra are normalized to the uncontrolled one in order for easy identification of control effectiveness. It is observed that the seismically induced peak displacement can be reduced by using optimally designed passive TMD over all structural periods and the reduction effects become significant with increasing mass ratio. The comparison between Fig. 1(a) and Fig. 1(b) shows that the increase of structural damping from 2% to 5% causes the deterioration of the performance of TMD if identical mass ratio is used. Considering that structural damping generally increases when the structure experiences large deformation under seismic load, one should be careful in evaluating the performance of passive TMD which is good for lightly damped structures based on the accurate assessment of the structural damping expected under the seismic load.

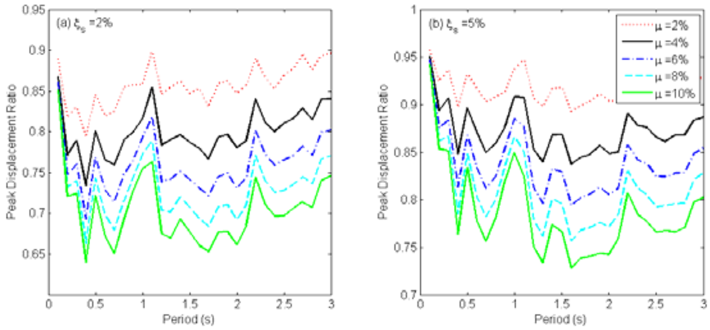


Figure 1. Displacement Response Spectra

4.1.2 Robustness of passive TMD

The performance of the passive TMD observed in Fig.1 is premised on accurate identification of the frequency of the structure and subsequent accurate tuning of TMD. Inaccurately tuned TMD may amplify the structural response on the contrary. In seismic application, it is very difficult to accurately identify the structural frequency since the targeted frequency should be determined to consider in some degree the crack of concrete element or damage of non-structural elements which affect the frequency. This is different from the condition in wind engineering in which initial stiffness of the structure including the effect of non-structural elements is considered and the corresponding frequency is possible to be measured in site. Accordingly, in this section, the robustness of the passive TMD is investigated by varying the tuning frequency ratio under the assumption that the frequency of the structure used in the design of TMD may have 10% error.

Fig. 2 shows the performance variation when different tuning frequency ratio from one in Eq.(4) is used. All the values in Fig.2 are normalized to the one obtained by using Eq.(4), and thus the value over 1 means the performance deterioration of TMD and the value less 1 indicates that the optimal tuning frequency ratio is different from Eq.(4) for the earthquake loads used in this study. Fig. 2(a) with 2% mass ratio shows that all the (+) off-tuning cases give the values over 1 while (-5%) off-tuning give one slightly less than 1. From Fig. 2(b)~(d), it is observed that the performance variation by off-tuning effect becomes insignificant with increasing mass ratio. Since (+)off-tuning always brings about undesirable results, one should be careful about overestimating the frequency of the structure.

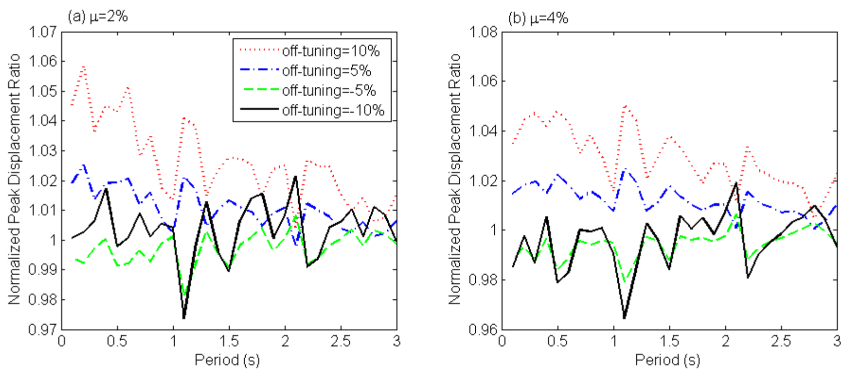


Figure 2. Normalized Peak Displacement Considering Off-tuning Effect

4.1.3 Displacement response spectra of SDOF systems with STMD

In this section, the performance of STMD is evaluated through the comparison with that of passive TMD. The 2% structural damping ratio and 2% mass ratio for both STMD and TMD are used. Following 4 cases are considered for designing STMD.

Case-1: $k_{\max} = 10k_d$, $k_{\min} = 0.1k_d$, $c_{\max} = 10c_d$, $c_{\min} = 0.1c_d$
Case-2: $k_{\max} = 5k_d$, $k_{\min} = 0.1k_d$, $c_{\max} = 5c_d$, $c_{\min} = 0.1c_d$
Case-3: $k_{\max} = k_d$, $k_{\min} = k_d$, $c_{\max} = c_d$, $c_{\min} = 0.1c_d$
Case-4: $k_{\max} = k_d$, $k_{\min} = k_d$, $c_{\max} = c_d$, $c_{\min} = 0.1c_d$ (different control algorithm from Case-3)

where k_d and c_d are, respectively, stiffness and viscosity realizing the tuning frequency ratio and damping ratio in Eq.(4). Both the stiffness and viscosity, respectively, switch from $k_{\min}$ and $c_{\min}$ to $k_{\max}$ and $c_{\max}$ for Case-1 and Case-2 while only viscosity is variable for Case-3 and Case-4. The property of STMD for Case-4 is identical to the one for Case-3, but control algorithm presented in Ref.[9] which are different from one proposed in this study in that damper of STMD plays a role of structural stiffness by determining the viscosity as

Displacement response spectra of SDOF systems with TMD and STMD are shown in Fig. 3. It is observed that STMD significantly improves the peak displacement mitigation performance of TMD. The performances of STMD for Case-1 and Case-2 is superior to those for Case-3 and Case-4, and Case-1 having larger variable stiffness magnitude provides more response reduction effect than Case-2. This fact implies that if it is practically realizable, not only viscosity but also stiffness should be made variable and the variation magnitude should be as large as possible for obtaining better control performance. It is identified that the Case-3 proposed in this study shows better performance than Case-4 although the difference is not so significant.

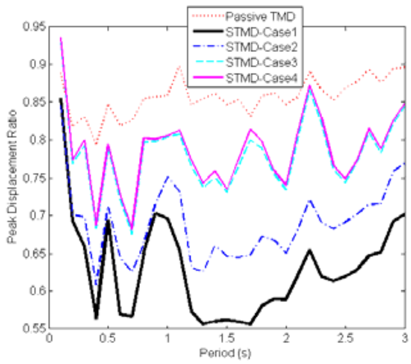
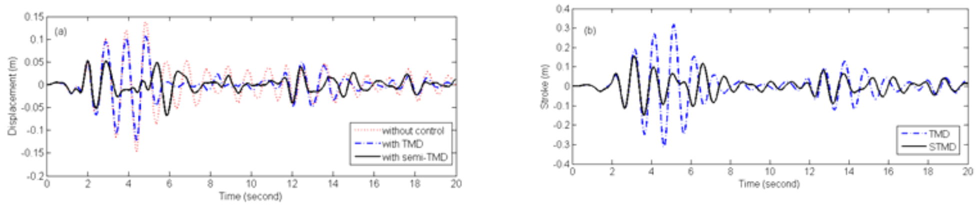


Figure 3. Displacement Response Spectra of Structures with STMD and TMD

4.1.4 Time histories of displacement and stroke

Figure 4(a) compares the displacement time histories of a SDOF system which has 2% damping ratio and 1.0 second natural period and is excited by El Centro (1942, NS component) of which peak acceleration is scaled to 0.3g. The property of TMD is determined by using Eq.(4) and Case-1 is considered for STMD. It is obviously shown in Fig. 4(a) that STMD is much more effective in reducing both initial non-stationary response and peak displacement than passive TMD. Because large stroke in mass type damper cause stability problem that moving mass may strike the rail end or reference wall, TMD generally has impact-proof bumper and the stroke expected under given load should be estimated. Fig 4(b) compares the strokes of TMD and

STMD. The peak strokes of TMD and STMD are, respectively, 31.8cm and 15.6cm, which implies that STMD can provide better control performance in spite of having about half the stroke of TMD.



(a) Displacement (b) Stroke

Figure 4. Time histories of Displacement and Stroke

4.2 Inelastic Structure

The structural period and damping change when a structure experiences inelastic ductile motion under seismic load. It is known that generally both period and damping increase with increasing ductility [11]. Since TMD is designed based on the elastic behavior, investigation on its performance with regard to the variation of structural period and damping is required.

Numerical analyses are conducted for a mass normalized SDOF system with 1.2 second period and 5% damping ratio by using El Centro earthquake (1942, NS component) as ground acceleration. α =1.0, 0.5, 0.25, 0.15, 0.05 and e =0.7, 0.5, 0.3 are considered as the parameters for modeling elastic and inelastic behaviors. α =1.0 denotes the elastic structures and the less value of α and e makes the inelastic behavior more dominant. Fig. 5 shows the peak and RMS response normalized to those of uncontrolled structures. The Case-1 is considered for designing STMD. The responses by passive TMD increases with decreasing α and e and approaches to 1, implying that TMD is almost useless in response control. STMD reduces all the responses much more than TMD except for the absolution acceleration when $e = 0.3$. The performance of STMD gets worse for smaller e as is the case for TMD, but the degree is not as significant as TMD and the smaller α does not always brings about performance deterioration of STMD. These facts indicate that STMD is comparatively insensitive to the variation of the structural properties unlike passive TMD and can be designed to show consistent performance for controlling inelastic structures under severe earthquake loads.

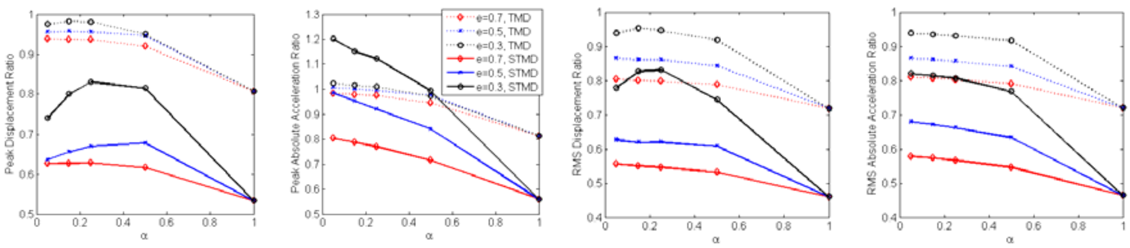


Figure 5. Performance Comparison of TMD and STMD for Various Inelastic Structures

5. CONCLUSIONS

In this study, the control performances of the passive tuned mass damper and semi-active TMD (STMD) which can modulate the stiffness and the damping by controlling the connectivity of the spring and dampers were evaluated in terms of seismic response control of elastic and inelastic structures under seismic loads. Elastic displacement spectra were obtained for the damped structures with a passive TMD, which was optimally designed using the frequency and damping ratio presented by previous study, and with a STMD proposed in this study. Also, the robustness of the passive TMD was evaluated by off-tuning the frequency of the TMD to that of the structure. The control performance of the passive TMD significantly deteriorated with increasing structural damping and (+) off-tuning while STMD provided 40% less response spectra and smaller stroke than the passive TMD. Finally, numerical analyses were conducted for an inelastic structure of which hysteresis was described by Bouc-Wen model and the results indicated that the performance of the passive TMD of which design parameters were optimized for a elastic structure considerably deteriorated when the hysteretic portion of the structural responses increased, while the STMD showed about 15-40% more response reduction than the passive TMD. Especially, it was identified in the frequency domain that the STMD had an ascendancy over the passive TMD in reducing the magnitude of the permanent deformation due to the inelastic behavior.

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