ELASTO-PLASTIC TUNED MASS DAMPER FOR CONTROLLING SEISMIC RESPONSE OF STRUCTURES

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ABSTRACT:

Tuned mass dampers (TMD) are considered to be effective in controlling the wind and seismic response of structures. Most of the studies have focused on the use of elastic TMD, wherein, energy dissipation is derived from the damping of TMD. From the past studies it is well established that an elastic TMD with proper mass and damping can be effective in controlling the seismic response of main system. It is also clear that if energy dissipation capability of TMD is enhanced, then, it would be more effective in controlling the overall response of the structure. In earthquake resistant design it is customary to rely on the energy absorbing capability of the structure by considering its elasto-plastic behavior. With this in view, in this study, elastoplastic TMD is considered. An elastic single degree of freedom system mounted with an elastoplastic TMD is analyzed. The nonlinear equations of motion are solved numerically, using the Newmark Beta method. Effectiveness of elasto-plastic TMD vis-à-vis an elastic TMD is established. Effect of yield level of elasto-plastic TMD on the response of main system is studied. Issues related with optimum parameters of elasto-plastic TMD are also discussed.

KEYWORDS: Elasto-plastic system, Tuned mass damper, Seismic response

1. INTRODUCTION

Tuned Mass Damper (TMD) is a passive energy absorbing device which consists of a mass, a spring and a viscous damper attached to a vibrating main system. TMD with properly tuned mass, stiffness and damping is proved to reduce, the dynamic response dominated by resonance. Many studies are performed on the effect of TMD on seismic response of structures. Kaynia, et al. (1981) studied the effect of TMD subjected to past earthquake ground motions. The sensitivity of the TMD to various earthquake excitations was also studied. Warburton (1981) determined optimum parameters for TMD attached to one mass of main system with two-degrees-of-freedom system. Sladek and Klinger (1983) studied the effect of TMD on seismic response of multi degree of freedom (MDOF) subjected to El Centro earthquake and found that the reduction in response due to TMD is not significant. It is found that there is very less effect on the peak displacement of the main structure due to TMD. Villaverde and Koyama (1993) shown that, the response reduction is large for resonant ground motions and diminishes as the dominant frequency of the ground motion gets further away from the structures natural frequency to which the TMD is tuned. Sadek et al. (1997) proposed the optimum parameters of TMD for SDOF as well as for MDOF system to control the particular mode.

Jagdish et al. (1979) studied two storey bilinear hysteretic structures using the dynamic vibration absorber concept in earthquake resistant design. They studied the influence of frequency and yield displacement ratios on the maximum ductility response of the lower storey. Lukkunaprsit & Wanitkorkul (2001) investigated the effectiveness of linear TMD in vibration control of elastoplastic building under moderate ground shaking caused by the long distance earthquake. Pinkaew et al. (2003) found that effectiveness of TMD in the controlling the peak displacement of the structure after yielding of the main structure is very insignificant, but TMD helps in damage reduction of the structure.

It is noted that, most of the studies have focused their attention on elastic TMD and there are very few studies on elasto-plastic TMD. In the present study, the effect of elasto-plastic TMD on the response of main system under harmonic base excitation and seismic base excitation is studied. The main system is considered to be elastic.

The governing equations of motion are solved numerically using Newmark Beta method. The effect of parameters of elastoplastic TMD, viz., yield level, viscous damping and its equivalent linear natural frequency on the response of structure is studied.

2. SYSTEM WITH TMD

A main system (SDOF) with TMD subjected to base excitation is shown in Figure 1, where, m, k, c are mass, stiffness, and viscous damping coefficient of the main system and m_d, k_d, c_d, are corresponding parameters of TMD.

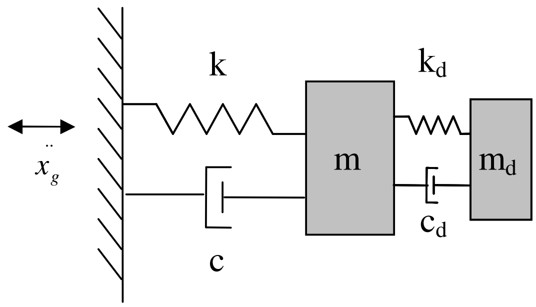


Figure 1: SDOF system with Tuned Mass Damper

For the linear TMD, the equations of motion are given by

$$\begin{bmatrix} m & 0 \\ 0 & m_d \end{bmatrix} \begin{Bmatrix} \ddot{u} \\ \ddot{u}_d \end{Bmatrix} + \begin{bmatrix} c + c_d & -c_d \\ -c_d & c_d \end{bmatrix} \begin{Bmatrix} \dot{u} \\ \dot{u}_d \end{Bmatrix} + \begin{bmatrix} k + k_d & -k_d \\ -k_d & k_d \end{bmatrix} \begin{Bmatrix} u \\ u_d \end{Bmatrix} = -\begin{Bmatrix} m \\ m_d \end{Bmatrix} \ddot{x}_g \qquad 2.1$$

Similarly, for nonlinear system, the equations of motion for base excitation are given by

$$[m]\{\ddot{u}\} + [c]\{\dot{u}\} + \{fs(u, \dot{u})\} = -\begin{Bmatrix} m \\ m_d \end{Bmatrix} \ddot{x}_g \qquad 2.2$$

Where, the restoring force, $fs(u, \dot{u})$, for nonlinear system depends on the velocity and displacement at any time step which changes depending on the loading variation. In the present study, the system is idealized as the elastoplastic system, which is explained in detail in the next section.

A tuned mass damper is characterized in terms of frequency ratio and damping ratios which are given by

$$f = \omega_d / \omega_0 \text{ and } \mu = m_d / m$$

where, ω_0, ω_d are natural frequency of main system and TMD respectively.

For a given mass ratio μ, the optimum parameters like optimum viscous damping coefficient η_d and frequency ratio f which leads to stiffness harmonic base excitation are taken from Tsai & Lin (2003) and that for earthquake time history excitation are taken from Sadek, et al. (2003).

2.1 Elastic and Elastoplastic TMD

In the elastic TMD, the force–deformation relation is linear (Figure 2) for all the values of deflection. In elastoplastic TMD, the yielding occurs at yield displacement of u_y (Figure 3).

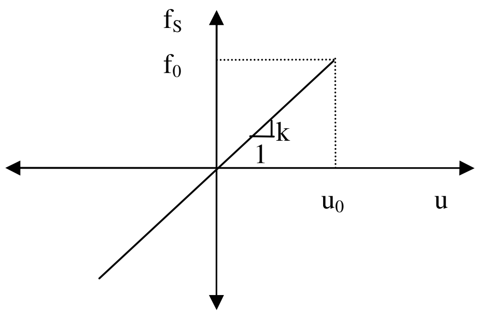


Figure 2: Force-Deformation Relationship of elastic system

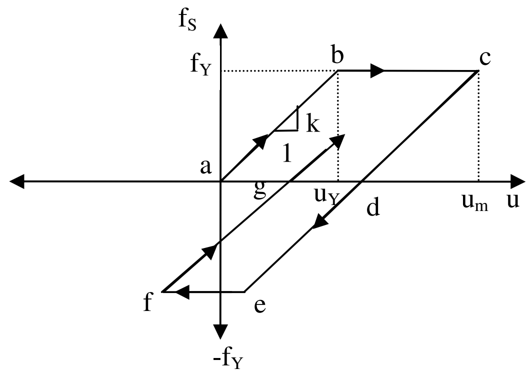


Figure 3: Force-Deformation Relationship of elastoplastic system

Figure 3 shows a typical cycle of loading, unloading, and reloading for an elastoplastic system. The yield strength is same in the two directions of deformation. Unloading from a point of maximum deformation takes place along a path parallel to the initial elastic branch. Similarly, reloading from a point of minimum deformation takes place along a path parallel to the initial elastic branch. The cyclic force-deformation relation is no longer single valued; for deformation u at time t the resisting force f_S depends on the prior time history of motion of the system and whether the deformation is currently increasing (velocity $\dot{u} > 0$) or decreasing (velocity $\dot{u} < 0$).

For the elastoplastic TMD, the normalized yield strength $\overline{f_y}$ (Chopra, 2006), is given by

$$\overline{f_y} = \frac{f_y}{f_0} = \frac{u_y}{u_0} \qquad 2.4$$

Where f_o and u_0 are the peak values of the resisting force and deformation, respectively, in the corresponding linear system. In other words, f_o is the minimum strength required for the structure to remain linearly elastic during the ground motion. u_y is the yield deformation and fy, the corresponding force. u_m is the maximum deformation of the elastoplastic system.

2.2 Numerical Solution

Analytical solution to the dynamic response of elastoplastic system is not feasible. Numerical methods are therefore essential in the analysis of elastoplastic systems. Newmark beta method, an implicit method of direct integration, is used in the present study. A FORTRAN program is developed to determine the response of a multi degree of freedom system for linear as well as elastoplastic behavior of the system. The average acceleration method is used, for which, γ = 1/2, and β = 1/4.

The restoring force in the system is checked for the linear or nonlinear i.e. elastoplastic range which depends on the yield strength of the system. Depending on the restoring force the stiffness of the system is switched for each time step.

3. RESULTS

The effect of TMD on the response is studied for harmonic base excitation and seismic base excitation. For harmonic base excitation, the frequency response curve is obtained. The seismic response is studied for ten recorded time histories. The results are obtained for two main systems. One is a rigid system with time period, T= 0.5 sec and other flexible system with time period, T=2.0 sec. The viscous damping ratio for main system is taken as η = 0.05.

3.1 Harmonic Base Excitation

Harmonic base excitation $\ddot{x}_g(t) = A\sin\lambda t$ is applied and response is obtained for various values of λ. A typical time history of main system is shown in Figure 4. It is seen that in initial stages, transient behavior is present and subsequently steady state is achieved. The effect of various parameters is studied through frequency response curve. The frequency response function is plotted for the maximum value of the steady state response of the main system.

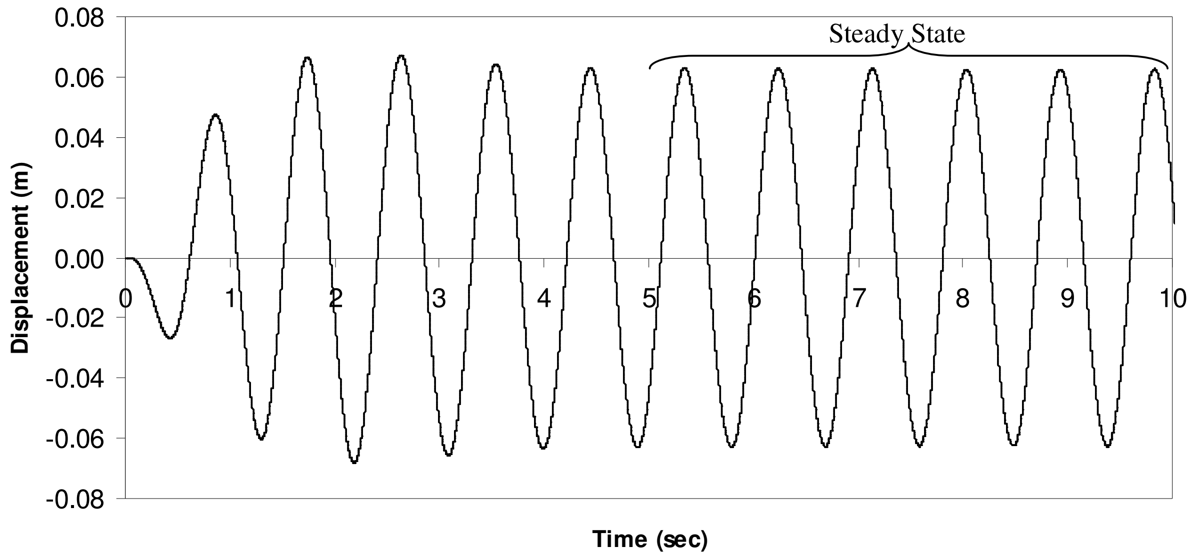


Figure 4: Steady state Response of a main system, $T = 0.8$ sec, $\mu = 0.1$, $\ddot{x}_g = \sin 7t$

The effect of yield level of TMD on the frequency response is shown in Figure 5 for system with T= 0.5 sec and in Figure 6 for T = 2.0 sec. It is observed that the linear TMD reduces the response near resonance range. However, for the low frequency range, i.e. $\lambda/\omega < 0.8$, the response of main system is higher due to deployment of TMD. As compared to the elastic TMD, the inelastic TMD is less effective near the resonance range, but it gives more reduction in low frequency range. For the high frequencies i.e. $\lambda/\omega > 1.2$, there is no appreciable change in the response due to elastic or inelastic TMD.

The TMD parameters considered are for the linear TMD. The same damping is used for inelastic TMD except that it is made to yield at f_y. In order to ascertain if elastoplastic TMD may have different optimum damping, the frequency response curve is obtained for different damping values. The results are shown in Figure 7 and 8 for T = 0.5 sec and T = 2.0 sec respectively. For the lower damping values, than the optimum damping, the response is less in resonant region, but it increases in the other regions.

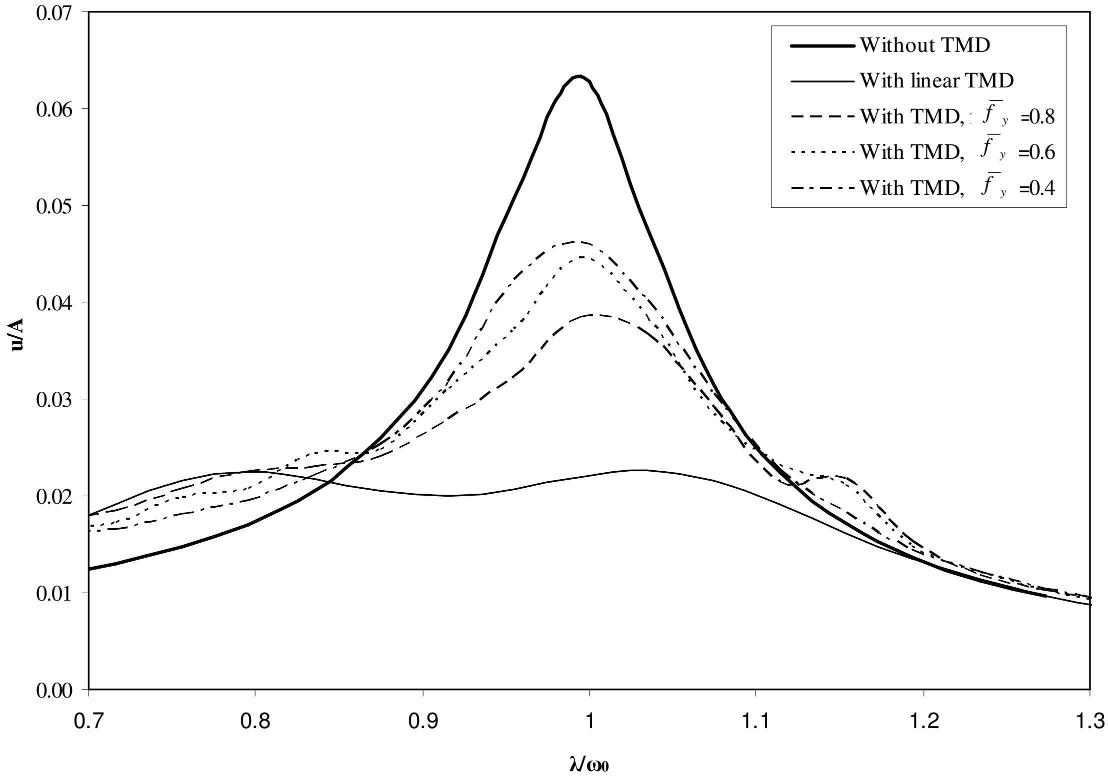


Figure 5: Effect of yield strength on response of main system, $T = 0.5$ sec, $\mu = 0.1$

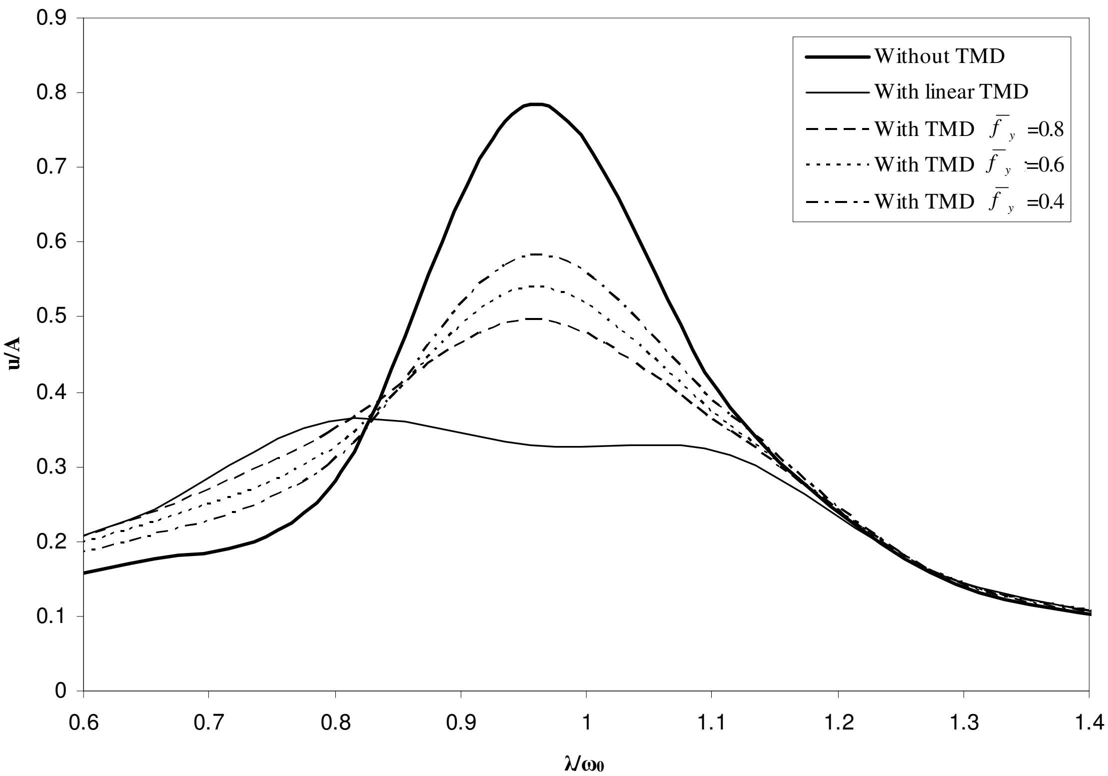


Figure 6: Effect of yield strength on response of main system, $T = 2.0$ sec, $\mu = 0.1$

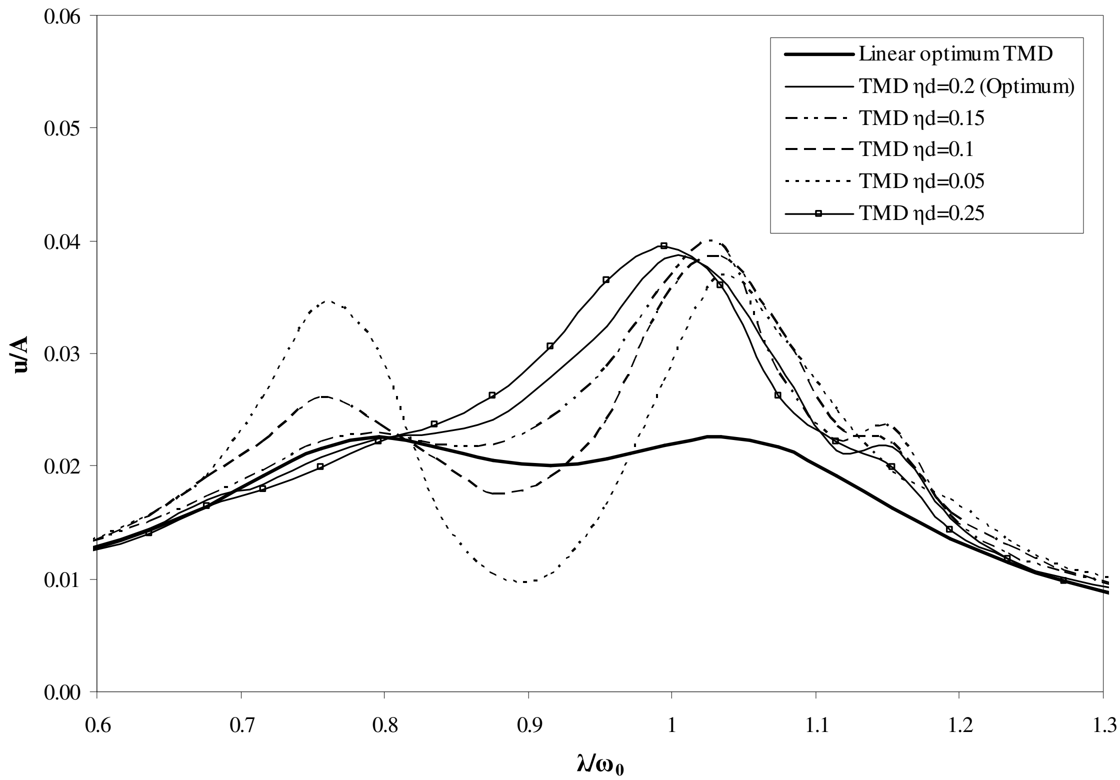


Figure 7: Effect of damping of TMD on response of main system, $T = 0.5$ sec, $\mu = 0.1$, $\overline{f}_y = 0.8$

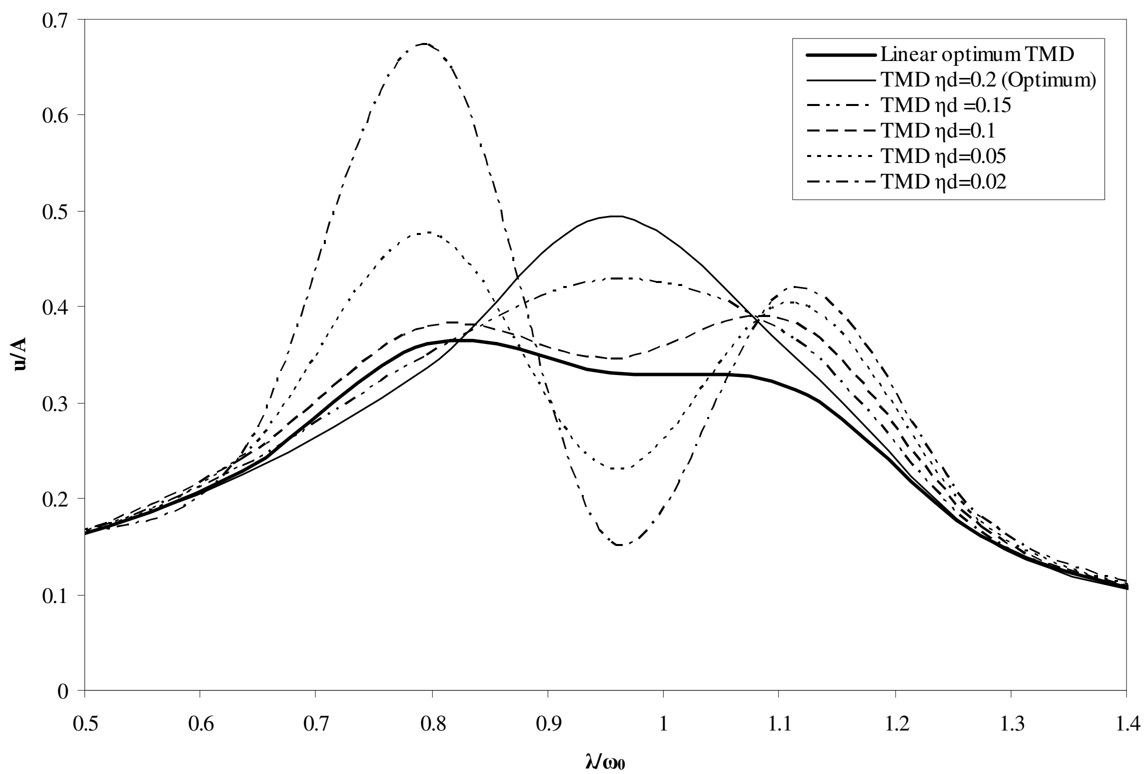
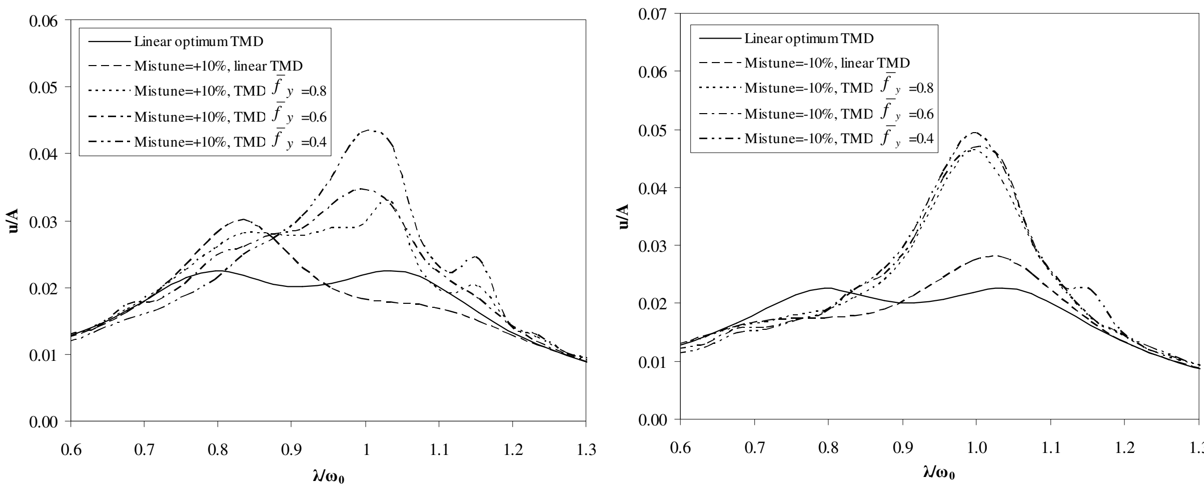


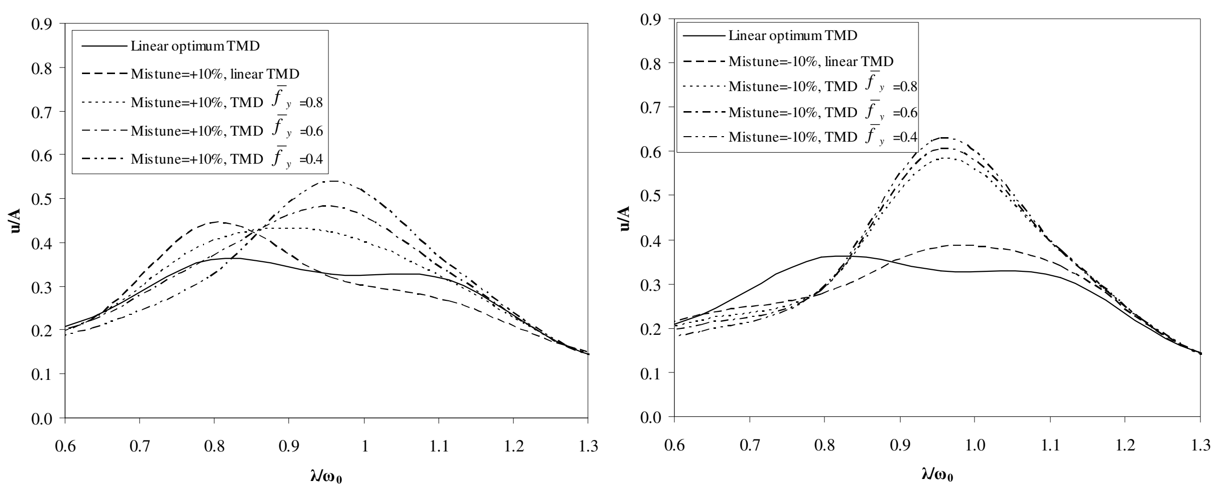
Figure 8: Effect of damping of TMD on response of main system, $T = 0.5$ sec, $\mu = 0.1$, $\overline{f}_y = 0.8$



a. Frequency Response Curve $T = 0.5$ sec, $\mu = 0.1$, $\eta_d = 0.2$

b. Frequency Response Curve $T = 0.5$ sec, $\mu = 0.1$, $\eta_d = 0.2$

Figure 9: Effect of mistuning of TMD on response of main system, $T = 0.5$ sec



a. Frequency Response Curve $T = 2.0$ sec, $\mu = 0.1$, $\eta_d = 0.2$

b. Frequency Response Curve $T = 2.0$ sec, $\mu = 0.1$, $\eta_d = 0.2$

Figure 10: Effect of mistuning of TMD on response of main system, $T = 2.0$ sec

Similarly, the effect of change in the stiffness of TMD (i.e. mistuning of TMD) is also studied and results are shown in Figure 9 and 10 for systems of T = 0.5 sec and T = 2.0 sec respectively, where the mistuning is done by changing the frequency of TMD by ±10%. Due to mistuning, the peak response reduces in certain frequency ranges, but at the same time, peak response increases in one other frequency ranges.

3.2 Response to Earthquake Time History Excitation

Ten different time histories are used to study the effect of TMD. The effect of yield level of TMD on the main system is shown in Table 1. Response time history for San Fernando earthquake is shown in Figure 11. The main system is of time period, T = 0.8 sec and the TMD has optimum parameters but its yield level is changed. It is seen that the yielding of TMD reduces the peak response of main system to a very limited extent only in certain cases. The extent of reduction also varies for different earthquakes. In some cases, the elastoplastic TMD even increases the peak response of main system.

Table 1: Effect of yield strength on the maximum displacement of main system.

Earthquake Time History	Loma Prieta	Altadena - Eaton Canyon Park	Corralitos - Eureka Canyon Rd.	El Centro	Hollister -South Street And Pine Drive	Kern County	Newhall - La County Fire Station	Northridge	Park field	San Fernando
PGA	0.28g	0.34g	0.63g	0.35g	0.37g	1.8g	0.59g	0.88g	0.24g	1.08g
u_1(Without TMD)	103.5	43.4	98.3	79.0	162.6	452.4	241.2	76.2	25.0	114.1
u_1(Linear TMD)	92.4	43.7	87.5	62.7	146.5	364.1	225.1	58.5	21.6	114.7
$u_1(\bar{f}_y=0.8)$	92.0	43.1	86.5	66.0	146.4	377.7	227.5	58.2	21.4	118.9
$u_1(\bar{f}_y=0.6)$	91.2	42.5	86.5	65.1	145.1	387.1	224.3	58.1	21.3	118.2
$u_1(\bar{f}_y=0.4)$	90.9	41.7	86.5	66.0	147.0	395.1	222.9	59.7	21.4	118.1
Note: u_1 is the peak displacement of main system in mm, μ =0.1, f = 0.9, η_d =0.35										

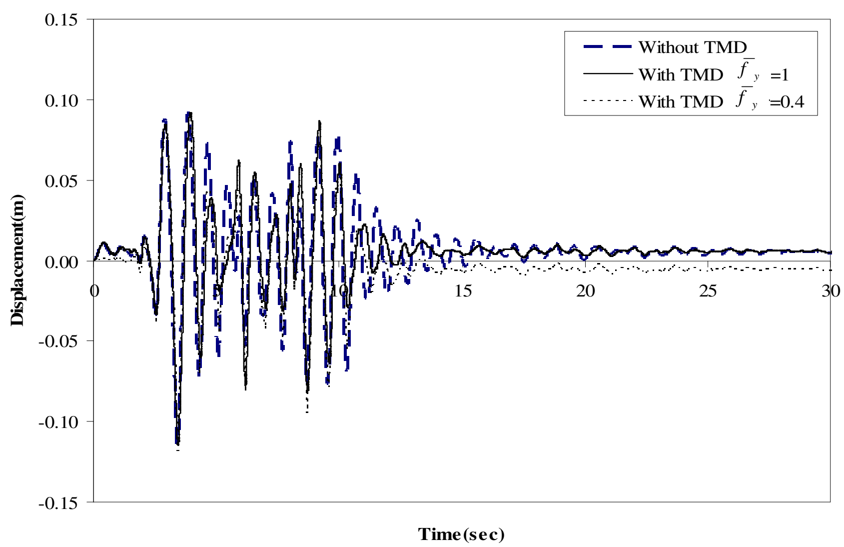


Figure 11: Response of a main system subjected to San Fernando earthquake, μ = 0.1, f = 0.9, η_d = 0.35

4. CONCLUSIONS

The use of elasto-plastic TMD is expected to impart more energy dissipation as compared to the corresponding elastic TMD. The present study indicates that the optimum parameters (viz., mass, damping, and stiffness) of elasto-plastic TMD could be entirely different than that for elastic TMD. In the present study, for elasto-plastic TMD, the parameters used are same as the optimum parameters of elastic TMD. It is seen that, such an elasto-plastic TMD becomes more efficient than elastic TMD, only in certain frequency range of input excitation. Moreover, such an elastoplastic TMD becomes less effective in the other frequency ranges. Similar observation is seen in the case of seismic analysis under recorded time histories. The limited study on optimum parameters of elasto-plastic TMD is taken by changing the damping and stiffness of elasto-plastic TMD, has revealed that these parameters indeed influence the effectiveness of elastoplastic TMD. The present study highlights the need for more rigorous study on identifying the optimum parameters of elastoplastic TMD for use in seismic application.

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