Engineering Structures 172 (2018) 712–722

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Seismic response control with inelastic tuned mass dampers

Saman Bagheri*, Vahid Rahmani-Dabbagh

Faculty of Civil Engineering, University of Tabriz, Tabriz, Iran

ARTICLE INFO

Keywords:
Tuned mass damper
Passive control
Inelastic behavior
Seismic response
Energy dissipation

ABSTRACT

An elasto-plastic spring is utilized in a tuned mass damper (TMD) with eliminating its viscous damper to establish a new seismic response control system. A novel method to find the most appropriate parameters of the proposed elasto-plastic TMD (P-TMD) including its initial stiffness/frequency and yield strength is presented so as to reduce the seismic response of the main system with the P-TMD to a level of that obtained with a previously suggested optimum TMD. The parameters are used to compute the responses of several main structures in the form of single-degree of freedom systems with the proposed P-TMD under different earthquake excitations. To evaluate the effectiveness of the proposed device and tuning method, maximum displacements and accelerations are compared to those of optimum TMD systems as well as those obtained from uncontrolled ones. The numerical results show that the proposed device, when using the introduced procedure for selecting its design parameters, reduces the seismic responses significantly and can be used instead of the optimum TMD without the need for a viscous damper.

1. Introduction

The tuned mass damper (TMD) is a typical passive control device attached to the main system with the goal of reducing vibrations of mechanical and structural systems under the action of external loads. This device consists of a mass, a spring and a viscous damper which all should be selected properly according to the properties of the main system and the applied loads. Because of its simple and reliable implementation, TMD has been widely used and studied. Effectiveness of TMDs depends on their properties, such as mass ratio, frequency and damping ratios, hence various studies have been carried out to obtain the optimal parameters of these devices.

Den Hartog [1] derived closed-form expressions for the optimum TMD parameters for undamped single-degree-of-freedom (SDOF) main systems under harmonic external forces. Simple expressions for optimum TMD parameters are also derived by Warburton [2] for undamped main systems subjected to external forces or support accelerations in the forms of harmonic and white noise random excitations. The effect of light damping in the main system on the optimum parameters of the TMD has also been investigated in [2] for random excitations and in [3,4] for harmonic force excitations. Tsai and Lin [5] developed a numerical searching procedure to find the optimum tuning frequency and damping ratio of the TMD for minimizing steady-state response of damped main systems subjected to harmonic support motions. In addition to harmonic excitations, the effectiveness of TMDs for wind loads has also been confirmed by several investigations [6–8]. Performance of single TMD systems, however, in structures subjected to earthquake loads, which possess many frequency components, is expected to be different and to depend on the ground motion properties [9–11]. While effectiveness of a TMD will be greatest when a real structure with a number of degrees of freedom oscillates around a predominant mode, this device does not reduce the structural response to a great extent when several modes contribute significantly to the main system response. Nevertheless, several successful studies have been devoted to improve the seismic performance of TMDs in different structural systems [12–16].

The well-known high modal damping criterion was used by some researchers such as Sadek et al. [12] and Miranda [13,14] to determine the optimum parameters of TMDs for the purpose of seismic response reduction. Some other criteria (or objective functions) have also been considered for this purpose [15–18].

Most of the studies on TMDs including those discussed above have employed the devices with elastic springs and linear behavior. However, the nonlinear behavior in TMDs has been considered for more effective control of unwanted vibrations in some investigations. The nonlinearity can be achieved with some simple implementation of practical engineering options such as combined action of several elastic and linear springs coming into action sequentially [19], equipping with friction-spring elements [20], using nonlinear viscous damping elements [21], and using Duffing spring for stiffness element of TMD [22,23]. Contrary to these sources of nonlinearity, here the nonlinear behavior of a TMD arising from inelastic behavior of its spring is of

* Corresponding author at: Faculty of Civil Engineering, University of Tabriz, P. O. Box: 51666-16471, Tabriz, Iran.
E-mail address: s_bagheri@tabrizu.ac.ir (S. Bagheri).

https://doi.org/10.1016/j.engstruct.2018.06.063
Received 22 November 2017; Received in revised form 8 May 2018; Accepted 17 June 2018

Nomenclature

a_{pb}	acceleration ratio of the P-TMD, $= \ddot{u}_{b0}/a_y$
a_y	yield acceleration of the P-TMD, $= F_y/m_d = \omega_p{}^2 u_y$
c	damping coefficient of the main system
c_d	damping coefficient of the TMD
f	frequency (tuning) ratio of the TMD, $= \omega_d/\omega$
f_p	frequency (tuning) ratio of the P-TMD, $= \omega_p/\omega$
F_y	yield strength of the P-TMD, $= k_p u_y$
k	stiffness of the main system
k_d	stiffness of the TMD
k_{eff}	secant stiffness of the P-TMD at u_0
k_p	initial stiffness of the P-TMD
m	mass of the main system
m_d	mass of the mass damper (TMD and/or P-TMD)
T	natural period of the main system, $= 2\pi/\omega$
u_0	resonant response amplitude of the mass damper (TMD and/or P-TMD)
u_y	yield deformation of the P-TMD
$\ddot{u}_{b0}$	acceleration amplitude in the base of the P-TMD
γ	mass ratio of the mass damper (TMD and/or P-TMD), $= m_d/m$
ζ	damping ratio of the main system, $= c/2m\omega$
ζ_d	damping ratio of the TMD, $= c_d/2m_d\omega_d$
ω	natural circular frequency of the main system, $= (k/m)^{0.5}$
ω_d	natural circular frequency of the TMD, $= (k_d/m_d)^{0.5}$
ω_p	natural circular frequency of the P-TMD vibrating within its linearly elastic range, $= (k_p/m_d)^{0.5}$

particular interest.

Jaiswal et al. [24] examined the effectiveness of an elasto-plastic TMD in controlling the seismic response of SDOF systems. For such a TMD, they used the same parameters that had already been suggested for the optimum elastic TMD with a limited parameter study on that TMD. It was seen that such an elasto-plastic TMD became more efficient than the elastic one only in certain frequency range of base excitations, while it became less effective in the other frequency ranges. However, they did not propose an approach to identify the optimum parameters of this TMD for seismic applications and highlighted the need for more rigorous studies on this issue. Moreover, to the best of our knowledge, any approach to determine optimum parameters of an elasto-plastic TMD has not previously been reported in the literature. Here, as a first attempt to establish a framework for utilizing the elasto-plastic behavior of the spring of TMDs, we try to present a novel method for estimating the most appropriate parameters of the elasto-plastic TMD (hereafter referred to as P-TMD) under seismic loads and to assess the effectiveness of the proposed technique. The proposed P-TMD consists of a mass and an elasto-plastic spring without the need to employ a supplementary viscous damper which is essential in the traditional/optimal TMDs.

It is important to note that the inelastic behavior of the TMD not only is proposed to be utilized in a new passive control device in the present study, but also can be activated in traditional TMDs undergoing large displacements during severe earthquake events. From this point of view, inelastic response analysis of TMDs is also of practical interest in structural and earthquake engineering.

2. Mathematical model of the tuned mass dampers

A SDOF system with a TMD as shown in Fig. 1(a) is modeled by two masses, springs and viscous dampers where m, k, and c are the mass, stiffness and damping coefficient of the main system. For this system, $\omega = (k/m)^{0.5}$ and $\zeta = c/2m\omega$ are the natural frequency and damping ratio of the main system, respectively. The parameters of the TMD are the mass, m_d, stiffness, k_d, and damping coefficient, c_d. The natural frequency and damping ratio of the TMD are $\omega_d = (k_d/m_d)^{0.5}$ and $\zeta_d = c_d/2m_d\omega_d$, respectively. A TMD is usually characterized in terms of mass ratio $\gamma = m_d/m$, frequency (tuning) ratio $f = \omega_d/\omega$, and damping ratio ζ_d.

The P-TMD suggested in this paper consists of only a mass and an elasto-plastic spring as shown in Fig. 1(b). The idealized elastic-perfectly plastic behavior of the spring is shown in Fig. 2. The spring has an initial stiffness of k_p, a yield deformation of u_y and a yield strength of $F_y = k_p u_y$.

The spring of the proposed P-TMD with an idealized elastic-perfectly plastic behavior is representative of a structural element having elasto-plastic behavior with a negligible hardening. A well-known class of such devices has already been used as metallic-yielding dampers in different structural systems. There are several simple and economical types of these devices with large deformation capacities and good low cycle fatigue performances such as U-shaped steel strips [25–27] and crawler steel damper [28] among others. The energy dissipating steel elements of such devices can be easily calibrated to obtain the desired initial elastic stiffness and the plastic threshold, as well as to undergo as large as desired displacements. Furthermore, the elastic-perfectly plastic behavior can be achieved with a combination of a conventional linear spring in series with a friction element. Such friction elements have wide structural applications such as those used as friction dampers in series with the bracing elements in building structures.

It should be noted that both above-mentioned ideas to achieve the elasto-plastic behavior have already been used in the base isolation systems. Of course, other practical suggestions can be made to achieve this behavior in the theoretical proposition of the P-TMD.

The natural frequency of the P-TMD vibrating within its linearly elastic range is $\omega_p = (k_p/m_d)^{0.5}$. Assuming $F_y = m_d a_y$, the yield acceleration of the proposed device becomes $a_y = \omega_p{}^2 u_y$ which can be interpreted as the acceleration of the mass m_d to produce the yield force similar to that defined in a general inelastic SDOF system [29]. Therefore, the proposed P-TMD can be characterized in terms of non-dimensional parameters of mass ratio $\gamma = m_d/m$, frequency (tuning)

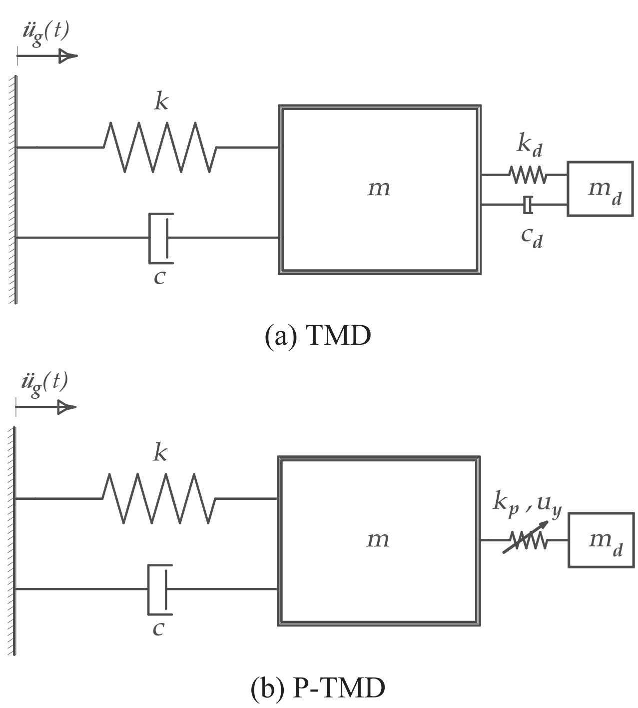

Fig. 1. Mass dampers attached to main systems.