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Research Paper / Makale

Optimization of Three-Element Tuned Mass Damper for Single Degree of Freedom Structures under Ground Acceleration

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Abstract: Passive control devices have been used for a long time to reduce unwanted vibrations. The most commonly used of these devices are tuned mass dampers. The optimum parameters of the three-element tuned mass damper for damped main structures due to ground acceleration are investigated in this paper. Unlike the traditional tuned mass damper, the three-element tuned mass damper contains two spring elements and one of them is connected in series with the damping element. The optimum parameters are obtained by simulated annealing algorithm. Numerical results show that the three-element tuned mass damper is very effective in reducing dynamic vibrations of the damped structures.

Keywords: dynamic response, ground acceleration, vibration control, tuned mass damper

Yer İvmesi Etkisi Altındaki Tek Serbestlik Dereceli Yapılar İçin Üç Elemanlı Ayarlı Kütle Sönümleyicinin Optimizasyonu

Öz: Pasif kontrol cihazları istenmeyen titreşimlerin azaltılması amacıyla uzun zamandır kullanılmaktadır. Bu cihazlardan en yaygın olarak kullanılanı ise ayarlı kütle sönümleyicilerdir. Bu çalışmada, yer ivmesi etkisindeki sönümlü ana yapılar için üç elemanlı ayarlı kütle sönümleyicilerin optimum parametreleri araştırılmıştır. Geleneksel ayarlı kütle sönümleyicinin aksine, üç elemanlı ayarlanmış kütle sönümleyicide iki rijitlik elemanı bulunur ve bunlardan biri sönüm elemanına seri olarak bağlıdır. Optimum parametreler benzetilmiş tavlama algoritması kullanılarak elde edilmiştir. Sayısal sonuçlar, üç elemanlı ayarlanmış kütle sönümleyici'nin sönümlü ana yapılardaki dinamik titreşimlerin azaltılmasında etkili olduğunu göstermektedir.

Anahtar Kelimeler: dinamik davranış, yer ivmesi, titreşim kontrolü, ayarlı kütle sönümleyici

1. Introduction

Passive tuned mass dampers (TMDs) are more effective in reducing the resonant vibrations. TMD consists of a stiffness element, a dashpot element and a mass which is a single degree of freedom system. TMDs are usually installed in high-rise building, footbridges, railway bridges, chimneys and towers under environmental excitations such as wind loads, earthquake loads and moving loads, and so on.

Den Hartog [1] obtained analytical solution for the TMD with dashpot element called the traditional TMD. This study was followed by other works that suppressing the resonant vibrations of the main structure due to various excitations [2-15]. These works indicate that a TMD device yields a higher level of control performance in suppressing the vibrations of the main structures. In the studies mentioned above, the main structure is modeled as a single degree of freedom (SDOF) system.

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Recently, a different type of TMD system has received increasing attention from many investigators. This is called as three-element TMD (T-TMD). In 1999, the exact solution for the optimization of the T-TMD with the undamped main system was first found by Asami and Nishihara [16]. Asami and Nishihara [17] studied on the optimization of T-TDM based on H_2 optimization criterion for undamped structures. Anh et al. [18] investigated the optimum paramters of T-TMD for damped linear structures. Nishihara [19] studied the exact optimization of T-TMD for minimization of the maximum amplitude magnification factor. Javidialesaadi and Wierschem [20] proposed a novel inerter-based T-TMD device.

So far, most of the previous studies on the T-TMD are concerned with an undamped main structure under harmonic excitations. To the best of the authors' knowledge, there is no work on the effectiveness of the T-TMD for damped main structures due to ground acceleration in the literature. Thus, there is a potential for further improvement of the T-TMD to be applied in the damped main structure due to ground acceleration. The main purpose of this study is to obtain the tuning parameters of the T-TMD for damped SDOF structure and compare its effectiveness with traditional TMD for various structural damping ratios.

2. Structural Model

Consider a damped main system with the T-TMD that is under ground acceleration in Fig. 1. Let m_s, c_s and k_s respectively indicate the mass, damping and stiffness of the main system. The following is the equation of motion for the structural system

$$\mathbf{M}\ddot{x}(t)+\mathbf{C}\dot{x}(t)+\mathbf{K}x(t)=-\mathbf{m}\ddot{x}_g(t) \tag{1}$$

where M, C and K are the mass, damping and stiffness matrices, respectively. m indicates the response vectors.

$$\mathbf{M}=\begin{bmatrix} m_s & 0 & 0 \\ 0 & m_1 & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{2}$$

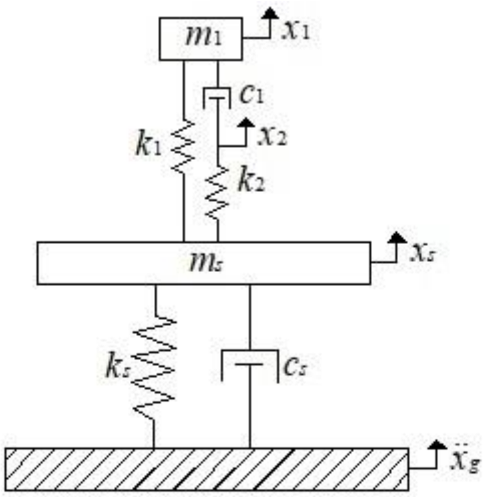

Figure 1. Structural model subjected to ground motion

$$\mathbf{C} = \begin{bmatrix} c_s & 0 & 0 \\ 0 & c_1 & -c_1 \\ 0 & -c_1 & c_1 \end{bmatrix} \tag{3}$$

$$\mathbf{K} = \begin{bmatrix} k_s + k_1 + k_2 & -k_1 & -k_2 \\ -k_1 & k_1 & 0 \\ -k_2 & 0 & k_2 \end{bmatrix} \tag{4}$$

$$\mathbf{m} = \begin{bmatrix} m_s & m_1 & 0 \end{bmatrix}^T \tag{5}$$

where m_1, k_1, k_2 and c_1 are the design parameters for the T-TMD. m, c and k are the mass, damping and the stiffness coefficient of the T-TMD, respectively.

The main structure is induced by the harmonic-base acceleration given by

$$\ddot{x}_g = \ddot{x}_o e^{i\omega t} \tag{6}$$

where $\ddot{x}_g$ is the base acceleration, $\ddot{x}_o$ is the amplitude and ω is the circular frequency.

By substituting Eq. (6) into Eq. (1), the steady-state response of the structure with the STMD can be formulated as

$$x(\omega) = \begin{bmatrix} x_s(\omega) \\ x_1(\omega) \\ x_2(\omega) \end{bmatrix} = (-\omega^2\mathbf{M} + i\omega\mathbf{C} + \mathbf{K})^{-1}\mathbf{m} \tag{7}$$

The displacement dynamic magnification factor (DMF) of the main system is finally given as

$$DMF = \frac{\omega_s^2 \left| x_s(\omega) \right|}{\ddot{x}_o} \tag{8}$$

where ω_s is the natural frequency of the main structure and x_s is amplitude of steady-state displacement of the main system.

The non-dimensional parameters for the T-TMD are given as follow

$$\xi_1 = \frac{c_1}{2m_1\omega_1}, \quad f_1 = \frac{\omega_1}{\omega_s}, \quad \kappa = \frac{k_2}{k_1}, \quad \mu = \frac{m_1}{m_s} \tag{9}$$

where f_1 and ξ_1 represent the tuning ratio and damping ratio of the T-TMD, respectively; μ is the ratio of the T-TMD mass to the mass of the main system; κ is the stiffness ratio. The natural frequency of the T-TMD system is defined as $\omega_1 = \sqrt{k_1 / m_1}$.

3. Determination of the Optimum Parameters

The optimization problem is solved using a MATLAB toolbox so-called *simulannealbnd* which uses the simulated annealing algorithm and the optimum parameters of the T-TMD are obtained for four different structural damping ratios. Considering practical applications, the mass ratio μ is taken between 0.01 and 0.1 in the analysis. As explained in previous sections, it is aimed to minimize the maximum values of DMF of the main system in determining the optimum parameters. Objective function is defined as in Eq. (8). The lower and upper bound vectors of the design variables are $0.6 < f_1 < 1$ and $0 < \kappa < 1.5$.

The optimum frequency ratios of the T-TMD for four different damping ratios is plotted in Fig. 2. Fig. 2 depicts the optimum frequency ratio decreases with increasing mass ratio and damping ratio of the main structure.

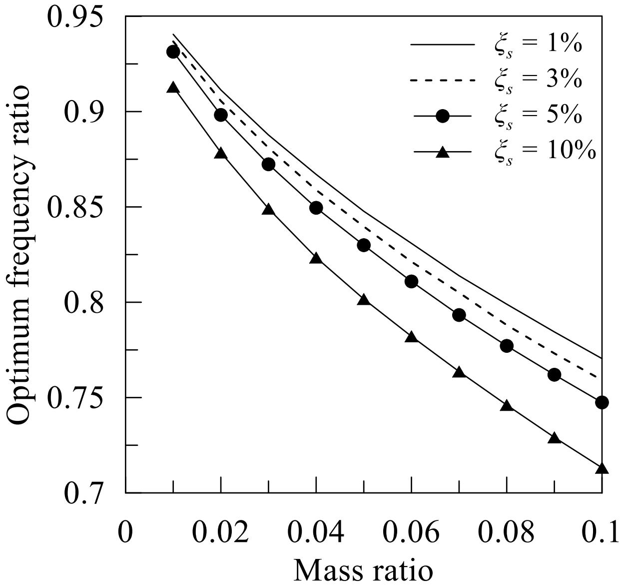

Figure 2. The optimum frequency ratio of the T-TMD under ground acceleration

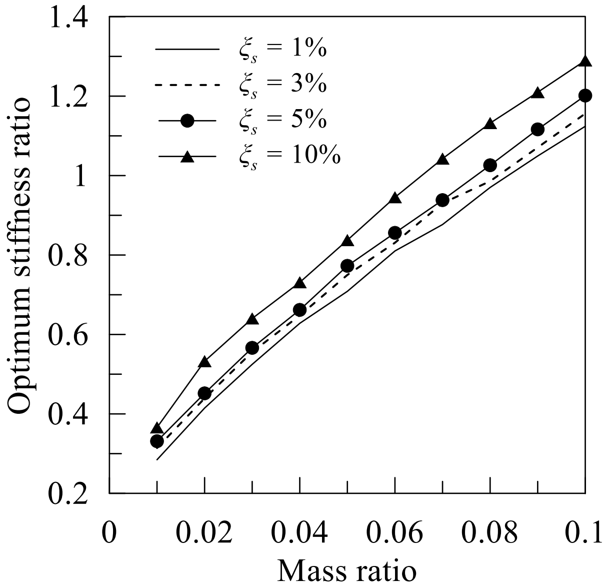

Figure 3. The optimum stiffness ratio of the T-TMD under ground acceleration

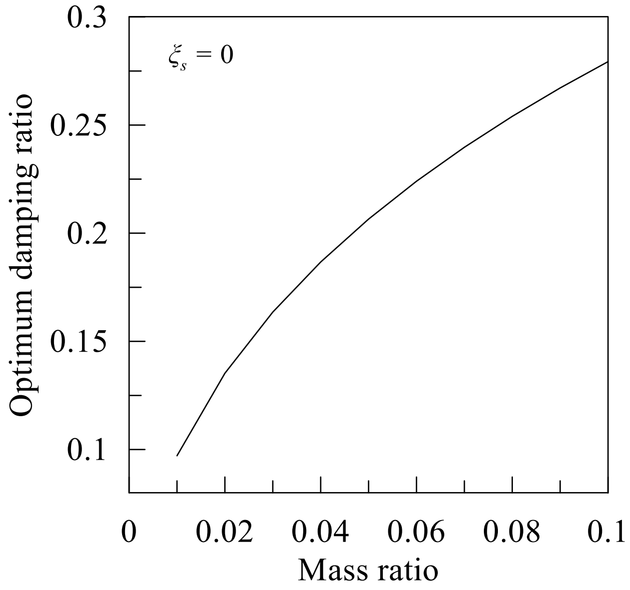

Figure 4. The damping ratio of the T-TMD for undamped main structure

Fig. 3 shows the variation of the stiffness ratio with different mass ratios. Fig. 3 indicates that the optimum stiffness ratio increases with increasing mass ratio and damping ratio of the main structure.

Previous studies have stated that the change in the damping ratio of TMD or T-TMD has a very low effect on the behavior of the main system [18]. Therefore, the damping ratios of T-TMD are obtained by using the expression proposed by Asami and Nishihara [16] for an undamped main structure. The damping ratio of T-TMD for an undamped main structure is plotted in Fig. 4. Fig. 4 shows that the damping ratio of the T-TMD increases as mass ratio increase.

4. Evaluation of the T-TMD Performance

Numerical results based on DMF has been presented to demonstrate the performance of the T-TMD on reducing the displacement response of the main structure. In addition, T-TMD's control performance is compared with traditional TMD. The optimum parameters for the both devices are given in Table 1.

Using the optimum values based on simulated annealing algorithm, the maximum DMF for the main structure installed with the T-TMD are calculated for four different damping ratios of the main structure and shown in Fig. 5. Fig. 5 depicts with increasing mass ratio, the maximum DMF values decrease considerably. It is also seen from Fig. 5 that the DMF values obtained for different damping ratios get closer to each other with the increase in the mass ratio.

Table 1. The optimization results for $\mu = 0.05$

	T-TMD			**TMD**	
ξ_s	f_1	ξ_1	κ	f_1	ξ_1
1%	0.8477	0.2065	0.7086	0.9355	0.1365
3%	0.8397	0.2065	0.7498	0.9249	0.1384
5%	0.8299	0.2065	0.7727	0.9137	0.1443
10%	0.8017	0.2065	0.8374	0.8808	0.1525

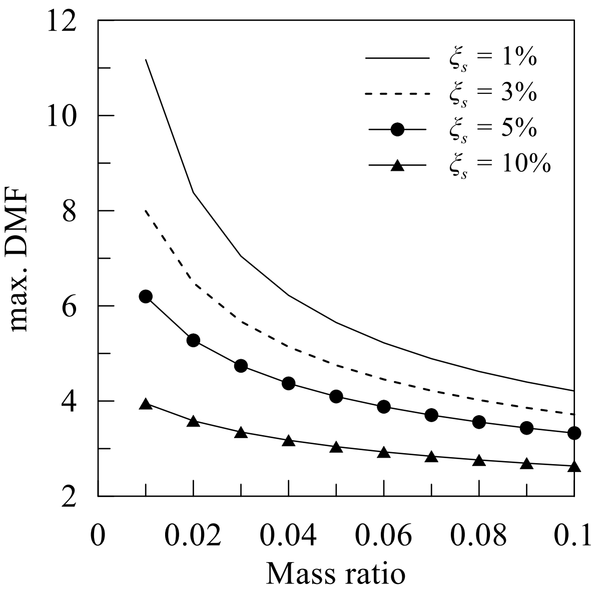

Figure 5. The maximum DMF versus the mass ratio

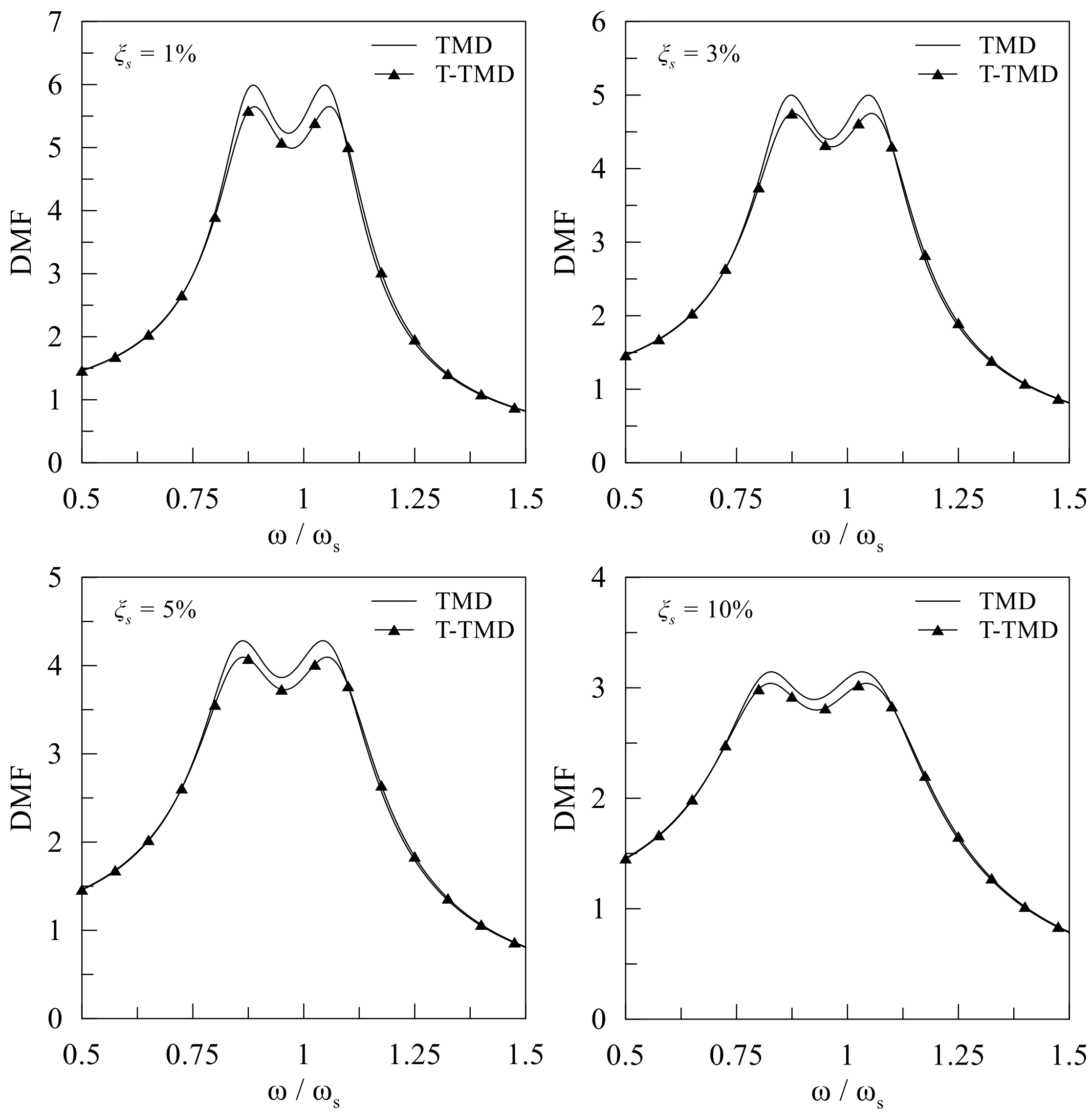

Figure 6. Comparison control performance with traditional TMD for μ = 0.05

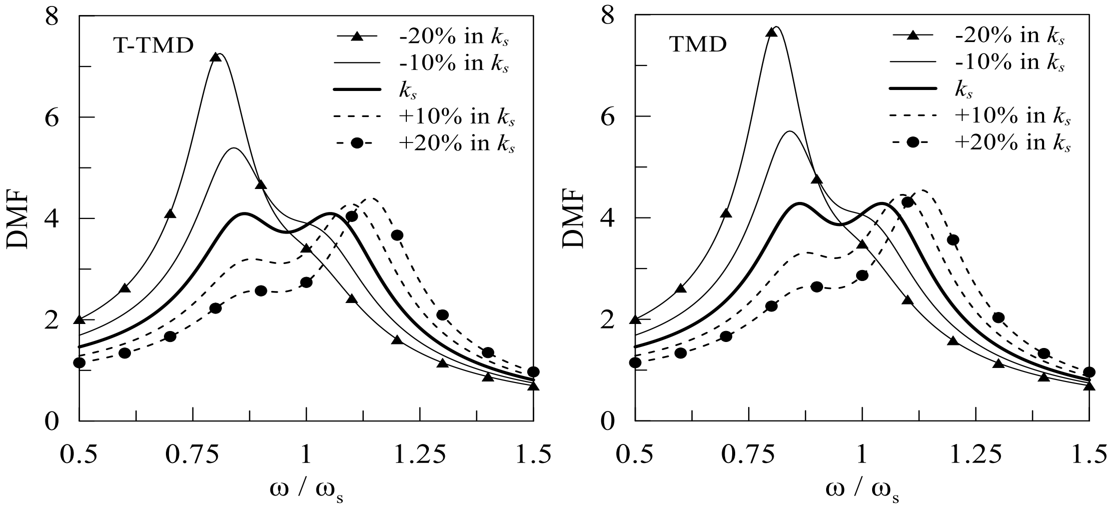

Figure 7. Variation of DMF curves of the structure with optimal TMD for various deviations, where $\mu = 0.05$ and $\xi_s = 5\%$

The displacement curves of the structure installed with the optimum T-TMD and TMD are plotted in Fig. 6. Fig. 6 indicates that the both devices have two peak points in the response curve Another observation from this figure is that the T-TMD provides better performance than the TMD in reducing the response values around the resonance.

The effectiveness of passive control devices is severely affected by the deviation in the natural frequencies of the structures that is called frequency detuning. Thus, the effect of the errors in the stiffness of the structure on the control effectiveness will be examined in the following section. As an example of such a detuning, the stiffness of the main structure is deviated by -10% from the designed value, resulting in a deviation of -5.132% in the natural frequency of the structure.

The displacement curves of the structure with various deviations in the stiffness of the structure are plotted in Fig. 7. Fig. 7 shows that the effectiveness of both devices has significantly deteriorated when the structural stiffness contains error. It is also seen in Fig. 7 that the DMF response increases if the stiffness of the main structure is either decreased or increased in comparison with the real value. Compared with the TMD, the T-TMD provides better performance than the TMD for all error values.

5. Conclusions

In this paper, simulated annealing algorithm is utilized for the optimal design of T-TMD parameters for the damped structures due to ground acceleration. As the design variables of the optimization problem, the effective parameters of T-TMD such as frequency tuning ratio, damping ratio and stiffness ratio are selected. Some of the main points of this paper are:

- The optimum tuning ratio f_1 of the T-TMD decreases with the increase of the mass ratio and damping ratio of the structure.
- The optimum stiffness ratio κ of the T-TMD increases with the increase of damping ratio of the structure and the mass ratio.
- The T-TMD provides better performance than the TMD when the estimation errors in the main system's design parameters occur.
- Considering the displacement DMF responses of the main system due to ground acceleration, it is seen that the T-TMD performs better than the TMD in reducing the dynamic response.

Authors' Contributions

All contributions belong to the author in this paper.

Competing Interests

The author declares that they have no competing interests.

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