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Parameter optimization of tetrahedral tuned mass damper for three-directional seismic response reduction

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ABSTRACT

An optimization approach is presented for design of a tetrahedral tuned mass damper called TD-TMD for three-directional seismic response reduction of structures. The mass damper consists of a viscous damper and a mass connected by springs and a rigid bar. By utilizing flexibility of the springs, movement of the mass in three-directions and elongation of the viscous damper are amplified, and vibration energy of the structure is effectively dissipated by the viscous damper. The objective function of the parameter optimization problem is the mean norm of the response displacements of the structure. The bounds of parameters are determined by solving an auxiliary nonlinear programming problem to maximize the minimum deformation of the damper against unit static loads in various directions. Approximate optimal solutions are found using a heuristic approach called simulated annealing combined with pure random search that generates efficient initial solutions. The TD-TMD is attached to a simple three-degree-of-freedom structure, and the seismic responses are compared with those with conventional single-directional tuned mass dampers.

1. Introduction

Among various devices for passive control of vibration, tuned mass damper (TMD) is effectively used for reduction of vibration due to seismic and/or wind excitations. However, a conventional TMD can reduce the responses in a single direction dominated by a single mode of vibration. Therefore, several TMDs are needed for reduction of multi-directional and multi-modal vibrations [1,2]. Viet and Nghi [3] proposed a two-mode control device utilizing geometrically nonlinear effect of a spring and a pendulum. Ueng et al. [4] proposed a design method of multiple TMDs for buildings under torsional vibration. Yoshinaka and Kawaguchi [5] investigated performances of multiple TMDs for vibration control of long span structures. The authors presented a mass damper that can reduce two-directional vibration of an arch using single mass and a viscous damper [6,7]. Almazán et al. [8] proposed a bi-directional TMD supporting a mass by vertical cables and bars.

Design of TMDs is strongly related to optimization, because the parameters of TMDs should be appropriately tuned so that the vibration of the mass is amplified by the vibration of the structure. De Angelis et al. [9] optimized the parameters of a large-mass-ratio TMD that is connected to the structure using a high-damping rubber bearing. Lavan and Daniel [10] optimized the locations and parameters of multiple TMDs for a building frame with irregular plan. Lin et al. [11] assigned an upper bound for the stroke for tuning the parameters. Garrido et al. [12] used a computational approach to optimize the TMD with rotational degree of freedom. Heuristic approaches such as harmony search [13] and particle swarm optimization [14] are also used for optimizing TMDs.

In this paper, a mass damper called three-directional TMD (TD-TMD) is proposed for reduction of three-directional vibration of a structure subjected to multi-component ground motions. The mass damper has a tetrahedral shape consisting of a viscous damper and a mass connected by springs and a rigid bar. By utilizing the flexibility of springs, the movement of the mass in three-directions and the elongation of viscous damper are amplified, and the vibration energy of the structure is effectively dissipated by the viscous damper. The variables consisting of stiffnesses of the springs, damping coefficient of the viscous damper, and locations of the nodes are discretized into integer values, and their optimal values are found using a global pure random search (PRS) [15,16] combined with a heuristic method of local search called simulated annealing (SA) [17,18]. Effectiveness of optimizing TD-TMD is demonstrated by comparing the response reduction properties of

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a simple three-degree-of-freedom (3DOF) structure with those of the conventional TMDs with the same total mass.

2. Description of TMD models and seismic motions

2.1. TD-TMD model

Fig. 1 illustrates the proposed TD-TMD, which can reduce the three-directional vibration using a single set of mass and viscous damper. The TD-TMD has a tetrahedral shape, and a mass M is located at node D, which is connected to nodes A and C by the springs with the extensional stiffness K_2, and K_3, respectively. Node A is attached to the structure, and node C has the same three-directional displacements as node A. Node B has the same X- and Y-directional displacements as node A, and is free in Z-direction so that the viscous damper with the damping ratio C_1 can deform in accordance with vibration of the mass at node D. Furthermore, nodes B and D are connected by a rigid bar.

Springs with small extensional stiffness K_1 is added between nodes A and B, and a small mass is attached at node B to stabilize the device. We assume that the tetrahedral device is contained in a box so that it can be attached to the structure easily. The three-directional vibration of node D leads to deformation of the viscous damper between nodes A and B, which dissipates seismic energy. By tuning the parameters of the TD-TMD, three-directional vibration of the structure can be reduced by a pair of mass and viscous damper.

2.2. SD-TMD model

We compare the vibration reduction property of the TD-TMD with that of the single-directional TMD (SD-TMD), which consists of a mass connected by a spring and a viscous damper. Three SD-TMDs called dampers 1, 2, and 3 are installed, as shown in Fig. 2, for vibration reduction in X-, Y-, and Z-directions, respectively. Node A is to be attached at the structure. The mass, extensional stiffness of spring, and damping coefficient of damper i (= 1, 2, 3) are denoted by m_i, k_i, and c_i, respectively. When comparing the performances of TD-TMD and SD-TMDs, the total value of m_1, m_2, and m_3 is the same as the mass of TD-TMD; i.e., $m_1 + m_2 + m_3 = M$.

The parameters of dampers 1, 2, and 3 are adjusted to reduce the responses in each direction. Let M_i denote the equivalent mass of the dominant mode $\boldsymbol{\Phi}_i$ of a structure, for which the vibration is to be reduced by damper i in X-, Y-, or Z-direction. The mass ratio is given as $\mu_i = m_i/M_i$ $(i = 1, 2, 3)$. The frequency ratios γ_i and damping factors ξ_i $(i = 1, 2, 3)$ of dampers 1, 2, and 3 are determined using the following optimal values of SD-TMD against various dynamic loading conditions [19]:

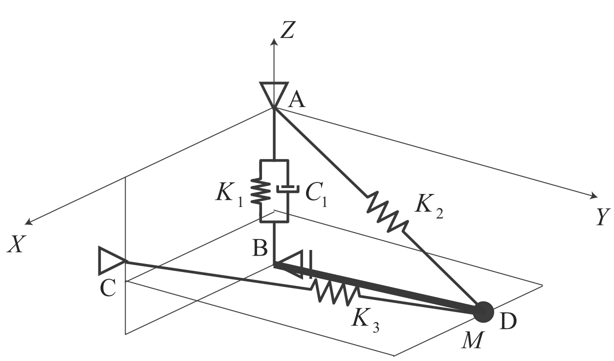

Fig. 1. Components of TD-TMD; a mass at node D, vertical viscous damper between nodes A and B, three springs, and a rigid bar.

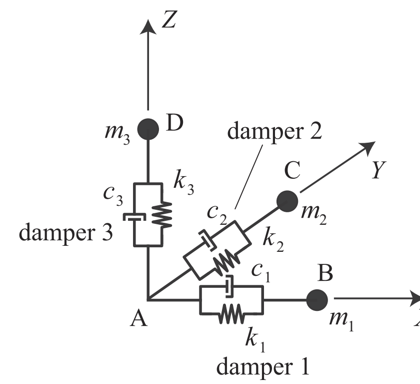

Fig. 2. A set of three SD-TMDs for vibration control in three-directions.

- Case 1: Sinusoidal motion

$$\gamma_i = \frac{1}{1+\mu_i}, \quad \xi_i = \sqrt{\frac{3\mu_i}{8(1+\mu_i)}} \tag{1}$$

- Case 2: Sinusoidal ground motion

$$\gamma_i = \frac{1}{\sqrt{1+\mu_i}}, \quad \xi_i = \sqrt{\frac{3\mu_i}{8(1+\mu_i/2)}} \tag{2}$$

- Case 3: Random ground motion

$$\gamma_i = \frac{\sqrt{1+\mu_i/2}}{1+\mu_i}, \quad \xi_i = \frac{1}{2}\sqrt{\frac{\mu_i(1+3\mu_i/4)}{1+3\mu_i/2}} \tag{3}$$

Let ω_i denote the natural circular frequency of mode $\boldsymbol{\Phi}_i$ of the structure. The optimal stiffness $\widetilde{K}_i$ of the SD-TMD for controlling mode $\boldsymbol{\Phi}_i$ is computed from

$$\widetilde{K}_i = m_i(\gamma_i\omega_i)^2 \tag{4}$$

2.3. Seismic motion

Dynamic responses of the structure with TMDs are evaluated by time-history analysis using a software package called OpenSees Ver. 2.4 [20]. The design acceleration response spectrum is specified according to the Notification 1461 of Ministry of Land, Infrastructure, Transport, and Tourism (MLIT), Japan, corresponding to the performance level of operational limit for the "design based on calculation of response and limit state," which is similar to the capacity spectrum approach. The acceleration response spectrum $S_A(T,h)$ is given with respect to the natural period T and the damping factor h as

$$S_A(T,h) = \frac{1.5}{1+10h}\begin{cases} 0.96 + 9.0T \text{ for } T \leqslant 0.16 \\ 2.4 \text{ for } 0.16 \leqslant T \leqslant 0.864 \\ 2.074/T \text{ for } 0.864 \leqslant T \end{cases} \tag{5}$$

Five sets of ground motions are generated as combinations of ground motions compatible to the acceleration response spectrum in Eq. (5). The ground motions in each direction are generated using a standard approach of superposition of sinusoidal waves with random phase [21,22]. The duration of ground motion is 60 s; however, only the response for the first 40 s is computed. The time step for integration is 0.01 s.

An example of time-history of acceleration and its acceleration response spectrum for $h = 0.05$ are shown in Figs. 3 and 4, respectively. Different motions among the five are selected for X-, Y-, and Z-directions; therefore, the total number of sets is 60. The