PARAMETER OPTIMIZATION OF GEOMETRICALLY NONLINEAR TUNED MASS DAMPER FOR MULTI-DIRECTIONAL SEISMIC VIBRATION CONTROL

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ABSTRACT

A new type of mass damper is proposed for three-directional seismic response control of building structures, as well as long-span structures, subjected to multi-component ground motions. The mass damper consists of a viscous damper and a mass connected by springs. By utilizing the flexibility of springs and geometrical nonlinearity, the movement of mass in multi-directions and the elongation of viscous damper are amplified, and the vibration of the structure is effectively reduced. Parameters of the proposed mass damper, called MD-TMD, is optimized using a heuristic approach. Effectiveness of MD-TMD is demonstrated by comparing the response reduction properties with those of conventional tuned mass damper.

Keywords: TMD, Optimization, Multi-component motion, Long-span roof.

1. INTRODUCTION

TMD (Tuned Mass Damper) is effectively used for reduction of vibration due to seismic and/or wind excitations. However, a conventional TMD can reduce the responses in single direction. Therefore, several TMDs are needed for reduction of multi-directional and multi-frequency vibrations (Lin *et al*. 2010). The authors presented a mass damper that can reduce two-directional vibration of an arch using single mass and a viscous damper (Tsuda and Ohsaki 2012a, 2012b).

In this study, a mass damper, called MD-TMD (Multi-Directional TMD) is presented for reduction of three-directional vibration of a long-span structure subjected to multi-component ground motions. The mass damper consists of a viscous damper and a mass connected by flexible springs. By utilizing the flexibility of springs and geometrical nonlinearity, the movement of the mass in multi-directions and the elongation of viscous damper are amplified, and the vibration energy of the mass is effectively absorbed by the viscous damper.

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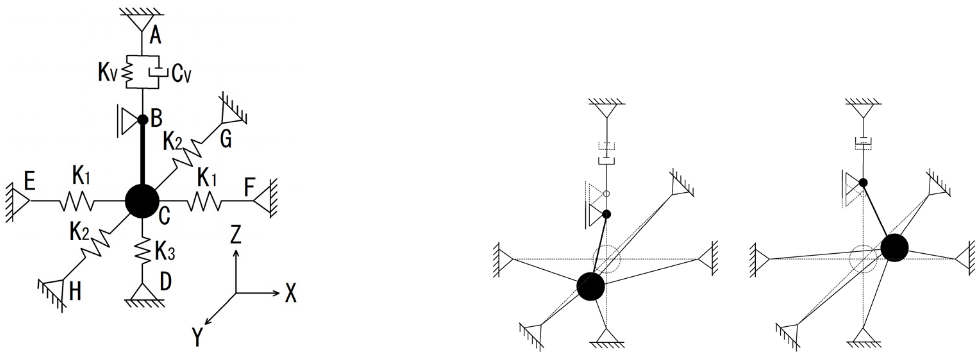
The effectiveness of the MD-TMD is demonstrated using a latticed roof model. The parameters consisting of stiffnesses of the springs, the damping coefficient of the viscous damper and the location of the mass are discretized into integer values, and their optimal values are found using a global random search and a heuristic approach called tabu search. Effectiveness of the MD-TMD is demonstrated by comparing the response reduction properties with those of the conventional TMD with the same total mass.

2. DESCPRITION OF MODEL AND OPTIMIZATION METHOD

2.1. TMD model

Fig. 1(a) illustrates the proposed MD-TMD, which can reduce the three-directional vibration using single mass and damper. It consists of a mass, a damper, a rigid bar, and six springs. The horizontal vibration of the mass at node C leads to the axial deformation of damper due to geometrical nonlinearity, as shown in Fig. 1(b). The Z-coordinates of nodes C, E, F, G, and H have the same value, and four springs have the same length.



(a) (b)

Figure 1: MD-TMD model; (a) components of MD-TMD, (b) deformation of damper due to horizontal displacements of mass

We assume that the MD-TMD in Fig. 1(a) is installed in a box so that the displacements of nodes A, D, E, F, G, and H have the same values. Node A is connected to the main structure, and nodes A and B have the same horizontal displacement.

2.2. Seismic motion

The dynamic responses of the structure with MD-TMD are evaluated by time-history analysis using a software package called OpenSees Ver. 2.4 (PEERC 2006). Five ground motions compatible to the acceleration response sprctrum in Table 1 are used. The duration is 20 s, and the time step for integration is 0.01 s.

Different motions among the five are selected for X-, Y-, and Z-directions; therefore the total number of sets is 60. The seismic motion is scaled by 5 in X- and Y-directions, and by 2.5 in Z-direction.

Table 1: Target acceleration response spectrum (damping factor = 0.05)

Period (s)	$T \le 0.16$	$0.16 \le T \le 0.864$	$0.864 \le T$
Acceleration (m/s^2)	$0.96 + 9T$	2.40	$2.074/T$

2.3. Parameter optimization method

Let k_1, k_2, and k_3 denote the ratios of the springs K_1, K_2, and K_3 to their standard values, which are defined in the next section. The ratio of the length of bar BC to its standard value (1 m) and the ratio of the damping coefficient to its standard value are denoted by L_C and c, respectively. These five parameters are chosen as variables to be optimized, while K_V is given as $K_V = K_3/3$.

The five sets of seismic motions among 60 sets are used for optimization. Let x_{ji}, y_{ji}, and z_{ji} denote the X-, Y-, and Z-directional displacements of node j of the roof at the ith step of analysis. The total number of analysis steps and nodes are denoted by N_1 and N_2, respectively. The mean value D_{XYZ} of square of nodal displacements is defined by

$$D_{XYZ} = \frac{1}{N_1 N_2} \sum_{j=1}^{N_2} \sum_{i=1}^{N_1} \{(x_{ji})^2 + (y_{ji})^2 + (z_{ji})^2\} \tag{1}$$

The reduction ratio R_{XYZ} is defined by the ratio of D_{XYZ} with MD-TMD to that without TMD, and the mean value of R_{XYZ} among five sets of motions is minimized to find the optimal parameter values.

3. OPTIMIZATION RESULT

The MD-TMD is attached at the center node A of the latticed shell as shown in Fig. 2. The spans in X- and Y-directions are 26.946 m and 20 m, respectively. The height of column is 4 m, and the roof nodes are located on a circular cylinder with open angle 15 deg. The material is steel, and all beams and columns are connected rigidly at joints, while the braces are modeled as truss members. The columns are pin-supported around Y-axis. All of 15 roof nodes have the mass of 500 kg. Although the details of member sections are omitted, the vibration properties of the structure are listed in Table 2.

The mass of MD-TMD is 1/20 of the total mass of the roof. In this case, the theoretical optimal values of stiffness (kN/m) under sinusoidal motion in X-, Y-, and Z-directions are 35.04, 119.6, and 58.53, respectively (Hartog 1985). The optimal damping coefficient in Z-direction is 5.028 kNs/m. These values are taken as the standard values for normalization of variables. The lower and upper bounds of normalized variables are assigned as shown in Table 3. Note that the 10% of the total mass of MD-TMD is placed at node B to stabilize analysis; i.e., node C has the 90% of the total mass of MD-TMD.

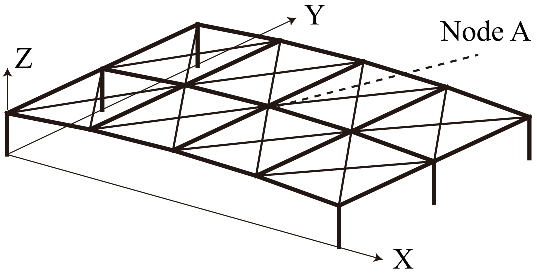


Figure 2: Latticed shell model

The mean value of R_{XYZ} for five sets of motions is chosen as the objective function to be minimized. The five variables are discretized into 21 equally spaced values in their specified ranges, and 2000 sets of variables are randomly generated to obtain the eight best objective values as listed in Table 4, where R_X, R_Y, and R_Z are the square of the response reduction ratios in each direction.

Table 2: Vibration properties of latticed shell

Order	Period	Effective mass ratio			Mode component of node A in dominant direction
		X	Y	Z	
1	0.4116	0.8596	0	0	0.01080
2	0.3136	0	0	0.6633	0.02047
5	0.2080	0	0.5733	0	0.01788

Table3: Ranges of variables and their optimal values

Variable	k_1	k_2	k_3	c	L_C
Lower bound	0.3	0.3	0.5	0.2	0.2
Upper bound	0.6	0.6	1.5	1.0	1.0
Optimal value	0.4650	0.4350	0.5000	0.4400	0.2000

Table4: Eight best solutions obtained by random search

Order	R_X	R_Y	R_Z	R_{XYZ}
1	0.3513	1.0563	0.4209	0.3846
2	0.3681	0.8758	0.4133	0.3908
3	0.359	0.9391	0.4435	0.3908
4	0.373	0.7377	0.4319	0.3936
5	0.3579	0.8675	0.4809	0.3943
6	0.3697	0.7289	0.4583	0.3944
7	0.3604	0.6671	0.5177	0.3945
8	0.3632	0.804	0.4693	0.3947

Although the best solution has the smallest value of R_{XYZ}, its reduction ratio in Y-direction is not small enough. Therefore, we select the 7th solution as the initial solution for TS (Tabu Search), which is an extension of local search (Glover 1989). The optimal solution obtained by TS with 5 neighborhood solutions and 100 steps is listed in Table 4. Note that the stiffnesses of springs in three directions are about a half of the theoretical optimal value; however, interaction of displacements in three directions leads to contribution of stiffness of each spring to vibration in different direction.

Table5: Response reduction ratios for 60 sets of motions

		Mean	Maximum	Minimum	Standard deviation
MD-TMD	X	0.3517	0.5104	0.2884	0.0807
	Y	0.7038	1.1132	0.5038	0.2011
	Z	0.4470	0.6713	0.3480	0.0794
	XYZ	0.3777	0.5450	0.3121	0.0781
SD-TMD	X	0.5267	0.6568	0.4061	0.1020
	Y	0.4556	0.5645	0.3232	0.0867
	Z	0.5302	0.7184	0.4097	0.0868
	XYZ	0.5236	0.6606	0.4067	0.0942

4. PERFORMANCE OF MD-TMD

For verification of effectiveness of the proposed MD-TMD, the responses against 60 sets of motions are compared with those of conventional TMD called SD-TMD. Note that SD-TMD has three sets of spring, damper, and mass in three directions, respectively, and the mass of each TMD is 1/3 of the total mass of MD-TMD. The theoretical optimal values are used for spring stiffness and damping coefficient in each direction.

As seen from Table 5, the MD-TMD has better performance than three SD-TMDs. The mean values of response displacements of node A of the model without TMD are 0.06662, 0.02331, and 0.02976 (m), respectively, in X-, Y-, and Z-directions, which shows that the reduction in Y-direction is less significant than X-direction, because the structure vibrates mainly in X-direction and the norm of displacement is considered as the objective function.

5. CONCLUSIONS

A mass damper called MD-TMD has been proposed for reduction of seismic responses in three directions using a set of single mass and damper. The horizontal vibration of a mass leads to axial deformation of the vertical damper due to geometrical nonlinearity.

It has been demonstrated that the parameters can be effectively optimized using a random search combined with a heuristic algorithm called TS. The performance of the proposed MD-TMD has been confirmed in comparison to the three conventional TMDs assigned in each direction.

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