Bi-directional seismic vibration control of spatial structures using passive mass damper consisting of compliant mechanism

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Summary

A new type of mass damper is presented for passive seismic response control of spatial structures subjected to bi-directional ground motions. The mass damper consists of a three-degree-of-freedom compliant mechanism with a mass, three springs and a viscous damper. The parameters of the mass damper are optimized by carrying out a series of dynamic response analyses.

Keywords: *Mass damper*; *Compliant mechanism*; *Vibration control*; *Spatial structure*; *Tabu search*

1. Introduction

Passive tuned mass damper (TMD) can be effectively used for seismic vibration control of spatial structures such as arch frames and dome structures[1]. Since these structures without flexible support structures may vibrate strongly in the normal direction of the curved roof under horizontal ground motions, the conventional mass damper system called SD-TMD (Single-Directional-TMD) has only single-degree-of-freedom and the displacement of the mass is constrained to the normal direction or vertical direction.

However, when a curved spatial structure with flexible support is subjected to bi-directional ground motions, its roof structure may vibrate in both horizontal and vertical directions. For this reason, a mass damper that can control vibration in multiple directions is considered to be useful for spatial structures subjected to bi-directional ground motions.

In this study, we present a new type of mass damper called BD-TMD (Bi-Directional-TMD) for passive seismic response control of spatial structures[2]. The proposed mass damper consists of a mass, three springs and a viscous damper, as shown in Figure 1, which are assembled to a three-degree-of-freedom compliant mechanism, i.e. mechanism utilising the stiffness of members that are modeled as springs. By utilizing the flexibility of springs, the movement of the mass is amplified in two directions and the vibration energy of the mass is absorbed by the viscous damper, as shown in Figure 2.

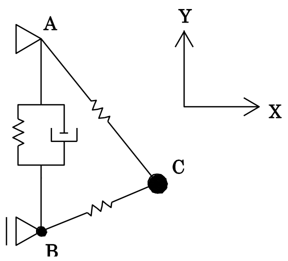

Figure 1: A 3DOF mass damper

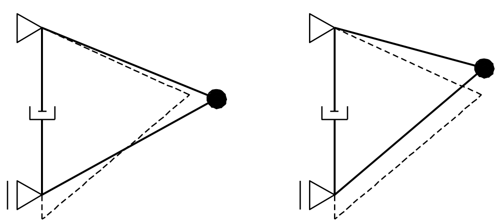

Figure 2: Motions of mass

The effectiveness of the proposed mass damper is demonstrated using a simplified one-mass model and an arch-frame model. The shape and the stiffness of the springs are optimized by carrying out a series of dynamic response analyses. The approximate optimal values of parameters of the mass damper are first searched globally using a random selection of the discretized parameter values. The parameters are further optimized using a heuristic approach called tabu search. The effectiveness of the mass damper with the optimized parameters is evaluated through further dynamic analyses with many other ground motions.

2. Method of numerical analysis

2.1 Method of Response Analysis

In order to study the performance of passive vibration control devices, a series of time-history response analyses is carried out using the Newmark-β method (β=0.25). Geometrical nonlinearity is considered because BD-TMD exhibits a large asymmetric deformation. An open-source finite element analysis software called "OpenSees" is used for response analysis.

Ten artificial seismic waves of different phases are generated using the standard approach of assemblage of sinusoidal waves. Table 1 shows the target acceleration response spectrum. Two different waves are chosen from 10 waves as the input ground motions; one is scaled by 5.0 for horizontal ground motion and the other is scaled by 2.5 for vertical ground motion. The plus and minus signs of the scaling factors are distinguished in order to consider the geometrical nonlinearity of the model. Therefore, the number of total wave sets is 360.

Table 1: Target Response Spectrum

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

2.2 Parameter optimization of BD-TMD

Figure 3 shows the BD-TMD model, which consists of a mass, three springs and a viscous damper. K_1, K_2, K_3 are the spring constants (N/m), C_V is the viscosity coefficient (N・s/m), X_C, Y_C are the coordinates of node C. In this study, K_3, $C_{V,}$ and coordinates of node A and node B are specified, and parameter set (K_1, $K_{2,}$ X_C, Y_C) is optimized. Since the parameter optimization problem described below is highly nonlinear and response analysis requires large computational cost, we cannot use a gradient-based approach or a population-based approach [3]. Therefore, a heuristic approach called tabu search (TS) [4] is used, as follows, in conjunction with the random selection (RS) [5] approach:

(i) Random Selection(RS): Compute the objective functions of randomly determined parameter sets.
(ii) Tabu Search(TS):Search the optimal solution in the neighborhood of the good initial solution obtained by RS.

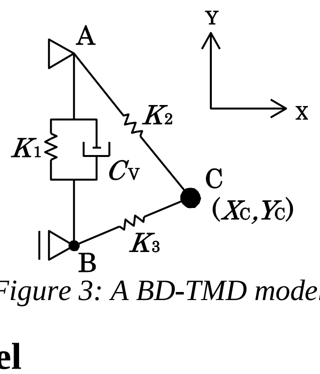

Figure 3: A BD-TMD model

3. Example-1: one-mass model

3.1 A one-mass model with BD-TMD

Figure 4 shows the primary structure that has a single mass (S) and two degrees of freedom (X- and Y-directions). The lumped mass at node S and the spring constants K_X and K_Y are 1,000kg, 128,000 N/m, and 64,000 N/m, respectively. Natural frequencies of the structure are 1.80 Hz and

1.27 Hz corresponding to X- and Y-directional vibrations, respectively. The damping factors are 2% for both frequencies.

The BD-TMD in Figure 3 is attached to the primary structure; node A of BD-TMD is attached to mass S and the displacement of node B in X-direction is constrained to be equal to that of node A. Masses at nodes C and B are 45 kg and 5 kg, respectively. Therefore, the total mass of BD-TMD is 50 kg, which is 5% of the mass of the primary structure. The coordinates of nodes A and node B are (0.0, 0.0) and (0.0, -1.0 m), respectively. The spring constant K_3 and viscosity C_V are fixed at 15,000 N/m and 160 N･s/m, respectively.

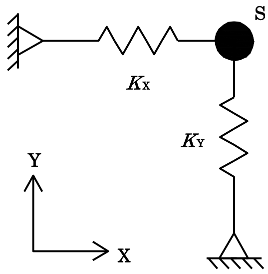

Figure 4: Primary structure

3.2 Parameter optimization of BD-TMD

Parameters of BD-TMD are optimized using 10 seismic motions described in section 2.1. The magnitude of vibration is defined by the mean square value of the structural response displacement D_{XY} as

$$D_{XY} = \sum_{i=1}^{N} \left\{ x(i \cdot \Delta t)^2 + y(i \cdot \Delta t)^2 \right\} / N \tag{1}$$

where $x(t)$ and $y(t)$ are the displacements of mass S as functions of time t in X- and Y-directions, respectively, and Δt is the time increment, N is the number of analysis steps.

D_{XY} is calculated for each seismic motion for two cases with TMD and without TMD. Then, the vibration reduction ratio R_{XY} is defined as the ratio of D_{XY} with TMD to D_{XY} without TMD. The objective function F to be minimized is the mean value of R_{XY} among 10 seismic motions. Table 2 shows the range of parameters in the optimization process, which are sampled to 50 values with constant ratio for spring constants K_1, K_2 and with constant difference for coordinates X_C, Y_C.

First, the objective functions F of 1,000 parameter sets determined randomly are calculated. Then, tabu search is carried out from good initial solutions obtained by random selection. In tabu search, the number of neighborhood solutions is 30, and the number of step is 30. Table 3 shows the optimal value of objective function and parameters.

Table 4 shows the natural frequencies of BD-TMD corresponding to the optimal parameters and their ratios to those of the primary structure.

Table 2: Range of parameters

Parameter	K_1	K_2	X_C	Y_C
Lower Limit	1,000	2,000	0.50	–1.00
Upper Limit	5,000	10,000	1.50	0.00

Table 3: Optimal parameters

F	K_1	K_2	X_C	Y_C
0.376	2,030	4,618	0.72	–0.36

Table 4: Natural frequencies and their ratios to primary structure

direction	BD-TMD	Primary structure	Ratio
X	1.71 Hz	1.80 Hz	0.95
Y	1.13 Hz	1.27 Hz	0.89

3.3 A one-mass model with SD-TMDs

In order to investigate the performance of vibration control of the optimized BD-TMD, we evaluate the responses of a model with SD-TMDs as shown in Figure 5. To control vibrations in two directions, two independent SD-TMDs are attached. Each mass of SD-TMD is 25 kg, i.e., the total mass 50 kg is equal to that of BD-TMD. The spring constant and viscosity coefficient are determined from the optimal tuning ratio γ_{opt} and the optimal damping ratio ξ_{opt} for harmonic vibration as follows [6]:

$$\gamma_{\mathrm{OPT}} = \frac{1}{1+\mu} \quad , \qquad \xi_{\mathrm{OPT}} = \sqrt{\frac{3\mu}{8(1+\mu)}} \tag{2}$$

where μ is the mass ratio of SD-TMD to that of the primary structure.

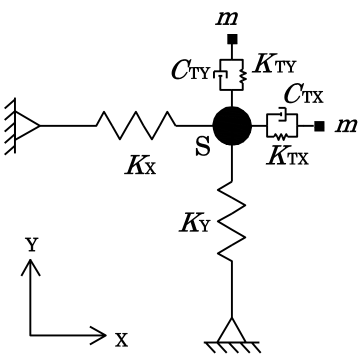

Figure 5: A one-mass model with SD-TMDs

3.4 Evaluation of performance

The performances of vibration control are evaluated for the two models with BD-TMD and SD-TMDs by calculating R_{XY} of 360 sets of seismic motions described in section 2.1. Table 5 shows the statistics of R_{XY}, where SD denotes the standard deviation. It is confirmed from Table 5 that BD-TMD can reduce vibrations more effectively than SD-TMD. The reason of the difference may be that the mass of SD-TMD is divided into two portions and one is not effective for another direction; on the other hand, the mass of BD-TMD is effective in two directions.

It should be noted here that BD-TMD has a correlation of vibrations in two directions; therefore, if the vibrations of X- and Y-directions are correlated and one of the movements of mass in two directions enforce the deformation of damper in the opposite direction, the performance could be deteriorated. However, if the frequencies of two directions are separated, this negative effect will not continue for a long period, and the influence of the correlation is considered to be limited.

Table 5: Statistics of R_{XY}

Model	Min.	Max.	Ave.	SD
BD–TMD	0.252	0.651	0.375	0.076
SD–TMD	0.345	0.769	0.467	0.095

Since R_{XY} is derived from D_{XY} calculated from Eq. (1), the vibration reduction level in each direction is not clearly evaluated. Therefore, the mean square values of the structural response displacement D_X and D_Y are defined as

$$D_X = \sum_{i=1}^{N}\{x(i \cdot \Delta t)^2\} / N \ , \ D_Y = \sum_{i=1}^{N}\{y(i \cdot \Delta t)^2\} / N \qquad (3)$$

The vibration reduction ratio R_X is defined as the ratio of D_X with TMD to D_X without TMD. R_Y is defined in the same way. Distributions of R_X and R_Y are shown in Figure 6, from which we can see that the vibrations in two directions are equally reduced.

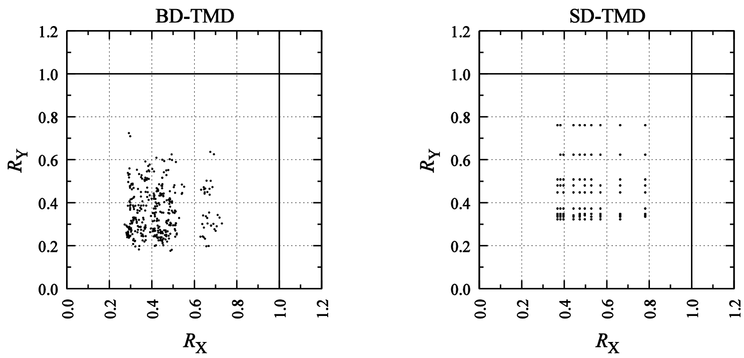

Figure 6: Distributions of R_X and R_Y

4. Example-2: arch-frame model

4.1 Description of the model

In this section, the performance of vibration control of BD-TMD is further investigated by attaching BD-TMD to an arch-frame model as shown in Figure 7 subjected to horizontal and vertical seismic motions. The radius, height, half-open-angle of the curved roof are 152.6 m, 5.2 m, 15 deg., respectively. The span and the height of columns are 79.0 m and 15.0 m, respectively. The cross-sectional area and the area moment of inertia are 5.38×10^4 mm^2 and 1.18×10^{10} mm^4 for the members of arch roof, and 5.89×10^4 mm^2 and 1.35×10^{10} mm^4 for the members of columns. Young modulus of members is 2.05×10^5 N/mm^2. The column base is rigidly supported. The lumped mass of 6,000 kg is placed at each node of the roof from nodes 1 to 13. Therefore, the total mass of the roof is 78,000 kg. Rayleigh damping is assumed for the arch-frame with damping factor 2.0% for both 1st and 2nd natural frequencies. Figure 8 shows the mode shapes and the natural frequencies of the four lowest modes.

A BD-TMD is attached at node 7 at the top of the roof. However, to control the vibration by TMD, it is more effective to place TMDs at the nodes with largest displacements of the dominant modes. Therefore, the best nodes for placing TMDs are node 7 for the 1st mode and node 4 (and node 10) for the 2nd mode. For this reason, node 7 is not the best point to attach a TMD; however, we investigate the performance of BD-TMD for controlling bi-directional vibrations by attaching it at the top of the arch-frame.

Node A of the BD-TMD in Figure 3 is attached to the node 7 of the arch-frame, and the X-directional displacements of nodes A and B are constrained to be equal. Masses of 3,705 kg and 195 kg are placed at nodes C and B, respectively. Therefore, the total mass of BD-TMD is 3,900 kg, which is 5% of the mass of the arch-frame. The coordinates of nodes A and B are (0.0, 0.0) and (0.0, -1.0 m). The spring constant K_3 and viscosity coefficient C_V are fixed at 2,000,000 N/m and 10,592 N･s/m, respectively.

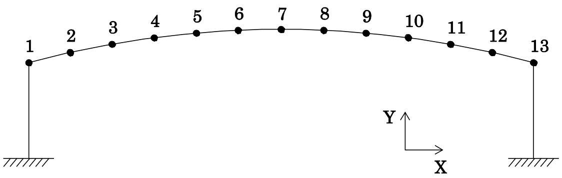

Figure 7: An arch-frame model

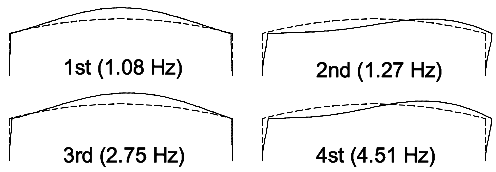

Figure 8: Mode shapes and natural frequencies

4.2 Parameter optimization of BD-TMD

Parameters of BD-TMD are optimized in the same procedure as section 3. The mean square value of the structural response displacement D_{XY} is defined as

$$D_{XY} = \sum_{j=1}^{7} \sum_{i=1}^{N} \{x_j(i \cdot \Delta t)^2 + y_j(i \cdot \Delta t)^2\} / N \tag{4}$$

where $x_j(t)$ and $y_j(t)$ are the displacements of node j of the arch-frame in X- and Y-directions, respectively.

Table 6 shows the range of parameters, and the optimal values of objective function and parameters are listed in Table 7. Table 8 shows the natural frequencies of BD-TMD corresponding to the optimal parameters and there tuning ratios.

Table 6: Range of parameters

Parameter	K_1	K_2	X_C	Y_C
Lower Limit	50,000	50,000	0.50	–1.00
Upper Limit	500,000	500,000	1.50	0.00

Table 7: Optimal parameters

F	K_1	K_2	X_C	Y_C
0.467	99,763	199,053	0.58	–0.36

Table 8: Natural frequencies and tuning ratios

direction	BD-TMD	arch-frame	ratio
X	1.21 Hz	1.27 Hz	0.95
Y	0.97 Hz	1.08 Hz	0.90

4.3 Evaluation of performance

The performance of vibration control is evaluated by calculating R_{XY} of 360 sets of seismic motions described in section 2.1. Table 9 shows the statistics of R_{XY}. Figure 9 shows R_{XY} calculated at each node individually from nodes 1 to 7. From the table and the figure, it is confirmed that vibrations are efficiently reduced all over the arch-frame.

Figures 10 and 11 show the case of response analysis, of which R_{XY} is 0.418. Figure 10 shows the tracks of response displacement of nodes 4 and 7. Figure 11 shows the time-history response displacement of node 7. In the figures, the title “w/o” indicates “without TMD” and the title “w/” indicates “with TMD”.

Table 9: statistics of R_{XY}

Model	Min	Max	Ave	SD
BD–TMD	0.293	0.912	0.512	0.116

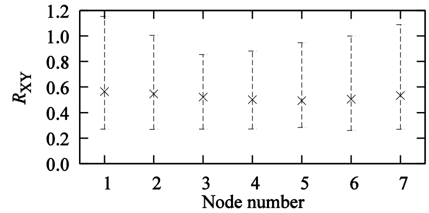

Figure 9: Distributions of R_{XY} at each node
(× indicates the mean value)

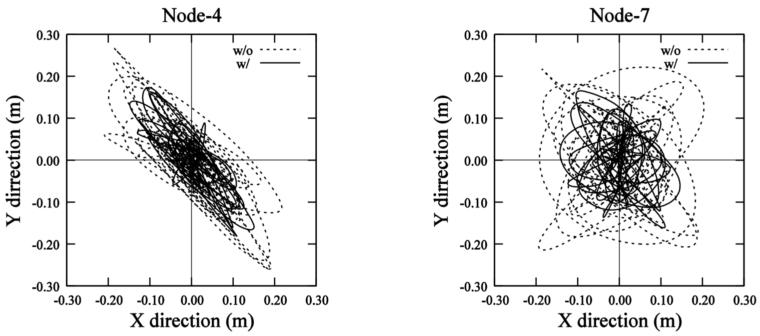

Figure 10: Tracks of response displacement

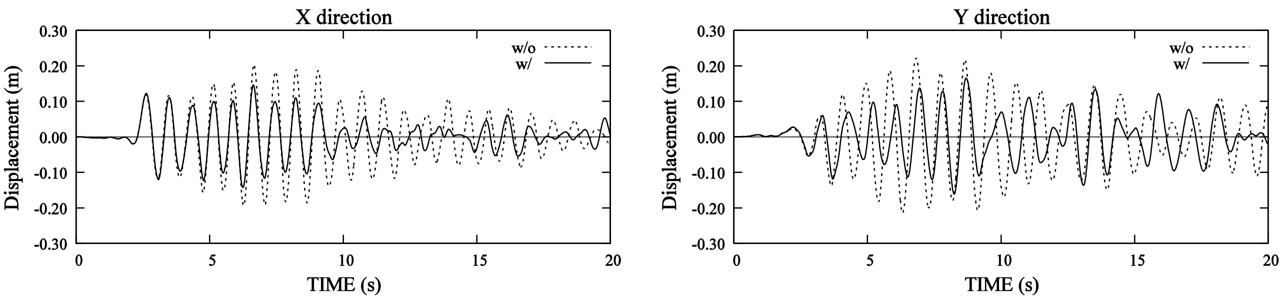

Figure 11: Time-history response displacement of node-7

Ground-motion frequency response analyses are carried out in both X- and Y-directions individually. Maximum acceleration is 0.5 m/s^2 and analysis duration time is 40 seconds. Figure 12 shows D_{XY} calculated by equation (4). We can see that responses are largely reduced around the dominant frequency of arch-frame and slightly increased before and after that frequency. This is a general characteristic of passive tuned mass damper.

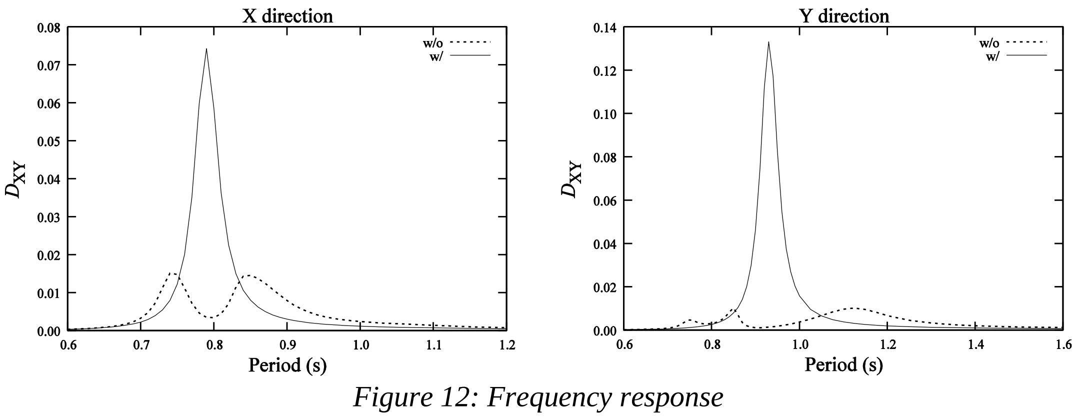

Figure 12: Frequency response

5. Design of BD-TMD

Analytical model of BD-TMD, as shown in Figure 3, is composed in a plane. In order to develop and design BD-TMD actually, the constraint for out-of-plane has to be considered. Figure 13 shows a conceptual image of BD-TMD. Two triangle-plane-frames are arranged in parallel and a mass is installed among them. For the constraint toward out-of-plane, bracings are installed. This is possible because spring constant K_3 is specified in much higher stiffness than the others in numerical analysis.

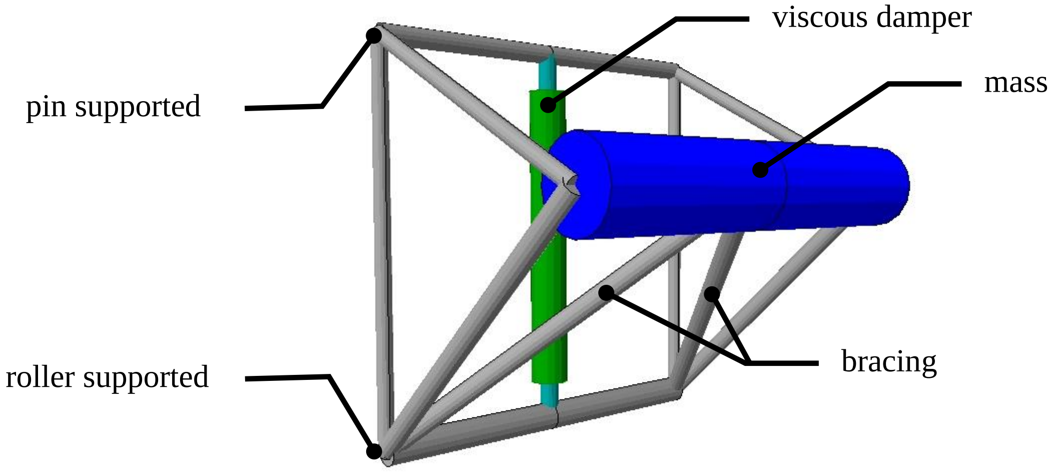

Figure 13: Conceptual image of BD-TMD

6. Conclusions

We proposed a new type of passive tuned mass damper called BD-TMD, which consists of a mass, three springs and a viscous damper. The BD-TMD can reduce bi-directional vibrations passively using a single damper. The performances of BD-TMD have been evaluated in comparison to those of the standard single-degree-of-freedom conventional TMDs attached to a one-mass model. Conclusions drawn from this study are summarized as follows:

(1) The BD-TMD can control bi-directional vibrations more effectively than the conventional TMDs consisting of two masses and dampers that can dissipate two directional vibrations independently.

(2) The BD-TMD can reduce the responses of an arch-type frame against two-directional seismic motions efficiently using a mass that vibrates in two directions due to horizontal and vertical seismic motions.

7. References

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