Optimum tuning of mass dampers for seismic structures using flower pollination algorithm

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Abstract: - For the design of damping of vibrations of seismic structures, tuned mass dampers can be used. For efficiency, the implemented mass damper (TMD) must be optimally tuned. The optimum values cannot be found by mathematical methods due to the consideration of multiple structural modes, inherent damping and earthquake excitations with random frequency. In that case, metaheuristic methods and swarm intelligence based algorithms are suitable in searching for the optimum values of tuned mass dampers. In this study, the flower pollination algorithm (FPA) is employed in order to find the optimum mass, period and damping ratio of tuned mass damper positioned on the top of the structure. In the numerical example, the best solution is search under a set of earthquake excitations for a ten story structure and the stroke capacity limit of TMD is considered. The comparisons with the existing approaches show the feasibility of the FPA based method.

Key-Words: Tuned mass damper, Optimization, Earthquake, Swarm Intelligence, Flower Pollination Algorithm, Structures.

1 Introduction

Tuned mass dampers (TMD) are a combination of stiffness and damping members attached to a mass and TMDs are used as vibration absorber devices in mechanical systems. Since structures are also designed according to principles of mechanics of materials, the stability of the structures under natural and human made excitations can be reduced by adding TMDs and the properties of TMDs must be tuned according to the frequency behavior of the structure for an effective gain in the reduction of structural vibrations.

For multi-story civil structures with damping, the optimum values of a tuned mass damper for random vibrations cannot be mathematically derived. For that reason, the idealization of structure to a single degree of freedom system is needed. In that case, the first natural frequency of the structure can be only considered. Additionally, the inherent damping of the structure cannot be mathematically considered. Also, the random frequency characteristic of earthquake excitations cannot be formulized in the mathematical methods. In documented methods, several mathematical expressions are proposed but only approximate optimum results are obtained by using these methods. The first optimum design solutions of TMDs were given by Den Hartog and the formulations of Den Hartog are only for undamped single degree of freedom (SDOF) systems [1]. Then, Warburton proposed simple expressions for frequency and damping ratio of TMDs for harmonic and random excitations [2]. Since the optimum formulations of TMD cannot be derived if the inherent damping is included for the main system, Sadek et al. used numerical trials results and curve fitting technique in obtaining several expressions. An approximate modification for multiple degree of freedom (MDOF) structures were also proposed by Sadek et al. [3]. Then, numerical optimization techniques are considered in several studies [4-7].

Metaheuristic methods and swarm intelligence based methods are suitable for TMD optimization for structure under random vibrations. Several metaheuristic methods such as genetic algorithms [8-12], particle swarm optimization [13-14], bionic optimization [15], harmony search (HS) algorithm [16-19], ant colony optimization [20], artificial bee optimization [21], shuffled complex evolution [22] and teaching learning based optimization (TLBO) [23].

In this paper, the flower pollination algorithm (FPA) developed by Yang [24] is employed in the development of the optimization approach for TMD tuning. In methodology, the stroke capacity limit is also considered for a TMD positioned on the top of the structure. The proposed method is applied for a 10-story structure and the optimum results were compared with the other method employing HS [19]. For a global solution, 44 different earthquake records were used and these earthquakes are grouped as a far-fault ground motion set in FEMA P-695 [25].

2 Methodology

In Fig. 1, a shear building model containing a TMD is shown. N is the number of stories and modes of uncontrolled structure. In TMD controlled structure, the number of the modes is N+1. The equations of motion of the shear building can be written as

$$\mathrm{M}\ddot{x}(t)+\mathrm{C}\dot{x}(t)+\mathrm{K}x(t)=-\mathrm{M}\{1\}\ddot{x}_g(t) \quad (1)$$

if the structure is underground acceleration excitation. The M, C and K matrices are diagonal lumped mass, damping and stiffness matrices, respectively. These matrices are shown as Eqs. (2)-(4). In these equations, $x(t)$, $\ddot{x}_g(t)$ and $\{1\}$ are the vector containing structural displacements of all stories and TMD (shown as Eq. (5)), ground acceleration in horizontal direction and a vector of ones with a dimension of (N+1,1), respectively.

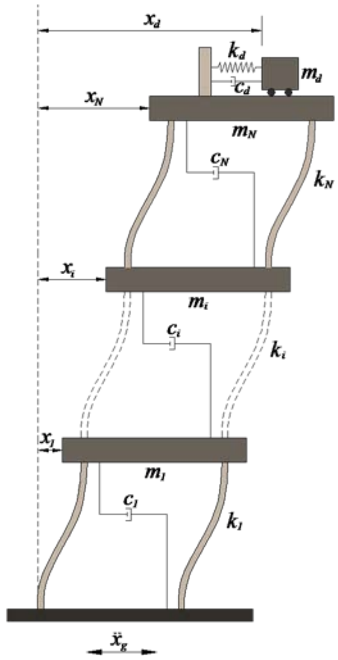

Figure 1 Model of N-story shear building including a TMD on the top.

$$M=\mathrm{diag}[m_1\ m_2 \ldots\ldots\ldots m_N\ \ m_d] \quad (2)$$

$$C=\begin{bmatrix} (c_1+c_2) & -c_2 & & & & \\ -c_2 & (c_2+c_3) & -c_3 & & & \\ & . & . & & & \\ & . & . & . & & \\ & & . & . & . & \\ & & & -c_N & (c_N+c_d) & -c_d \\ & & & & -c_d & c_d \end{bmatrix} \quad (3)$$

$$K=\begin{bmatrix} (k_1+k_2) & -k_2 & & & & \\ -k_2 & (k_2+k_3) & -k_3 & & & \\ & . & . & & & \\ & . & . & . & & \\ & & . & . & . & \\ & & & -k_N & (k_N+k_d) & -k_d \\ & & & & -k_d & k_d \end{bmatrix} \quad (4)$$

$$x(t)=\mathrm{diag}[x_1\ x_2 \ldots\ldots\ldots x_N\ \ x_d]^{\mathrm{T}} \quad (5)$$

In the matrices and vectors, m_i, c_i, k_i and x_i are mass, damping coefficient, stiffness coefficient and displacement of i_{th} story of structure. The properties of the TMD are mass (m_d), damping coefficient (c_d) and stiffness coefficient (k_d), respectively. The displacement of the TMD is shown as x_d. The properties can be also written as the period (T_d) and damping ratio (ξ_d) of TMD as shown in Eqs. (6) and (7).

$$T_d = 2\pi\sqrt{\frac{m_d}{k_d}} \quad (6)$$

$$\xi_d = 2c_d m_d\sqrt{\frac{k_d}{m_d}} \quad (7)$$

Flowers use pollination for reproduction and such pollination can be in two ways. Pollens can be transferred by pollinators such as insects, birds, bats or other animals (cross-pollination) or some flower types have ability for self-pollination. By using the flowing rules of the nature of the pollination, FPA is developed [24].

1.The pollinators obey the rules of a Lévy distribution by jumping or flying distance steps. Cross-pollination is the global pollination process.

2.Self-pollination is local pollination process which occurs from pollen of the same flower of other flowers of the same plant.

3.Flower constancy is used as a reproduction strategy which considers the similarity of two flowers involved in pollination.

4.A probability called the switch probability is controlled for selecting local pollination and global pollination.

In the methodology, structural properties, external excitations and ranges of design variables are defined as constants. Then, the structure without TMD is analyzed in order to compare the effectiveness of the TMD. After that, the initial solutions are generated for TMD parameters such as mass, period and damping ratio. For all set of variables, the dynamic analyses are done for the structure. Then, the essential optimization process starts.

In the global pollination, the first and third rules of nature are employed and the solution (or a design variable) of the next step (x_i^{t+1}) is found by using the values of the previous step (step t) defined as x_i^t (Eq. (8)).

$$x_i^{t+1}= x_i^t+L(x_i^t-g_*) \quad (8)$$

Here, Eq. (8), the subscript; i represents the *i*-th pollen (or flower), g_* is the current best solution and L is the strength of the pollination which is found by drawing a random number from a Lévy distribution. Local pollination is formulized according to second and third rule by using random walks as seen in Eq. (9).

$$x_i^{t+1}= x_i^t+\epsilon(x_j^t- x_k^t) \quad (9)$$

where x_j^t and x_k^t are solution of different plants while ϵ is randomized between 0 and 1. By using the fourth rule, a switch probability (p) is used to choose the type of pollination. The objective functions are given in Eqs. (10) and (11). The first one is the reduction of maximum top story displacement of the structure to a user defined value (x_{max}). The other objective is related with the stroke capacity of the TMD. The objective given as Eq. (11) is considered comparison of set of design variables. If this objective function is lower than *st_max*, the objective function given in Eq. (10) is considered. This iterative optimization is done until the criteria given by two objectives are provided.

$$|x_N| \le x_{max} \quad (10)$$

$$\frac{max[|x_{N+1}-x_N|]_{with\,TMD}}{max[|x_N|]_{without\,TMD}} \le st\_max \quad (11)$$

3 Numerical Example

A ten story structure with equal properties was optimized [10]. The mass, stiffness coefficient and damping coefficient of a story is 360 t, 6.2 MNs/m and 650 MN/m, respectively. The ranges for the design variables and optimum TMD parameters are given in Table 1 for two different stroke capacity cases. The *st_max* limitation is taken as 1 and 2 for Case 1 and 2, respectively. The user defined value, x_{max} was taken as zero and it is iteratively increased in order to find a solution with maximum efficiency. The detailed maximum responses of Case 2 are shown in Table 2. The table contains the maximum displacement, total acceleration values and the scaled maximum TMD displacement (x_d') all excitations. The most critical excitation is the second component of Duzce record (plot shown in Fig. 2 for Case 2) since the stroke objective is applied only for the critical excitation.

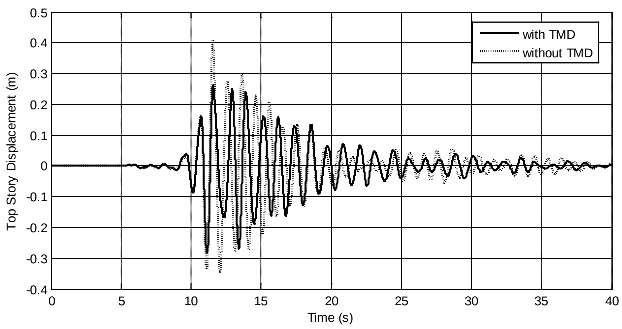

Figure 2 The time history displacement plot for the critical excitation.

4 Conclusions

The maximum displacement under the critical excitation is 0.41 m for the uncontrolled structure. This value is reduced to 0.3203 m and 0.2820 m for Case 1 and 2, respectively. The same values are found as 0.3280 m and 0.2902 m for HS approach. For such reason, FPA is found to be effective on updating the existing optimum solution by finding precise optimum values.

TABLE I. THE RANGES OF DESIGN VARIABLES AND OPTIMUM VALUES (FPA APPROACH)

Design variable	Range definition	Optimum values (Case 1)	Optimum values (Case 2)
Mass (t)	between 1% and 5% total mass of structure	180	180
Period (s)	between 0.5 and 1.5 times of the critical period of structure	0.9286	0.9418
Damping ratio (%)	between 0.1% and 30%	29.89	5.64

TABLE II. MAXIMUM RESPONSES WITH FEMA P-695 FAR-FIELD GROUND MOTION RECORDS..

Earthquake Number	Component	max. (x) (m) without TMD	max. (x) (m) with TMD	max. ($\ddot{x}+\ddot{x}_g$) (m/s^2) without TMD	max. ($\ddot{x}+\ddot{x}_g$) (m/s^2) with TMD	x_d'
Northridge	NORTHR/MUL009	0.37	0.21	15.80	8.25	1.94
	NORTHR/MUL279	0.31	0.28	12.99	10.31	2.52
Northridge	NORTHR/LOS000	0.13	0.09	6.33	5.25	1.33
	NORTHR/LOS270	0.22	0.15	9.21	6.73	1.73
Duzce, Turkey	DUZCE/BOL000	0.26	0.17	12.79	7.99	1.74
	DUZCE/BOL090	0.41	0.28	19.29	13.08	2.00
Hector Mine	HECTOR/HEC000	0.11	0.16	5.04	5.73	2.83
	HECTOR/HEC090	0.13	0.16	5.46	6.41	2.52
Imperial Valley	IMPVALL/H-DLT262	0.11	0.07	5.33	3.55	1.64
	IMPVALL/H-DLT352	0.19	0.11	7.90	4.75	1.50
Imperial Valley	IMPVALL/H-E11140	0.08	0.06	4.58	4.11	1.93
	IMPVALL/H-E11230	0.07	0.10	4.41	5.63	2.85
Kobe, Japan	KOBE/NIS000	0.11	0.12	5.91	5.25	2.15
	KOBE/NIS090	0.10	0.10	5.12	5.34	1.65
Kobe, Japan	KOBE/SHI000	0.10	0.14	5.00	5.99	3.13
	KOBE/SHI090	0.08	0.10	3.27	3.72	2.83
Kocaeli, Turkey	KOCAELI/DZC180	0.15	0.12	8.44	6.74	1.70
	KOCAELI/DZC270	0.22	0.20	9.81	9.21	2.07
Kocaeli, Turkey	KOCAELI/ARC000	0.04	0.04	2.07	2.29	2.74
	KOCAELI/ARC090	0.04	0.03	1.99	1.49	2.30
Landers	LANDERS/YER270	0.18	0.13	7.42	4.88	1.60
	LANDERS/YER360	0.11	0.08	5.00	3.08	1.50
Landers	LANDERS/CLW-LN	0.08	0.08	6.03	3.63	2.68
	LANDERS/CLW-TR	0.14	0.15	6.14	6.24	2.16
Loma Prieta	LOMAP/CAP000	0.15	0.17	8.95	7.57	2.04
	LOMAP/CAP090	0.09	0.11	5.01	6.17	3.22
Loma Prieta	LOMAP/G03000	0.11	0.07	6.68	6.48	1.59
	LOMAP/G03090	0.12	0.14	6.08	6.08	2.21
Manjil, Iran	MANJIL/ABBAR--L	0.12	0.08	6.06	5.41	1.90
	MANJIL/ABBAR--T	0.18	0.15	9.95	7.37	1.49
Superstition Hills	SUPERST/B-ICC000	0.08	0.15	5.53	6.65	3.43
	SUPERST/B-ICC090	0.08	0.10	3.35	3.14	1.88
Superstition Hills	SUPERST/B-POE270	0.12	0.13	5.11	5.62	2.39
	SUPERST/B-POE360	0.14	0.13	6.21	6.54	1.72
Cape Mendocino	CAPEMEND/RIO270	0.18	0.15	8.52	7.76	2.06
	CAPEMEND/RIO360	0.14	0.12	7.70	6.30	1.99
Chi-Chi, Taiwan	CHICHI/CHY101-E	0.16	0.11	7.67	5.04	2.08
	CHICHI/CHY101-N	0.35	0.21	13.83	9.03	1.48
Chi-Chi, Taiwan	CHICHI/TCU045-E	0.11	0.08	6.65	5.87	1.39
	CHICHI/TCU045-N	0.15	0.12	7.17	6.58	2.29
San Fernando	SFERN/PEL090	0.09	0.08	4.51	3.29	2.16
	SFERN/PEL180	0.06	0.03	2.81	1.54	1.33
Friuli, Italy	FRIULI/A-TMZ000	0.08	0.06	5.38	4.37	1.97
	FRIULI/A-TMZ270	0.10	0.09	5.27	4.93	1.75

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