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Optimum Design of Multiple Friction Tuned Mass Dampers Under Seismic Excitations

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ABSTRACT

External passive energy dissipation systems have been widely used in order to reduce vibrations in structures subjected to seismic excitations. Within this context, the performance of passive tuned mass dampers in vibration mitigation due to earthquakes is the study object of many researchers. This paper presents a study on global optimization of multiple friction tuned mass dampers (MFTMDs) to control vibrations in structures subjected to seismic excitations. Computational codes for calculating the dynamic response of structures with MFTMDs are elaborated considering nonlinear analysis in the time domain. For the optimization scheme, because of the nonconvex nature of the problem, a hybrid algorithm composed of the algorithms Firefly (FA) and Nelder-Mead (NMA) is applied. The seismic excitations are treated as a stationary stochastic process. Real seismic records are also considered. A numerical example on a ten story shear building with one, two and five dampers is demonstrated. The quantity and positioning of the MFTMDs in the structure are previously fixed. Results show that the use of multiple dampers is more efficient than the use of only one and the proposed approach demonstrates to be a suitable alternative to furnish the optimum MFTMDs parameters in structures subjected to seismic excitations.

Keywords: seismic excitations, optimization, MFTMDs, nonlinear analysis

1. INTRODUCTION

External passive energy dissipation systems have been widely used for reducing vibrations in structures subjected to seismic excitations [1,2]. This systems have an increasingly significant role in attenuating undesirable oscillations in slender and lighter structures, which are very susceptible to vibration problems. Within this context, it is highlighted the use of tuned mass damper (TMD), initially proposed by Frahm [3], that presents a wide range of application in the field of vibration control. This device consists of a spring-mass system without damping. Ormondroyd e Den Hartog [4] incorporated a viscous damper to Frahm's device and observed a significant improvement in its performance. Den Hartog [5] developed expressions of optimum stiffness and damping of a TMD attached to an undamped single degree of freedom (SDOF) system under harmonic load. Warburton [6] presented expressions of optimum parameters of a TMD connected to a SDOF system without damping subjected to harmonic and white noise random excitations.

In the sequence many researches have emerged addressing the TMDs, including the multiple tuned mass dampers (MTMDs). MTMDs with different dynamic characteristics showed to be more effective than a single TMD [7–9]. Joshi and Jangid [10] presented the optimization of MTMDs in a base excited structure and, since then, many researchers have focused their studies on the optimization of TMDs and MTMDs in structures subjected to seismic excitations [11–20]. It is also important to note that some studies considering TMD with nonlinear viscous damping are also found in the literature [21–23].

Nevertheless, although the TMD has been introduced in 1909, its behavior under seismic excitations remains an relevant research topic [24]. Moreover, in this sense, the state of the art is limited in the modeling and optimization of systems with nonlinear TMDs. This limitation needs to be better evaluated because some nonlinear behavior may be inherently present in the dissipative system, such as friction tuned mass damper (FTMD), where the friction damping characterizes the nonlinearity of the system. This nonlinearity can provide advantages in the performance, construction, installation and maintenance of the attenuator [25].

In this context, Inaudi and Kelly [26] studied a FTMD attached in an undamped SDOF system. The system was analyzed by a statistical linearization technique considering white noise random excitation. Ricciardelli and Vickery [27] assessed the behavior of a FTMD attached to a SDOF system subjected to harmonic excitation. Analytical expressions for the displacement amplitude and optimum FTMD parameters were proposed. Hartung, Schmieg and Vielsack [28] numerically and experimentally evaluated an undamped SDOF system, under harmonic excitation, with a FTMD attached to it. Lee et al. [29] showed that the friction between a TMD and the rail on which it slides, generally neglect in the damping optimization procedure, can improve the performance of the TMD. Gewei and Basu [25] studied the behavior of a single FTMD connected to a SDOF system under base acceleration. An analytical expression was obtained for the displacement of the system under harmonic excitation by the harmonic balance method and the root mean square value of the system displacement was evaluated under white noise random excitation by statistical linearization. Numerical simulations showed that FTMD performance is similar to that of TMD. Barbosa and Ramadhan [30] numerically evaluated the response of a 72 story building subjected to real seismic excitations with one and two FTMDs attached to it. The results showed that the use of MFTMDs is more efficient in controlling the dynamic response than the use of a single FTMD. C. Lin, L. Lin and Lung [31] developed a prototype of a system with three FTMDs to control vibrations in tall buildings, in that the damping derive from the friction between sliding blocks and rails. To verify the efficiency of the system, shaking table tests and numerical simulations were successfully performed, for harmonic excitations and for a real seismic record. Pisal and Jangid [32] investigated the performance of MFTMDs in reducing the dynamic response of a five story building. The motion equations were solved numerically by state space method, and optimum MFTMDs parameters were obtained for four real seismic records. It was concluded that the MFTMDs are more efficient in controlling the vibration of the structure than a single FTMD.

Within this context, this paper proposes a global optimization of MFTMDs in structures subjected to seismic excitations modeled as a stationary stochastic process via nonlinear time domain analysis. In Section 2, the scheme used to determine the dynamic response of structures equipped with MFTMDs and the hybrid optimization process, which uses the Firefly algorithm (FA) and the Nelder-Mead algorithm (NMA), sequentially, are presented. Section 3 shows a numerical example in order to check the efficiency of the proposed methodology. The conclusions from this research are presented in Section 4.

2. METHODOLOGY AND PROBLEM FORMULATION

The nonlinear differential equation that governs the motion of a n degrees of freedom structure equipped with n_F FTMDs arranged in parallel on the top story, subjected to seismic excitation, represented by the ground acceleration $\ddot{\vec{x}}_g(t)$ (a $d \times 1$ vector, where d is the number of directions of the ground movement), can be written as

$$\mathbf{M}\ddot{\vec{x}}(t)+\mathbf{C}\dot{\vec{x}}(t)+\mathbf{K}\vec{x}(t)+\vec{F}_f(t)=\mathbf{M}\Gamma\ddot{\vec{x}}_g(t), \tag{1}$$

where $\vec{x}(t)$, $\dot{\vec{x}}(t)$ and $\ddot{\vec{x}}(t)$ are, respectively, the displacement, velocity and acceleration system vectors relative to base, of size $(n + n_F) \times 1$. **M**, **C** and **K** are, respectively, the mass, damping and stiffness matrices of the system, of size $(n + n_F) \times (n + n_F)$. Γ is the $(n + n_F) \times d$ influence matrix of ground motion coefficients. $\vec{F}_f(t)$ is the friction force between the last story and the FTMDs, a $(n + n_F) \times 1$ vector.

Without loss of generality of the proposed methodology, the structure was discretized as a shear building (Figure 1). Hence, the matrices **M**, **C** and **K** are expressed by Equations 2, 3 and 4 hereinafter.

$$\mathbf{M}=diag\begin{bmatrix}m_1 & m_2 & \cdots & m_n & m_{F1} & m_{F2} & \cdots & m_{Fn_F}\end{bmatrix} \tag{2}$$

$$\mathbf{C}=\begin{bmatrix}
c_1+c_2 & -c_2 & \cdots & 0 & 0 & 0 & \cdots & 0\\
-c_2 & c_2+c_3 & \cdots & 0 & 0 & 0 & \cdots & 0\\
\vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \vdots\\
0 & 0 & \cdots & c_n & 0 & 0 & \cdots & 0\\
0 & 0 & \cdots & 0 & 0_{F1} & 0 & \cdots & 0\\
0 & 0 & \cdots & 0 & 0 & 0_{F2} & \cdots & 0\\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots\\
0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0_{n_F}
\end{bmatrix} \tag{3}$$

$$\mathbf{K}=\begin{bmatrix}
k_1+k_2 & -k_2 & \cdots & 0 & 0 & 0 & \cdots & 0\\
-k_2 & k_2+k_3 & \cdots & 0 & 0 & 0 & \cdots & 0\\
\vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \vdots\\
0 & 0 & \cdots & k_n+\sum\limits_{j=1}^{n_F} k_{Fj} & -k_{F1} & -k_{F2} & \cdots & -k_{Fn_F}\\
0 & 0 & \cdots & -k_{F1} & k_{F1} & 0 & \cdots & 0\\
0 & 0 & \cdots & -k_{F2} & 0 & k_{F2} & \cdots & 0\\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots\\
0 & 0 & \cdots & -k_{Fn_F} & 0 & 0 & \cdots & k_{Fn_F}
\end{bmatrix} \tag{4}$$

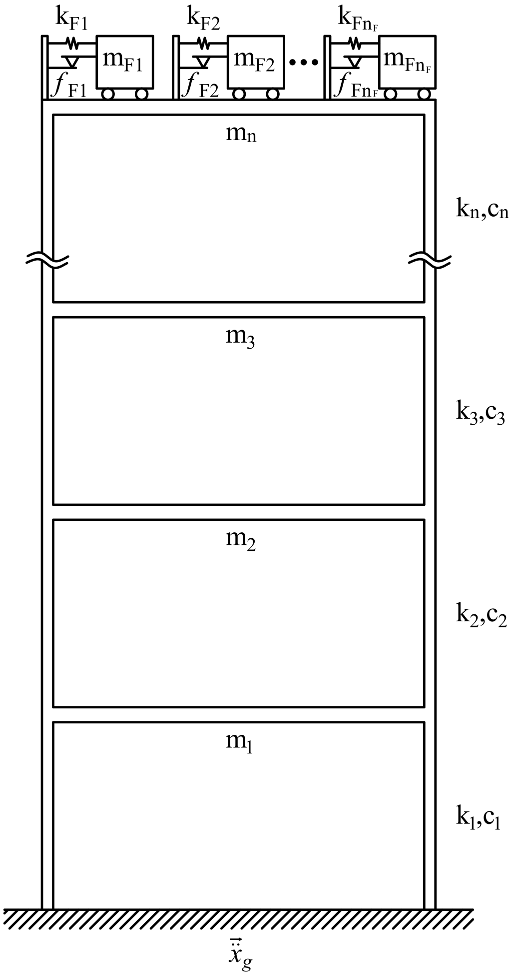

Figure 1. n-story shear building equipped with n_F FTMDs

The Coulomb friction force, developed at the interface of the *j-th* FTMD with the last story, is expressed by

$$F_{Fj}(t) = \mu_j m_{Fj} g sgn[\dot{x}_{Fj}(t) - \dot{x}_n(t)] = f_{Fj} sgn[\dot{y}_{Fj/n}(t)], \tag{5}$$

where μ_j is the dynamic friction coefficient (supposed to be constant and equal to the static), m_{Fj} is the mass of the *j-th* FTMD, g is the gravity acceleration and $sgn[.]$ is the signal function, presented in Equation 6.

$$sgn[\dot{y}_{Fj/n}(t)] = \begin{cases} +1 & \text{se} \quad \dot{y}_{Fj/n}(t) > 0 \\ 0 & \text{se} \quad \dot{y}_{Fj/n}(t) = 0 \\ -1 & \text{se} \quad \dot{y}_{Fj/n}(t) < 0 \end{cases} \tag{6}$$

It is noted from Equations 5 and 6 that the friction force direction depends on the direction of the relative velocity between the damper and the last story of the structure. The nature of the dynamic problem presented is characterized by frequent changes in the direction of this velocity, which allied with the complex stick slip movement, results in discontinuities in the friction force, characterizing the nonlinear behavior of the system and thus making its analysis even more difficult.

In order to evaluate this behavior, many authors have proposed alternative models to represent the friction force, of which the Mostaghel and Davis [33] model stands out, that proposes the replacement of the discontinuous friction force by continuous functions. This model was previously studied by some researchers for an another dissipative system, the friction dampers [2,34,35], and was adopted in this paper. Within this context, the signal function was replaced by $tanh[\alpha\dot{y}_{Fj/n}(t)]$, where α is a positive constant that controls the level of precision of the friction force representation. Its value was chosen as $\alpha = 1000$, as suggested by [33]. The accuracy of this representation was verified with the analytical solution for a SDOF system. Then, the friction force vector is presented in Equation 7.

$$\vec{F_f}(t) = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ -\sum_{j=1}^{n_F} F_{Fj}(t)_n \\ F_{F1}(t) \\ F_{F2}(t) \\ \vdots \\ F_{F_{nF}}(t) \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ -\sum_{j=1}^{n_F} f_{Fj} tanh[\alpha\dot{y}_{Fj/n}(t)] \\ f_{F1} tanh[\alpha_2\dot{y}_{F1/n}(t)] \\ f_{F2} tanh[\alpha_2\dot{y}_{F2/n}(t)] \\ \vdots \\ f_{F_{nF}} tanh[\alpha_2\dot{y}_{F_{nF}/n}(t)] \end{bmatrix} \tag{7}$$

A computational routine for numerical solution of Equation 1 was developed considering the Newmark [36] implicit integration method, which is a direct method of integration of the motion equation. An iterative procedure is performed at each time step in for the determination of the friction force.

To determine the MFTMDs optimum parameters in structures subjected to earthquake load, the seismic excitation was simulated by a zero mean Gaussian stationary stochastic process, $\vec{\ddot{x}_0}(t)$, filtered through the Kanai-Tajimi [37,38] model, with power spectral density function given by

$$S(\omega) = S_0 \left[\frac{\omega_f{}^4 + 4\omega_f{}^2\xi_f{}^2\omega^2}{(\omega^2 - \omega_f{}^2)^2 + 4\omega_f{}^2\xi_f{}^2\omega^2} \right], \tag{8}$$

where S_0 is the constant spectral density. ξ_f and ω_f are, respectively, the damping ratio and the natural frequency of the filter (local soil parameters).

2.1 MFTMDs optimization

The optimization problem was formulated in terms of the minimization of the displacement mean square value of the last story of the structure. As the design variables were considered the stiffness and the magnitude of the friction force parameters of each FTMD, both assumed continuous and bounded by constraints. The total mass of the FTMDs was fixed as a small percentage of the mass of the structure, by practical criteria. The optimization scheme was evaluated for a fixed number of FTMDs located on the last story of the structure and can be expressed by

$$\begin{aligned} &\text{Find} && \vec{z} = [k_{A1}, k_{A2}, ..., k_{A_{nA}}, f_{A1}, f_{A2}, ..., f_{A_{nA}}] \\ &\text{Minimize} && g(\vec{z}) = E[x_n(t)^2] \\ &\text{Subject to} && k_{Fj}^{min} \leqslant k_{Fj} \leqslant k_{Fj}^{max}, \ \forall \ FTMD\ j \\ & && f_{Fj}^{min} \leqslant f_{Fj} \leqslant f_{Fj}^{max}, \ \forall \ FTMD\ j \\ & && \sum_{j=1}^{nF} m_{Fj} = \theta\ \% \sum_{i=1}^{n} m_i, \ with\ \ m_{F1} = m_{F2} = ... = m_{F_{nF}}, \end{aligned} \tag{9}$$

in which $\vec{z}$ is the design vector, $g(\vec{z})$ is the objective function, k_{Fj}^{min} and k_{Fj}^{max} are, respectively, the lower and upper limits of stiffness, f_{Fj}^{min} and f_{Fj}^{max} are, respectively, the lower and upper limits of the magnitude of the friction force, and θ is the mass ratio between the dampers and the structure.

To solve this optimization problem, due to the nonconvex nature of the objective function when MFTMDs are considered, it is proposed to use a hybrid stochastic/deterministic algorithm composed by the Firefly algorithm (FA), stochastic part of global search, and by the Nelder-Mead algorithm (NMA), deterministic part of local search. The hybrid optimization algorithm applied, previously developed by Fadel Miguel et al. [20] for conventional MTMDs optimization, is based on the use of the NMA inside the FA to accelerate the global search convergence, that is, the FA furnishes a starting point close to the global solution, so that the NMA search starts from that point. The subsequent combination of these algorithms tends to improve the search efficiency. In the sequence, the algorithms FA and NMA, as well as the hybrid algorithm FA-NMA, are summarily described.

The FA is a metaheuristic optimization algorithm inspired in the bioluminescence characteristic of fireflies, which represent the design vectors, developed by Yang [39]. The variation of light intensity and the formulation of attractiveness are the two essential aspects of the FA. After determining the light intensity of an initial population of fireflies, which is related to the objective function, the movement of a firefly $\vec{z}_i$, attracted by another $\vec{z}_j$, brighter, is given by

$$\vec{z}_i = \vec{z}_i + \beta_0 e^{-\gamma r^2}(\vec{z}_j - \vec{z}_i) + \delta \vec{\varepsilon}_i, \tag{10}$$

in which β_0, γ, δ and $\vec{\varepsilon}_i$ are the FA parameters, chosen as suggested by the FA author, and r is the distance between the fireflies $\vec{z}_i$ and $\vec{z}_j$. It is pointed out that $\vec{\varepsilon}_i$ is a vector of random numbers that allows the algorithm to expand its search field, avoiding that it is restricted in local minimums. The limits due to restrictions are imposed so that the generation of infeasible samples are not allowed.

The NMA is zero order optimization algorithm, that is, it performs the direct search through the evaluation of the objective function without requiring gradients evaluation. It was developed by Nelder and Mead [40] and is a method widely used by researchers from various fields. The NMA is based on the comparison of the values assumed by the objective function at the η + 1 vertices $\vec{z}_i$ of a simplex, where η = dim($\vec{z}_i$). The initial simplex of size s is obtained from a first vertice $\vec{z}_0$, furnished by the FA, and the other η vertices are obtained by [41]

$$\vec{z}_i = \vec{z}_0 + p\vec{e}_i + \sum_{\substack{k=1 \\ k\neq i}}^{\eta} q\vec{e}_k, \; i = 1, ..., \eta, \tag{11}$$

in which $\vec{e}_i$ and $\vec{e}_k$ are versors that form the search space base,

$$p = \frac{s}{\eta\sqrt{2}}(\sqrt{\eta+1} + \eta - 1), \; and \tag{12}$$

$$q = \frac{s}{\eta\sqrt{2}}(\sqrt{\eta+1} - 1), \tag{13}$$

The principle of the NMA consists, in each iteration in the search for a better vertice, in the substitution of vertices by means of operations of reflection, expansion and contraction. As a parameter of convergence of the algorithm, it is considered as a stopping criterion the expression given by

$$\sqrt{\sum_{i=1}^{\eta+1} \frac{(g(\vec{z}_i) - \bar{g})^2}{\eta}} < \xi, \;\; com \;\; \bar{g} = \frac{1}{\eta+1}\sum_{i=1}^{\eta+1} g(\vec{z}_i), \tag{14}$$

in which ξ is a small positive scalar. In other words, the algorithm stops when the values assumed by the objective function at all vertices of the simplex are close enough, which makes the algorithm local. Since the NMA was developed for unconstrained optimization problems, the vertices of the simplex can leave the search domain after some iteration. To overcome this situation, since the presented problem involves constraints, it is applied

$$\begin{cases} \vec{z}_i = \vec{z}_{i,min} & \text{se} \quad \vec{z}_i < \vec{z}_{i,min} \\ \vec{z}_i = \vec{z}_{i,max} & \text{se} \quad \vec{z}_i > \vec{z}_{i,max}. \end{cases} \tag{15}$$

2.1.1 Hybrid optimization algorithm FA-NMA

As mentioned, it is proposed to use a hybrid stochastic/deterministic algorithm for solving the optimization problem presented in Equation 9, with global search provided by the FA and local by the NMA. The local search is performed by the NMA every $it_{FA,max}$ iterations of the FA, that is, it is initialized the global search by the FA an stop it at $it_{FA,max}$ iterations. At each stop of the FA, the best design vector is used as a starter point for the local search by the NMA, whose stopping criterion is a determined number of iterations $it_{NMA,max}$, different from the criterion previously presented and which should be small, in order to keep the global nature of the hybrid algorithm. The local search result is then introduced into the FA population and the optimization procedure is restarted. This procedure is repeated until a stop criterion is reached, in this case, a maximum number it_{max} of objective function evaluations is adopted.

3. NUMERICAL EXAMPLE

In order to assess the efficiency of the proposed methodology, which consists in the optimization of MFTMDs attached to the top story of a structure, subject to seismic excitations, through nonlinear analysis, a shear building with ten stories and with uniform distribution of mass (360.00 t), viscous damping (6.20 MN.s/m) and stiffness (650.00 MN/m) was analyzed. This properties were taken from [11]. The structure natural frequency of the first mode of vibration is equal to 1.01 Hz. The numerical example was conducted in three scenarios, S1, S2 and S3, relative to three different configurations corresponding to the number of dampers considered: one, two and five, respectively.

Initially, the optimum FTMDs parameters of stiffness and magnitude of the friction force were determined, according to the scheme presented in section 2. The filter parameters were adopted as $\xi_f = 0.3$ and $\omega_f = 37.3$ rad/s. The peak ground acceleration (PGA) was considered equal to 0.475g and the mass ratio θ equal to 3%. It was assumed, for the lower and upper limits of stiffness and magnitude of the friction force of each FMTD, respectively, $k_{Fj}^{min} = 0$, $k_{Fj}^{max} = 4000.00$ kN/m, $f_{Fj}^{min} = 0$ and $f_{Fj}^{max} = 200.00$ kN. For the optimization through integration of the motion equation, it was necessary to generate 200 excitation samples to stabilize the displacement mean square value, with a time step of 0.02 s. An initial population with 10 fireflies was considered, for all the scenarios evaluated. The NMA was called every $it_{FA,max}$ = 100 iterations, with additional $it_{NMA,max}$ = 1000 iterations. Table 1 presents the optimum FTMDs parameters and Table 2 presents the displacement standard deviation of the structure relative to the ground for each story.

For the scenario S1, which considers a single FTMD, the optimum frequency ratio between the FTMD and the first mode of vibration of the structure (FR_s^F) is equal to 0.92. The optimum parameters were found after it_{max} = 100 objective function evaluations (OFE). For the scenario S2, that considers two FTMDs, were also necessary it_{max} = 100 OFE and FR_s^F = 1.01 and 0.85. The optimum parameters for the scenario S3, which considers five FTMDs, were found after it_{max} = 300 OFE and FR_s^F = 1.10, 0.86, 0.93, 1.01 and 0.80. It should be noted that the optimum stiffness, as well as the optimum magnitude of the friction force, of each FTMD, decreases when MFTMDs are considered. The

Table 1. Optimum FTMDs parameters

FTMD	k_{Fj} (kN/m)	f_{Fj} (kN)
Scenario S1: 1FTMD		
1	3666.34	91.96
Scenario S2: 2FTMDs		
1	2198.39	42.22
2	1582.68	34.35
Scenario S3: 5FTMDs		
1	1048.51	14.07
2	649.35	10.61
3	759.79	11.44
4	882.70	12.80
5	557.50	9.17

Table 2. Displacement standard deviation (σ_{x_i}) relative to the ground for the Kanai-Tajimi excitations and its percent reduction (R) relative to the uncontrolled system

Story	1	2	3	4	5	6	7	8	9	10
Uncontrolled										
σ_{x_i} [m]	0.0072	0.0141	0.0207	0.0268	0.0324	0.0371	0.0411	0.0442	0.0463	0.0474
Scenario S1: 1 FTMD										
σ_{x_i} [m]	0.0047	0.0093	0.0136	0.0175	0.0211	0.0242	0.0268	0.0288	0.0302	0.0310
R [%]	34.17	34.05	34.36	34.57	34.94	34.85	34.89	34.86	34.73	34.61
Scenario S2: 2 FTMDs										
σ_{x_i} [m]	0.0046	0.0090	0.0131	0.0169	0.0203	0.0232	0.0257	0.0277	0.0290	0.0298
R [%]	36.56	36.48	36.82	37.06	37.45	37.39	37.45	37.44	37.33	37.23
Scenario S3: 5 FTMDs										
σ_{x_i} [m]	0.0045	0.0087	0.0127	0.0164	0.0197	0.0226	0.0250	0.0269	0.0282	0.0289
R [%]	38.19	38.16	38.52	38.79	39.19	39.15	39.23	39.21	39.10	38.99

computational effort required by the optimization scheme through nonlinear time domain analysis is considerably large. The time required is of the order of days when MFTMD are considered.

From Table 2, it can be noticed that the presence of the FTMDs considerably reduces the structure response in terms of the displacement standard deviation and that the larger the number of FTMDs, the greater the reduction, reaching almost 40% for the scenario S3. Figure 2 illustrates the results obtained.

To evaluate the generality of the proposed methodology, the performance of this control system was also checked in terms of the displacement of the structure. In this sense, the shear building was submitted to two simulated seismic records, with the same properties as those used in the optimization scheme, and to two real seismic records with different characteristics, the El Centro (USA, 1940, PGA = 0.349g) and the Hachinohe (Japan, 1968, PGA = 0.273g). The results for the scenarios S1, S2 and S3 are presented in Tables 3 to 6.

In order to obtain this structure response were considered the parameters of the FTMDs previously obtained for the scenarios S1, S2 e S3. It is noted that for all records and scenarios, there was a significant reduction in the maximum displacement of the structure relative to the structure without control. As expected, the reduction of the displacement observed for simulated earthquakes was higher than for real earthquakes. This behavior is justified because the characteristics of these records are the same as those of the 200 signals used in the optimization procedure (same PGA, Kanai-

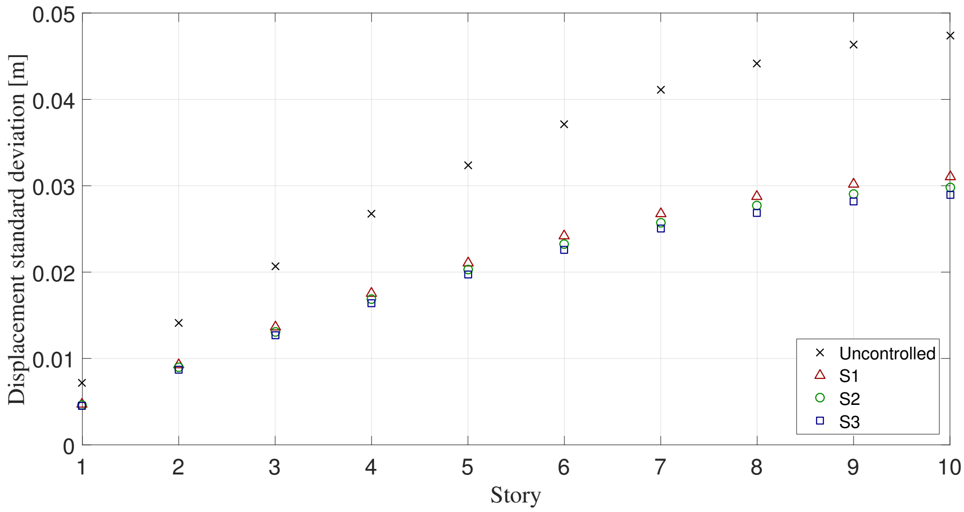

Figure 2. Displacement standard deviation relative to the ground for the Kanai-Tajimi excitations

Table 3. Maximum displacements relative to the ground for the Simulated 01 record and its percent reduction (R) relative to the uncontrolled system

Story	1	2	3	4	5	6	7	8	9	10
					Uncontrolled					
x_i^{max} [m]	0.0260	0.0510	0.0743	0.0953	0.1132	0.1281	0.1404	0.1493	0.1552	0.1582
					Scenario S1: 1 FTMD					
x_i^{max} [m]	0.0163	0.0314	0.0451	0.0574	0.0690	0.0796	0.0883	0.0959	0.1012	0.1041
R [%]	37.17	38.39	39.28	39.73	39.06	37.89	37.06	35.77	34.79	34.19
					Scenario S2: 2 FTMDs					
x_i^{max} [m]	0.0137	0.0270	0.0394	0.0506	0.0609	0.0701	0.0774	0.0828	0.0863	0.0879
R [%]	47.17	47.17	47.03	46.87	46.20	45.26	44.85	44.57	44.42	44.41
					Scenario S3: 5 FTMDs					
x_i^{max} [m]	0.0137	0.0264	0.0385	0.0488	0.0576	0.0652	0.0713	0.0759	0.0789	0.0801
R [%]	47.35	48.19	48.22	48.81	49.16	49.11	49.20	49.16	49.16	49.38

Table 4. Maximum displacements relative to the ground for the Simulated 02 record and its percent reduction (R) relative to the uncontrolled system

Story	1	2	3	4	5	6	7	8	9	10
					Uncontrolled					
x_i^{max} [m]	0.0241	0.0472	0.0685	0.0880	0.1050	0.1198	0.1321	0.1418	0.1484	0.1518
					Scenario S1: 1 FTMD					
x_i^{max} [m]	0.0166	0.0330	0.0481	0.0613	0.0723	0.0810	0.0880	0.0944	0.0997	0.1030
R [%]	31.28	30.11	29.85	30.30	31.16	32.40	33.39	33.41	32.82	32.17
					Scenario S2: 2 FTMDs					
x_i^{max} [m]	0.0156	0.0311	0.0453	0.0578	0.0680	0.0763	0.0832	0.0897	0.0953	0.0984
R [%]	35.36	34.11	33.94	34.31	35.26	36.30	37.01	36.72	35.76	35.18
					Scenario S3: 5 FTMDs					
x_i^{max} [m]	0.0155	0.0308	0.0449	0.0571	0.0671	0.0750	0.0816	0.0878	0.0933	0.0963
R [%]	35.76	34.64	34.50	35.08	36.09	37.37	38.25	38.05	37.14	36.55

Table 5. Maximum displacements relative to the ground for the El Centro (1940) record and its percent reduction (R) relative to the uncontrolled system

Story	1	2	3	4	5	6	7	8	9	10
Uncontrolled										
x_i^{max} [m]	0.0304	0.0595	0.0865	0.1111	0.1327	0.1509	0.1656	0.1766	0.1840	0.1877
Scenario S1: 1 FTMD										
x_i^{max} [m]	0.0218	0.0431	0.0636	0.0828	0.1004	0.1158	0.1287	0.1388	0.1457	0.1494
R [%]	28.39	27.59	26.50	25.48	24.37	23.26	22.26	21.44	20.83	20.42
Scenario S2: 2 FTMDs										
x_i^{max} [m]	0.0185	0.0362	0.0527	0.0676	0.0811	0.0933	0.1041	0.1128	0.1188	0.1218
R [%]	39.02	39.32	39.11	39.22	38.92	38.18	37.12	36.13	35.42	35.08
Scenario S3: 5 FTMDs										
x_i^{max} [m]	0.0184	0.0360	0.0523	0.0670	0.0805	0.0926	0.1034	0.1120	0.1179	0.1209
R [%]	39.40	39.49	39.54	39.68	39.36	38.65	37.56	36.60	35.90	35.58

Table 6. Maximum displacements relative to the ground for the Hachinohe (1968) record and its percent reduction (R) relative to the uncontrolled system

Story	1	2	3	4	5	6	7	8	9	10
Uncontrolled										
x_i^{max} [m]	0.0203	0.0399	0.0583	0.0753	0.0904	0.1036	0.1144	0.1229	0.1287	0.1316
Scenario S1: 1 FTMD										
x_i^{max} [m]	0.0147	0.0292	0.0434	0.0571	0.0704	0.0829	0.0941	0.1033	0.1097	0.1131
R [%]	27.54	26.68	25.63	24.17	22.19	19.94	17.73	15.97	14.72	14.06
Scenario S2: 2 FTMDs										
x_i^{max} [m]	0.0148	0.0294	0.0436	0.0572	0.0704	0.0828	0.0938	0.1029	0.1093	0.1126
R [%]	26.98	26.16	25.23	23.96	22.19	20.08	18.00	16.26	15.03	14.40
Scenario S3: 5 FTMDs										
x_i^{max} [m]	0.0150	0.0298	0.0440	0.0576	0.0705	0.0828	0.0937	0.1027	0.1091	0.1124
R [%]	26.12	25.35	24.56	23.50	22.00	20.07	18.07	16.44	15.22	14.61

Tajimi spectrum, filter parameters). The results from the scenario S3, which considers five FTMDs, proved to be more effective than the scenarios S1 and S2, which consider only one and two FTMDs, respectively. In other words, it was observed that the reduction in the response increases, in terms of the maximum displacement of the structure, as the amount of FTMDs increases. In order to illustrate some of the obtained results, the time history in terms of the displacement of the last story of the structure is presented in Figures 3 to 6 for the scenario S3.

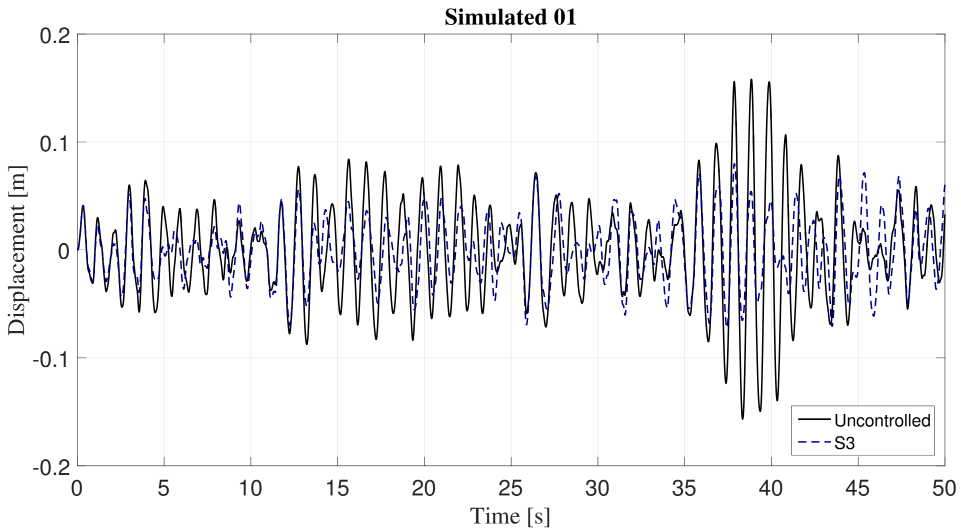

Figure 3. Last story displacements for the Simulated 01 record with scenario S3 parameters

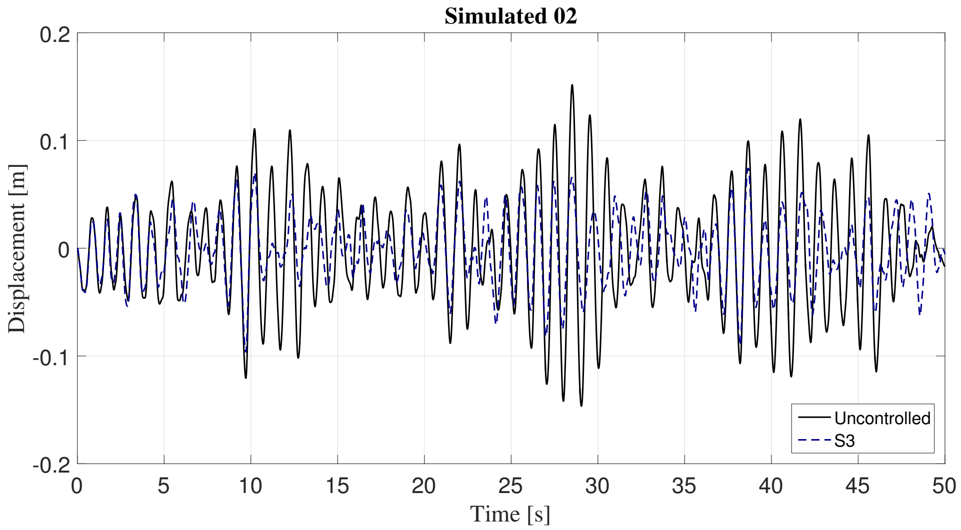

Figure 4. Last story displacements for the Simulated 02 record with scenario S3 parameters

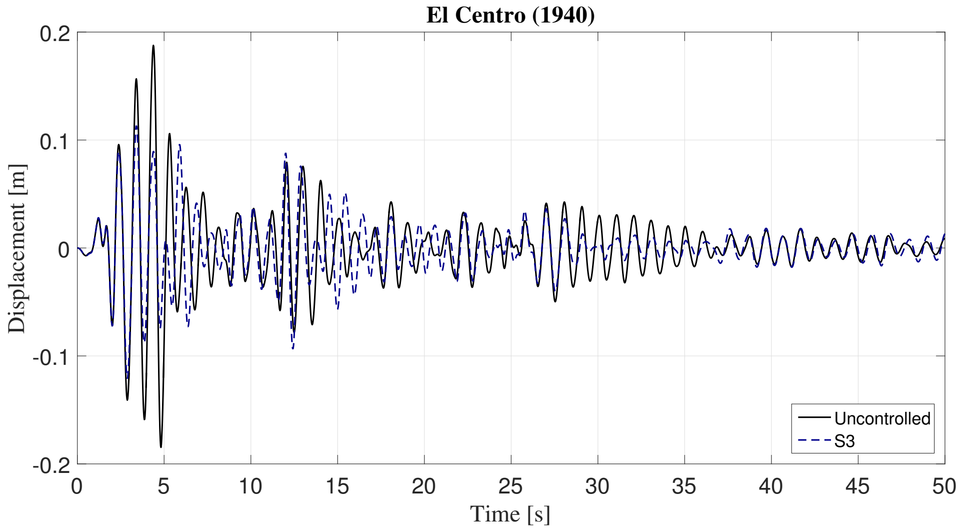

Figure 5. Last story displacements for the El Centro record with scenario S3 parameters

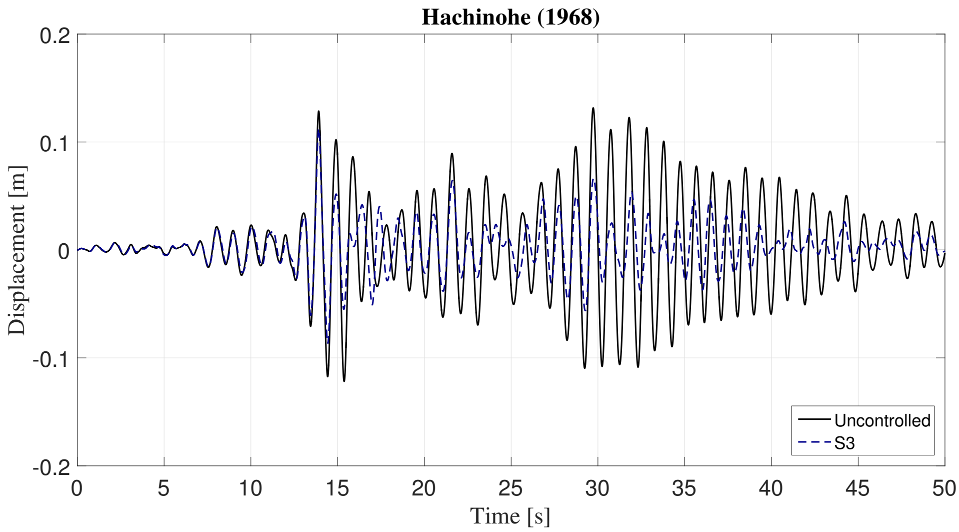

Figure 6. Last story displacements for the Hachinohe record with scenario S3 parameters

4. CONCLUSIONS

This paper presented an optimization scheme of multiple friction tuned mass dampers (MFTMDs) in structures subjected to seismic excitations. The number and positioning of the MFTMDs in the structure were previously determined. The structure response was obtained by means of nonlinear analysis in the time domain. Due to the nonconvex nature of the problem, the optimization was performed by a hybrid algorithm, which uses the FA and NMA sequentially. Although the procedure presented request a large computational effort, it proved to be a feasible alternative to provide the optimum MFTMDs parameters in structures subjected to seismic excitations. The use of MFTMDs was more effective in controlling the structure response than the use of only one FTMD. When this control system was submitted to seismic records with different frequency content and PGA from that used in the optimization scheme, it was also observed a reduction in the structure displacement, however lower than the observed for earthquakes with the same characteristics.

5. ACKNOWLEDGEMENTS

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REFERENCES

[1] Curadelli, R. O. and Amani, M. (2014). “Integrated structure-passive control design of linear structures under seismic excitations.” Engineering Structures, 81:256–264.

[2] Miguel, L. F. F., Fadel Miguel, L. F., and Lopez, R. H. (2014). “Robust design optimization of friction dampers for structural response control.” Structural Control and Health Monitoring, 21(9):1240–1251.

[3] Frahm, H. (1909). “Device for damping vibrations of bodies.” Patent US 989958 A.

[4] Ormondroyd, J. and Den Hartog, J. P. (1928). “The theory of the dynamic vibration absorber.” Transactions of the ASME, 50(7):9–22.

[5] Den Hartog, J. P. (1956). Mechanical Vibrations. McGraw-Hill, New York.

[6] Warburton, G. B. (1982). “Optimum absorber parameters for various combinations of response and excitation parameters.” Earthquake Engineering & Structural Dynamics, 10(3):381–401.

[7] Igusa, T. and Xu, K. (1994). "Vibration Control Using Multiple Tuned Mass Dampers." Journal of Sound and Vibration, 175(4):491–503.

[8] Yamaguchi, H. and Harnpornchai, N. (1993). "Fundamental characteristics of Multiple Tuned Mass Dampers for suppressing harmonically forced oscillations." Earthquake Engineering & Structural Dynamics, 22(1):51–62.

[9] Abe, M. and Fujino, Y. (1994). "Dynamic characterization of multiple tuned mass dampers and some design formulas." Earthquake Engineering & Structural Dynamics, 23(8):813–835.

[10] Joshi, A. S. and Jangid, R. S. (1997). "Optimum parameters of multiple tuned mass dampers for base-excited damped systems." Journal of Sound and Vibration, 202(5):657–667.

[11] Hadi, M. N. S. and Arfiadi, Y. (1998). "Optimum Design of Absorber for MDOF Structures." Journal of Structural Engineering, 124(11):1272–1280.

[12] Chen, G. and Wu, J. (2001). "Optimal Placement of Multiple Tune Mass Dampers for Seismic Structures." Journal of Structural Engineering, 127(9):1054–1062.

[13] Hoang, N. and Warnitchai, P. (2005). "Design of multiple tuned mass dampers by using a numerical optimizer." Earthquake Engineering & Structural Dynamics, 34(2):125–144.

[14] Lee, C. L., Chen, Y.-T., Chung, L.-L., and Wang, Y.-P. (2006). "Optimal design theories and applications of tuned mass dampers." Engineering Structures, 28(1):43–53.

[15] Leung, A. Y. T. and Zhang, H. (2009). "Particle swarm optimization of tuned mass dampers." Engineering Structures, 31(3):715–728.

[16] Lin, C.-C., Wang, J.-F., Lien, C.-H., Chiang, H.-W., and Lin, C.-S. (2010). "Optimum design and experimental study of multiple tuned mass dampers with limited stroke." Earthquake Engineering & Structural Dynamics, 39(14):1631–1651.

[17] Marano, G. C., Greco, R., and Sgobba, S. (2010). "A comparison between different robust optimum design approaches: Application to tuned mass dampers." Probabilistic Engineering Mechanics, 25(1):108–118.

[18] Arfiadi, Y. and Hadi, M. N. S. (2011). "Optimum placement and properties of tuned mass dampers using hybrid genetic algorithms." International Journal of Optimization in Civil Engineering, 1:167–187.

[19] Mohebbi, M., Shakeri, K., Ghanbarpour, Y., and Majzoub, H. (2013). "Designing optimal multiple tuned mass dampers using genetic algorithms (GAs) for mitigating the seismic response of structures." Journal of Vibration and Control, 19(4):605–625.

[20] Fadel Miguel, L. F., Lopez, R. H., Miguel, L. F. F., and Torii, A. J. (2016). "A novel approach to the optimum design of MTMDs under seismic excitations." Structural Control and Health Monitoring.

[21] Rudinger, F. (2007). "Tuned mass damper with nonlinear viscous damping." Journal of Sound and Vibration, 300(3-5):932–948.

[22] Chung, L. L., Wu, L.-Y., Huang, H.-H., Chang, C.-H., and Lien, K.-H. (2010). "Optimal design theories of tuned mass dampers with nonlinear viscous damping." Earthquake Engineering and Engineering Vibration, 8(4):547–560.

[23] Chung, L. L., Wu, L.-Y., Yang, C.-S. W., Lien, K.-H., Lin, M.-C., and Huang, H.-H. (2013). “Optimal design formulas for viscous tuned mass dampers in wind-excited structures.” Structural Control and Health Monitoring, 20(3):320–336.

[24] Giuliano, F. (2013). “Note on the paper "Optimum parameters of tuned liquid column gas damper for mitigation of seismic-induced vibrations of offshore jacket platforms" by Seyed Amin Mousavi, Khosrow Bargi, and Seyed Mehdi Zahrai.” Structural Control and Health Monitoring, 20(5):852.

[25] Gewei, Z. and Basu, B. (2010). “A study on friction-tuned mass damper: harmonic solution and statistical linearization.” Journal of Vibration and Control, 17(5):721–731.

[26] Inaudi, J. A. and Kelly, J. M. (1995). “Optimum absorber parameters for minimizing vibration response.” Journal of Engineering Mechanics, 121(1):142–149.

[27] Ricciardelli, F. and Vickery, B. J. (1999). “Tuned vibration absorbers with dry friction damping.” Earthquake Engineering & Structural Dynamics, 28(7):707–723.

[28] Hartung, A., Schmieg, H., and Vielsack, P. (2001). “Passive vibration absorber with dry friction.” Archive of Applied Mechanics, 71(6):463–472.

[29] Lee, S., Woo, S., Cho, S., and Chung, L. (2008). “Computation of Optimal Friction of Tuned Mass Damper for Controlling Base-Excited Structures.” International Conference on Computational & Experimental Engineering and Sciences, 8(3):115–120.

[30] Barbosa, A. R. and Ramadhan, G. (2014). “Seismic Performance of a Tall Diagrid Steel Building with Tuned Mass Dampers.” International Journal of Innovations in Materials Science and Engineering, 1(2):90–102.

[31] C. Lin, C., L. Lin, G., and Lung, H. Y. (2014). “Dynamic test of multiple tuned mass dampers for vibration control of high-rise buildings.” Tenth U.S. National Conference on Earthquake Engineering, Anchorage.

[32] Pisal, A. Y. and Jangid, R. S. (2014). “Seismic response of multi-story structure with multiple tuned mass friction dampers.” International Journal of Advanced Structural Engineering, 6(1):1–13.

[33] Mostaghel, N. and Davis, T. (1997). “Representations of coulomb friction for dynamic analysis.” Earthquake Engineering & Structural Dynamics, 26(5):541–548.

[34] Curadelli, R. O., Miguel, L. F. F., and Riera, J. D. (2003). “Consideraciones sobre el uso de amortiguadores en el proyecto de estructuras sismorresistentes.” XI SIBIS: Décimo Primer Seminario Iberoamericano de Ingeniería Sísmica, Facultad de Ingeniería, Universidad Nacional de Cuyo, Argentina.

[35] Li, H., Li, J., and Song, G. (2007). “Improved suboptimal Bang–Bang control of aseismic buildings with variable friction dampers.” Acta Mechanica Sinica, 23(1):101–109.

[36] Newmark, N. M. (1959). “A Method of Computation for Structural Dynamics.” Journal of the Engineering Mechanics Division, 85(3):67–94.

[37] Kanai, K. (1961). “An empirical formula for the spectrum of strong earthquake motions.” Bulletin of the Earthquake Research Institute, University of Tokyo, 39:85–95.

[38] Tajimi, H. (1960). “A statistical method of determining the maximum response of a building structure during an earthquake.” Proceedings of 2nd World Conference in Earthquake Engineering, Tokyo, pages 781–797.

[39] Yang, X.-S. (2009). “Firefly algorithms for multimodal optimization.” Stochastic algorithms: foundations and application, SAGA. Lecture notes in computer sciences, 5792:169–178.

[40] Nelder, J. A. and Mead, R. (1965). “A simplex method for function minimization.” The Computer Journal, 7(4):308–313.

[41] Haftka, R. T. and Gürdal, Z. (1992). Elements of structural optimization. Kluwer Academic Publishers, Dordrecht, 3rd edition.

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OPTIMUM DESIGN OF MULTIPLE FRICTION TUNED MASS DAMPERS UNDER SEISMIC EXCITATIONS

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Abstract: External passive energy dissipation systems have been widely used in order to reduce vibrations in structures subjected to seismic excitations. Within this context, the performance of passive tuned mass dampers in vibration mitigation due to earthquakes is the study object of many researchers. This paper presents a study on global optimization of multiple friction tuned mass dampers (MFTMDs) to control vibrations in structures subjected to seismic excitations. Computational codes for calculating the dynamic response of structures with MFTMDs are elaborated considering nonlinear analysis in the time domain. For the optimization scheme, because of the nonconvex nature of the problem, a hybrid algorithm composed of the algorithms Firefly (FA) and Nelder-Mead (NMA) is applied. The seismic excitations are treated as a stationary stochastic process. Real seismic records are also considered. A numerical example on a ten story shear building with one, two and five dampers is demonstrated. The quantity and positioning of the MFTMDs in the structure are previously fixed. Results show that the use of multiple dampers is more efficient than the use of only one and the proposed approach demonstrates to be a suitable alternative to furnish the optimum MFTMDs parameters in structures subjected to seismic excitations.

Keywords: seismic excitations, optimization, MFTMDs, nonlinear analysis.