XXXVII IBERIAN LATIN AMERICAN CONGRESS
ON COMPUTATIONAL METHODS IN ENGINEERING
BRASÍLIA - DF - BRAZIL

OPTIMAL LOCATION OF OPTIMIZED FRICTION DAMPERS IN CIVIL STRUCTURES FOR THE SEISMIC PASSIVE CONTROL

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Abstract. *This paper presents a methodology to improve installation of friction dampers in civil structures. The proposed methodology involves a metaheuristic optimization technique called Firefly Algorithm linked with a computational routine based in the Finite Differences Method to carry out the simultaneous optimization of the friction forces and positions of friction dampers. The proposed method is illustrated in a ten-story shear building, that is, the method finds the best stories to locate the dampers with optimal mechanical parameters. The objective function used in this study is to minimize the maximum inter-story drift of the ten-story shear building, which is located in Cúcuta, Colombia. For this purpose, the authors used the NSR-10 (Colombian Seismic Code).*

Keywords: *Optimization, seismic passive control, friction dampers.*

1 INTRODUCTION

In order to avoid structural damage due to natural hazards like earthquakes, the structural engineering has presented several advances in seismic energy dissipation control devices. These devices could be active or passives and their implementation depend on the project investment. The active devices change their properties in function of the structural response, for this reason, they are the most expensive. On the other hand, the passive devices are cheaper than active devices, presenting a low cost for installation and maintenance.

Because of their characteristics, passive devices stand out between energy dissipation devices. Due to this, recently several researchers have worked in dampers optimization methodologies. In the literature is possible to find several papers about optimization of Tuned Mass Dampers, as, for instance (Sgobba et al., 2010; Rakicevic et al. 2012; Mohebbi et al. 2013; Miguel et al. 2013), and another sort of devices like MR dampers (Amini et al., 2012). On the other hand, few papers about the optimization of friction dampers are found in the literature (Miguel et al., 2014). Some researches (Fang et al., 2012; Takewaki et al., 2013) have worked on optimization of viscous or viscoelastic dampers, using objective functions such as inter story drift, throughout the optimal location of these devices.

The metaheuristic algorithms are able to deal with dampers optimization problems and some of the salient characteristics of these sort of algorithms are: (a) they do not require gradient information; (b) if they are correctly tuned, they do not become trapped in local minima; (c) it is possible to apply in problems with discontinuous functions; (d) they provide a set of optimal solutions rather than a single one, giving to the designer a range of options to choose; (e) it is possible to use to solve mixed-variable optimization problem (Miguel et al., 2013).

Finally, it is important to mention that the optimization of friction dampers is a relatively unexplored subject in the world, and this paper proposes a methodology for optimization of this kind of passive energy dissipation device.

2 OPTIMIZATION PROBLEM

Concerning civil structures located in regions with high seismic activity, engineers are usually able to suggest a suitable set of solutions to avoid structural damage. In order to avoid classical approaches based on trial and error, optimization techniques applied to energy dissipation devices have been become into an important tool for the design engineers, avoiding high costs in the project. In this way, it is possible obtain optimal device parameters. For the friction damper location problem, calculation of the structure response for every possible arrangement of friction dampers mechanical parameters take out to be a very time consuming procedure because each case requires a dynamical analysis of the structure subjected to an external force such as earthquake.

The optimization problem consist in an objective function to be minimize, a search space defined over a set of discrete design variable and continuous design variables. Appropriate locations for a limited number of friction dampers in a civil structure can be represented by discrete variables and appropriate mechanical parameters for each optimal located damper is best represented by continuous variable.

In the last years, some researches such as Mousavi et al. (2012) have been optimizing the location of viscoelastic dampers using Genetic Algorithms (G.A.) for reducing the structure dynamic response in terms of displacement. In this research, with the aim to carry out the simultaneous optimization, this is, obtain the optimal location and optimal mechanical parameters (friction forces), at same time, of three friction dampers, the optimization technique has been improved through linking the computational routine developed in *MATLAB* with the *Firefly Algorithm*. The objective function of the simultaneous optimization of friction dampers proposed in this paper is to reduce the maximum inter-story drift. Additionally the complexity of the optimization problem, a criterion to choose the Firefly Algorithm, developed by Yang (2008), was because its capability to perform optimization problems with mix-design variables, that is, continuous variables and discrete variables at same time.

Calculating inter-story drift for each arrangement of friction dampers requires a dynamic analysis of the structure during an earthquake. This is possible solving the motion equation (Eq. 1) using the routine developed based in the *Finite Difference Method.*

$$\mathbf{M}\ddot{x}(t) + \mathbf{C}\dot{x}(t) + \mathbf{K}x(t) + \mathbf{F_a}(t) = \mathbf{F_{ex}}(t). \tag{1}$$

Equation (1) represents the dynamic behavior of a multi-degree of freedom (MDOF) system with friction dampers and subjected to external force, in which **M** and **K** are the n x n size structural mass and stiffness matrices, respectively, and n is the number of degree of freedoms. **C** is the damping matrix proportional to **M** and **K** matrices. The n-dimensional vector $x(t)$ represents the relative displacement with respect to the base and the differentiation with respect to the time is represented with a dot over the displacement vector symbol. The external force and the Coulomb friction force are represented by $\mathbf{F_{ex}}(t)$ and $\mathbf{F_a}(t)$, respectively.

Coulomb friction force is representing by Eq. 2 in which μ is the friction coefficient (assumed as constant), ***N*** is the normal force vector, *sgn()* is the signal function and *v(t)* is the relative velocity vector between the ends of the damper.

$$\mathbf{F_a} = \mu\mathbf{N}sgn(v(t)) \tag{2}$$

It is important to highlight that the magnitude of the friction force is constant but its direction is always opposite to the sliding velocity. The changes in the direction of the velocity cause discontinuities in the friction force, leading to difficulties to evaluate the response of a system with friction dampers. For this reason, it was implemented the continuous function $f_2(\alpha_2 v) = \tanh(\alpha_2 v)$ with $\alpha_2 = 1E9$, proposed by Mostaghel and Davis (1997) that represents the discontinuity of Coulomb friction force, where α_2 is the parameter that control the level of accuracy of the function representing the friction force. The continuous function f_2 was already used in previous studies, as Miguel and Riera (2008).

Before perform the friction dampers optimization, the numerical routine developed was validated using the commercial software *ANSYS*. The system in free vibration showed in the Fig. 1 is represented by Eq. (3). For its similarity to Eq. (1), the reader can take the explanation given above. Thus, the system response obtained by the proposed numerical routine is compared and validated using *ANSYS*. The properties of the three degree of freedom (3-DOF) system implemented to the numerical routine validation are presented in Table 1.

$$\mathbf{M}\ddot{x}(t) + \mathbf{C}\dot{x}(t) + \mathbf{K}x(t) + \mathbf{F_a}(t) = 0 \tag{3}$$

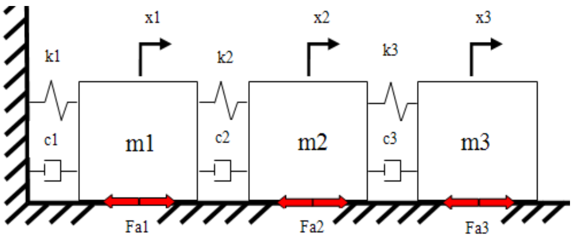


Figure 1. Three DOF system.

Table 1. Properties of the three DOF system

DOF (i)	Mass (mi) in [kg]	Stiffness (ki) in [N/m]	Viscous Damping (ci) in [Ns/m]	Friction Force (Fai) in [N]	Initial displacement (xi) in [m]	Initial Velocity in [m/s]
1	103017.33	4.04x108	6.4513x104	3x105	0.08	0
2	103017.33	4.04x108	6.4513x104	3x105	0.10	0
3	103017.33	4.04x108	6.4513x104	3x105	0.12	0

The response of the system obtained by the developed numerical routine was compared with the response obtained in the transient analysis from *ANSYS*. The comparison was done using all the response information from *ANSYS* and plotted with the numerical response using an integration interval of 2e-3 seconds in *MATLAB*. As can be seen in Fig. 2, there is overlapping between the numerical response and the *ANSYS* response, leading to the conclusion that the developed numerical routine is correct.

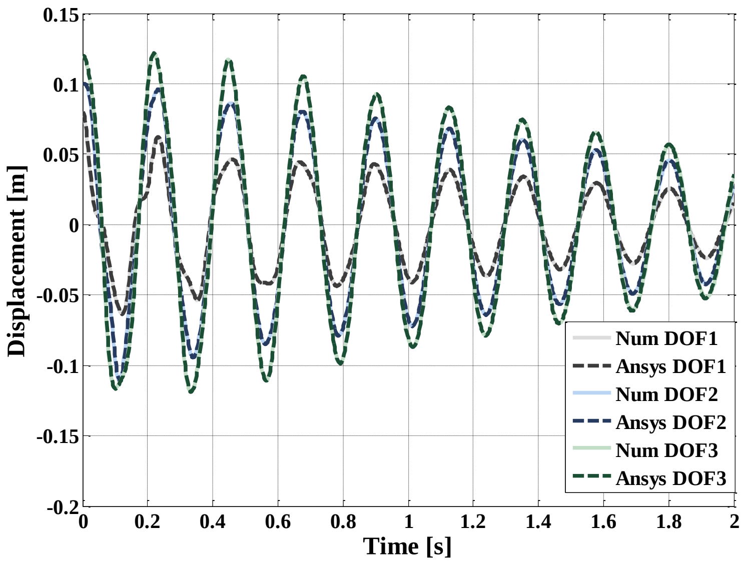


Figure 2. Comparison of response between ANSYS and the proposed numerical method

The *Firefly Algorithm* will evaluate the objective function, *i.e.*, the inter-story drift, after solving the equation of motion for each optimal arrangement of friction dampers through the routine developed. In each iteration, *n* objective functions are evaluated where *n* is the fireflies' population, in other words, each firefly will evaluate one objective function. *Firefly Algorithm* pseudo code is shown in Fig. 3.

```
Firefly Algorithm
Objective function f(x),     x = (x_1, ..., x_d)^T
Generate initial population of fireflies x_i (i = 1, 2, ..., n)
Light intensity I_i at x_i is determined by f(x_i)
Define light absorption coefficient γ
while (t <MaxGeneration)
for i = 1 : n all n fireflies
    for j = 1 : n all n fireflies (inner loop)
    if (I_i < I_j), Move firefly i towards j; end if
        Vary attractiveness with distance r via exp[-γr]
        Evaluate new solutions and update light intensity
    end for j
end for i
Rank the fireflies and find the current global best g_*
end while
Postprocess results and visualization
```

Figure 3. Firefly pseudocode.

For purposes to guarantee optimal response preventing the *Firefly Algorithm* converges to local optimum, the fireflies' population settled in one hundred fireflies and the iterations settled in one thousand. In every iteration, *Firefly Algorithm* will analyze one hundred objective functions, saving the best objective in each iteration and comparing it with the above until accomplish number of iterations. In terms of compute time, convergence criteria by iterations number present a moderated cost, around five hours using an Intel Core I7-4700MQ processor. In order to improve the optimization technique, the authors developed other convergence criteria using the mean and standard deviation of all the objective functions evaluated, iteration by iteration. Thus, the *Firefly Algorithm* may converge by either of the two convergence criteria. It is worth highlighting that the convergence criteria developed reduces the computational time, in the best case, up to a third of the time spent by the convergence criteria of number of iterations.

The location of friction dampers is a discrete design variable and the friction forces of each device is represented by a continuous number, this is, a continuous variable. On the other hand, the constraints of the optimization problem are the number of available positions for the friction dampers and the maximum number of dampers to be installed. In the ten-story shear building, the maximum number of positions is ten (one in each story) and the maximum number of friction dampers to be optimized, determining its position and its friction force simultaneously is three. For the discrete design variables (positions) the lower and upper boundaries highlight stories of the structure. For the continuous design variable (friction forces) the limits adopted are 100kN-1500kN.

In order to guarantee acceptable levels of acceleration in all stories, ten inequality constraints were implemented for accelerations, one for each story (Table 2).

Table 2. Acceleration constraints [m/s^2].

Story 1	Story 2	Story 3	Story 4	Story 5	Story 6	Story 7	Story 8	Story 9	Story 10
$\ddot{x}1<6.0$	$\ddot{x}2<6.0$	$\ddot{x}3<6.0$	$\ddot{x}4<6.0$	$\ddot{x}5<6.0$	$\ddot{x}6<6.0$	$\ddot{x}7<6.0$	$\ddot{x}8<6.0$	$\ddot{x}9<6.0$	$\ddot{x}10<6.0$

Thus, grouping the design variables (positions and friction forces) in vector $\vec{x}$, the optimization problem can be posed as shown in Eq. (4), in which the objective function $Z(\vec{x})$ is minimize the maximum value of the inter-story drift vector$(\overrightarrow{Drf})$, subjected to number of available positions, maximum number of dampers and acceleration for each story.

Find $\vec{x}$
Minimize $Z(\vec{x}) = Max(\overrightarrow{Drf})$ (4)
Subjected to n_p (number of available positions),
n_d (maximum number of dampers),
$g(\vec{x}) \leq \vec{\ddot{x}}_{min_j}$ $\quad j = 1,2, \ldots 10$ (acceleration constraints for each story)

3 NUMERICAL SIMULATION

This section presents a numerical example. A ten story shear building, 3.96m high on each floor and 6.10m wide is adopted in the numerical simulations. The structure is represented as lumped mass system as shown in Fig. 4, in which is shown diagonal disposition of the friction dampers and the arrows represent the degrees of freedom of each mass. The properties of the structure are given in Table 3. It is noteworthy that the damping ratio assumed for the first and second vibration mode is 0.5 percent (ζ=0.005). Table 4 shows the natural frequencies of the ten story shear building.

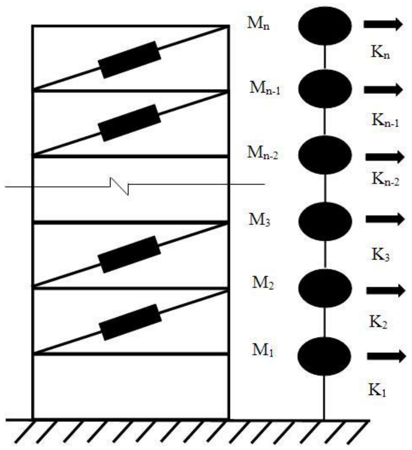


Figure 3. Schematic model of a shear building represented as lumped mass system.

Table 3. Mechanical properties of the ten-story shear building.

Story (i)	Mass (mi) in [kg]	Stiffness (ki) em [N/m]
1-4	60000	3.0×10^7
5-7	50000	2.4×10^7
8-10	40000	2.1×10^7

Table 4. Frequencies (Hz) of the ten-story shear building.

f 1	f 2	f 3	f 4	f 5	f 6	f 7	f 8	f 9	f 10
0.585	1.562	2.549	3.557	4.402	5.187	5.796	6.387	6.790	6.925

As dynamic load, a one-dimensional artificial earthquake was implemented in which the acceleration $\vec{A}(t)$ are zero-mean normal random processes simulated by superposition of harmonic waves, as showed by Shinozuka and Jan (1972).

$$\vec{A} = \sum_{j=1}^{N} \sqrt{2S_{\omega}(f_j)\Delta f_j}\cos(2\pi f_j t + \phi_j) \quad (5)$$

In this method, the frequency band of interest must be divided into N intervals, such that $\Delta f_j = f_{j+1} + f_j$ and ϕ_j is the phase angle, which is a random variable with a uniform probability distribution function between 0 and 2π. The power spectral density function S_ω (Eq. 6 and Fig. 5) used in this paper is the proposed by Kanai (1961) and Tajimi (1961) known as the Kanai-Tajimi filter technique.

$$S_\omega = S_0\left[\frac{\omega_g^4 + 4\omega_g^2\xi_g^2\omega^2}{(\omega^2 - \omega_g^2)^2 + 4\omega_g^2\xi_g^2\omega^2}\right], \qquad S_0 = \frac{0.03\xi_g}{\pi\omega_g(4\xi_g^2+1)} \quad (6)$$

In which, S_0 is a constant spectral density, ξ_g is the ground damping, assumed equal to 0.3, and ω_g is the ground frequency, assumed equal to 20rad/s.

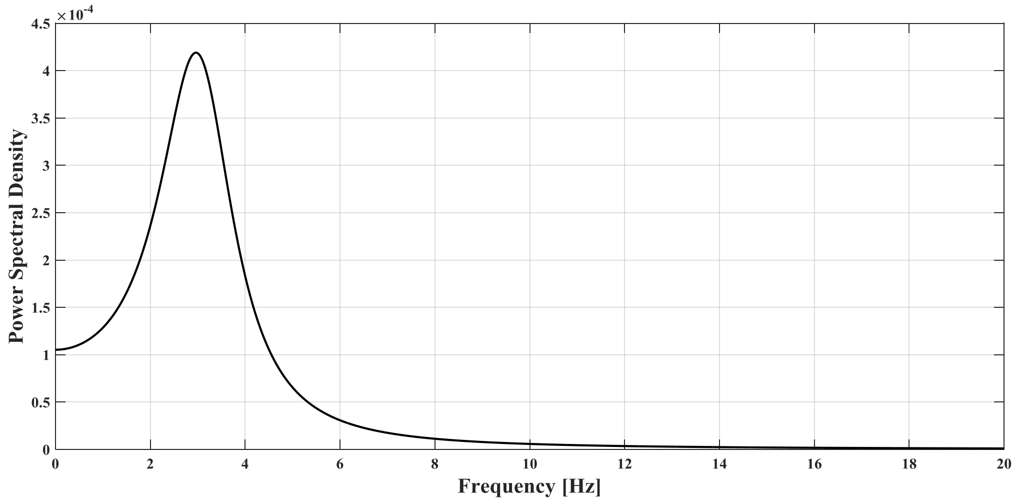


Figure 5. Power Spectral Density Function S_ω of Kanai Tajimi.

In order to simulate common earthquakes that have taken place in Cucuta, Colombia, the authors have used horizontal peak ground acceleration (PGA) equal to 0.3g of intermediate vibration periods from the mentioned region. ξ_g is equal to 0.3 and ω_g is equal to 20rad/s. Thus, the time history of the Kanai-Tajimi excitation, with PGA equal to 0.3g, used for the friction damper's optimization, is shown in Fig. 6.

4 ANALYZING RESULTS

This section presents the numerical results obtained with the proposed methodology. After three simulations, the optimization algorithm has converged in the same optimal positions for the three friction dampers with similar friction forces for each one when the ten-story structure is subjected to the artificial earthquake presented in Fig.6. Furthermore, in each simulation has obtained similar best objectives as shown in Table 5.

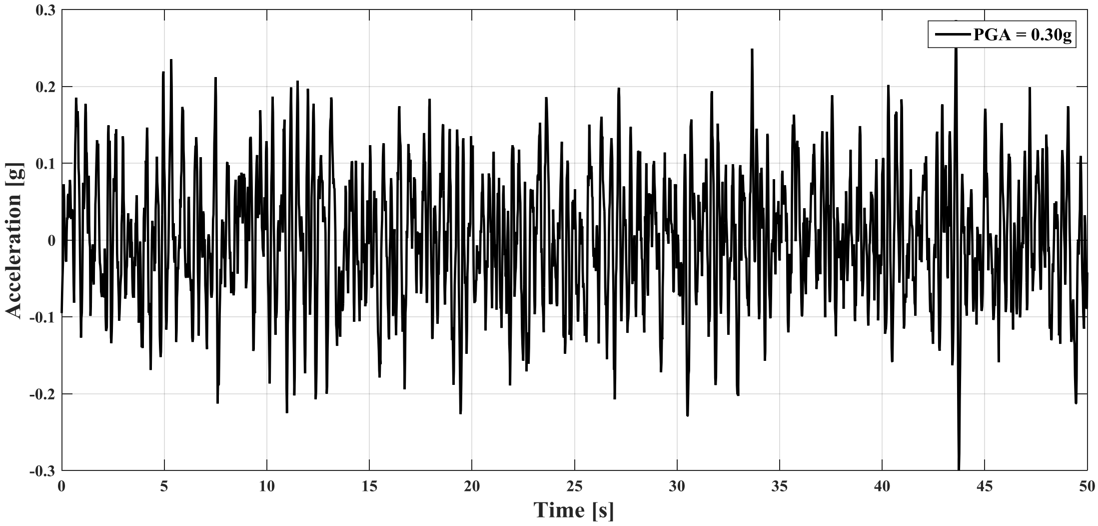


Figure 6. Time history of the Kanai-Tajimi excitation.

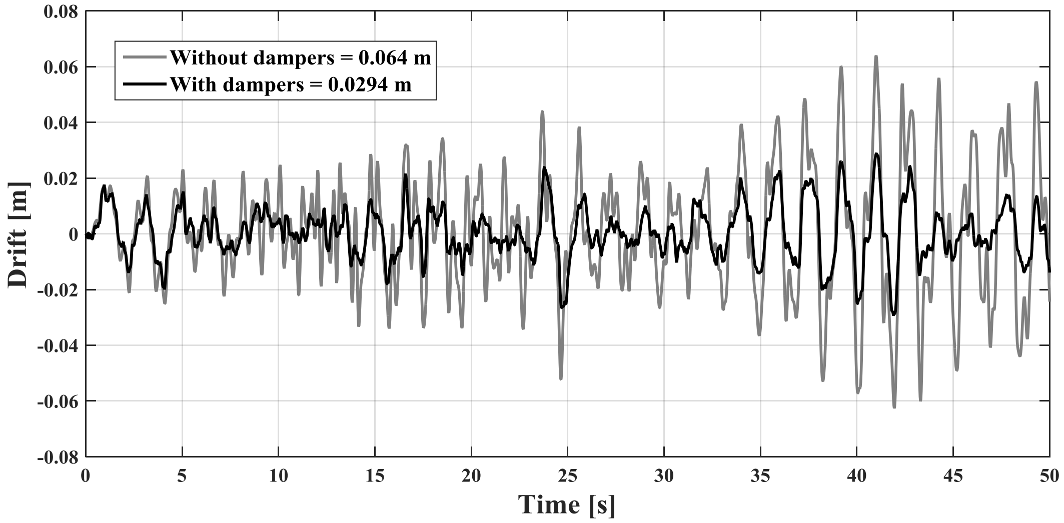
Table 5. Results of the three simulations.

Simulation 1		Simulation 2		Simulation 3	
Number of iterations = 426		Number of iterations = 673		Number of iterations = 385	
Best objective = 0.0299 [m]		Best objective = 0.0294 [m]		Best objective = 0.0297 [m]	
Stories for the optimal location	Optimal friction forces [N]	Stories for the optimal location	Optimal friction forces [N]	Stories for the optimal location	Optimal friction forces [N]
1	104560	1	88974	1	96900
2	41306	2	58997	2	51617
3	80517	3	71739	3	66835

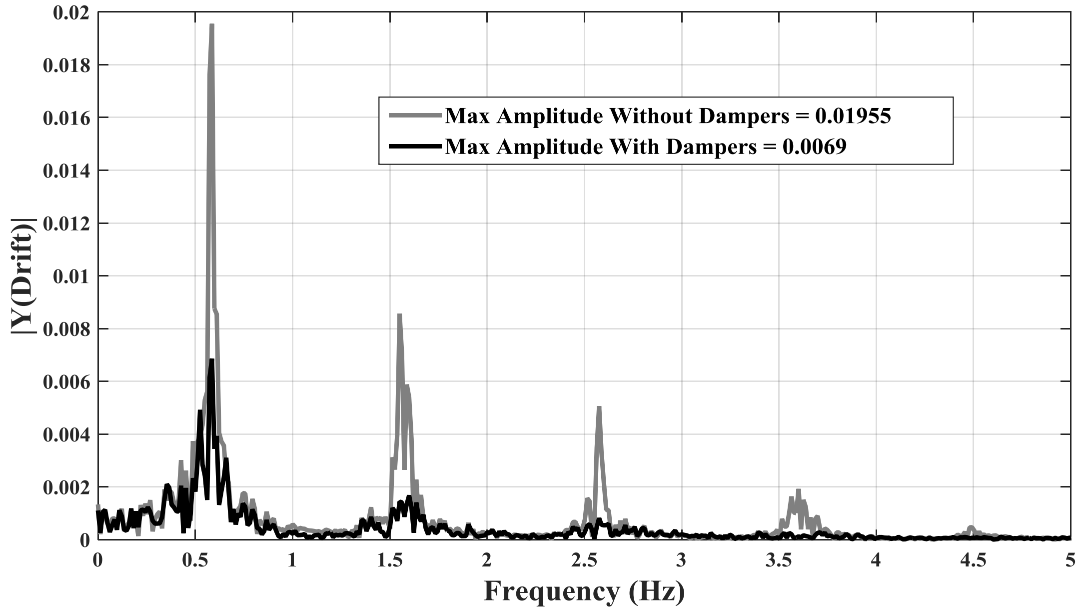
As was mentioned before, a new convergence criteria was performed, in this way, the Firefly Algorithm has two convergence criteria. Concerning to the results shown in Table 5, for three simulations the optimization algorithm converges with a number of iterations smaller than the programmed number for convergence criteria by iterations (1000 iterations), so, the computation time is reduced.

Is noteworthy that in three simulations, inter-story drift is less than one percent of the height of the story, respecting the limit imposed by the Seismic Code of Colombia, NSR 10. In the case of study, the structure has a height of 3.96 m for each story, thus, according to the limit imposed by the referred code, the inter-story drift must to be less than 0.0396 m.

The optimization results concerned with second simulation are given in the following. The goal is to reduce the maximum inter-story drift to accomplish the Colombian Seismic Code NSR 10 and with that, is possible to reduce several dynamic variables like the displacement and acceleration in each story, as shown in Figs 7 a) to 9 a). The responses on the frequency domain are shown in Figs. 7 b) to Fig. 9 b) and are possible to appreciate the reduction on the amplitude. It is also interesting to note that the greatest peaks are presented in the value of first natural frequency of the structure.

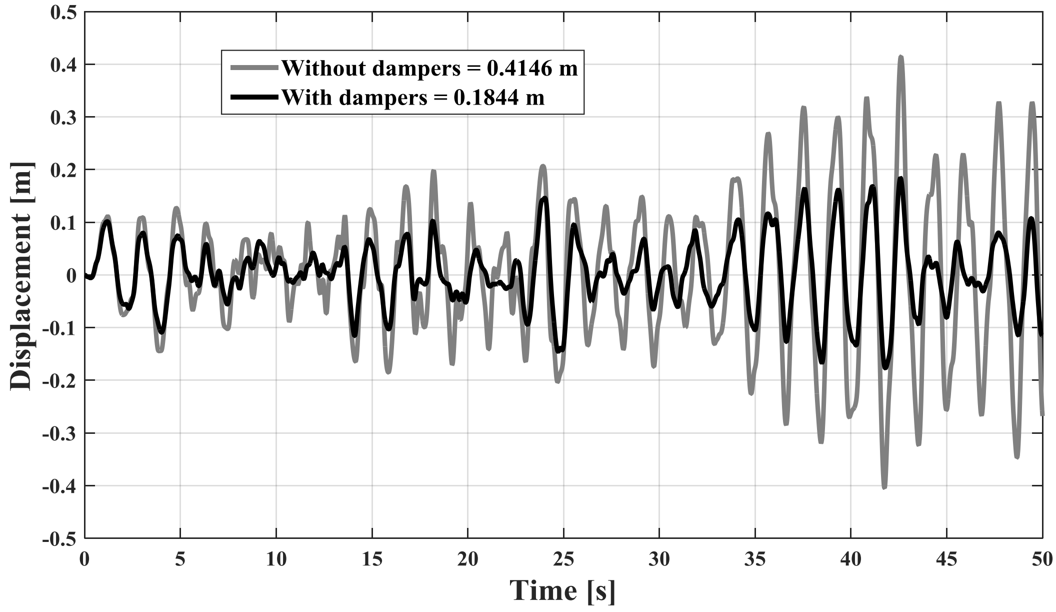


a)

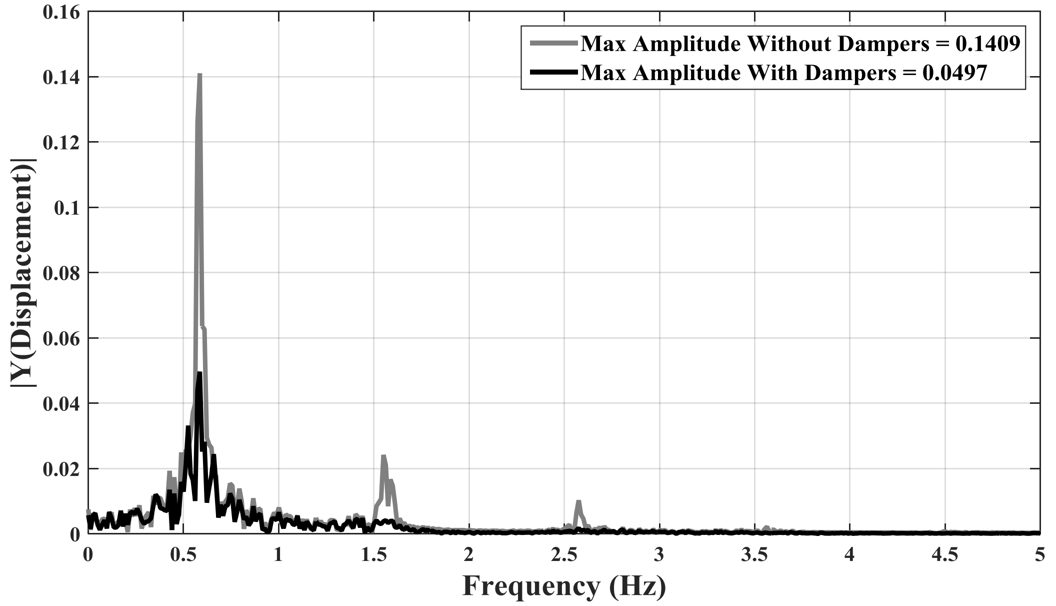


b)

Figure 7 a) Inter-story drift for first story on the time domain. b) Inter-story drift for first story on the frequency domain.

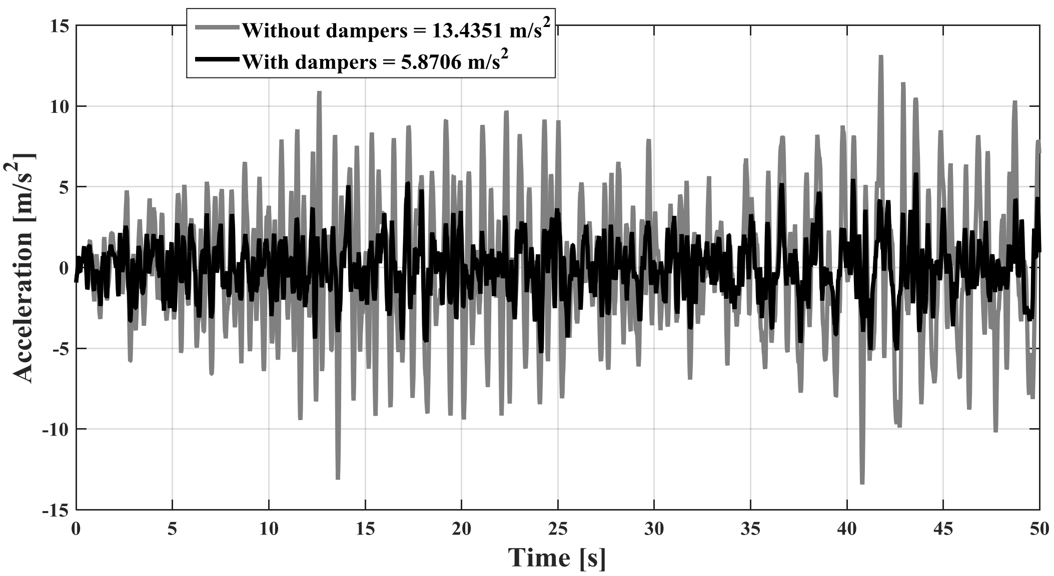


a)

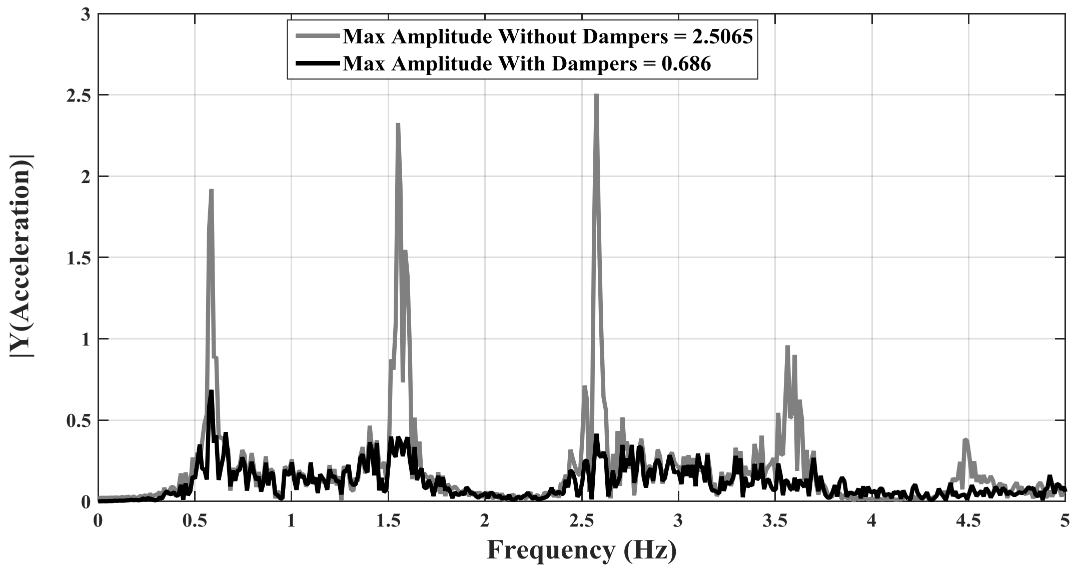


b)

Figure 8. a) Displacement for tenth story on the time domain. b) Displacement for tenth story on the frequency domain.



a)



b)

Figure 9. a) Acceleration for tenth story on the time domain. b) Acceleration for tenth story on the frequency domain.

Table 6 shows the behavior of each response (drift, displacement and acceleration) for each story when the three dampers are located in its optimal places with optimal forces and how decrease each response in terms of percentage.

Table 6. Comparison of the structure responses with and without friction dampers.

Story	Max. Drift [m]			Max. Displacement [m]			Max. Acceleration [m/s2]		
	Wh./D (1)	W./D (2)	%R (3)	Wh./D (1)	W./D (2)	%R (3)	Wh./D (1)	W./D (2)	%R (3)
1	0.064	0.0294	54.07	0.064	0.0294	54.07	7.404	4.777	35.47
2	0.059	0.0289	51.34	0.122	0.0577	52.56	9.330	5.858	37.21
3	0.054	0.0264	51.25	0.173	0.0832	52.02	8.787	5.166	41.20
4	0.048	0.0242	49.22	0.216	0.1058	50.99	10.174	4.682	53.97
5	0.063	0.0268	57.14	0.254	0.1303	48.63	9.580	4.888	48.96
6	0.065	0.0249	61.47	0.280	0.1488	47.21	8.348	4.935	40.88
7	0.061	0.0232	61.97	0.308	0.1595	48.19	10.916	4.913	54.99
8	0.055	0.0231	57.93	0.360	0.1670	53.67	10.042	4.598	54.20
9	0.040	0.0181	54.82	0.397	0.1751	55.90	11.331	4.903	56.72
10	0.026	0.0120	52.94	0.414	0.1844	55.51	13.435	5.870	56.30

(1)Without Dampers, (2)With Dampers, (3)Reduction in terms of percentage.

5 CONCLUSIONS

Concerning the results, it is possible to appreciate that the proposed optimization technique is efficient, reducing the response in terms of inter-story drift in more than 50%, with only three friction dampers, becoming below the limit imposed by the Seismic Code of Colombia, NSR 10. The response in terms of displacement decreases over 50% and the response in terms of acceleration is reduced over 55%, respecting all acceleration constraints.

Additionally, the technique developed in this research has demonstrated its robustness because after three simulations and a few iterations, the objective function has gotten similar values in all simulations and the optimal places for the friction dampers did not change.

Acknowledgements

The authors acknowledge the financial support of CNPq and CAPES

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