SIMULTANEOUS OPTIMIZATION OF PASSIVE DAMPERS FOR THE SEISMIC CONTROL IN STRUCTURES

Sergio Pastor Ontiveros Pérez
Letícia Fleck Fadel Miguel
Department of Mechanical Engineering, Federal University of Rio Grande do Sul, Rua Sarmento Leite, 425, Porto Alegre, Brazil
sergio.ontiveros@ufrgs.br
letffm@ufrgs.br

Leandro Fleck Fadel Miguel
Department of Civil Engineering, Federal University of Santa Catarina, Florianópolis, Brazil.
leandro.miguel@ufsc.br

Abstract. *The damper's optimization is a new area which has been investigated in recent years. There are various methods employed in optimization, among which are highlighted the classic and the most recent that are playing in reliability, rapidly and efficient for optimum result. This work demonstrates the simultaneous optimization of friction dampers using the Firefly Algorithm, which is a recent meta-heuristic algorithm inspired by the behavior of the fireflies. The friction dampers, despite showing a more complex mathematical formulation than others types, as viscous dampers, for example, stands out among the passive devices due to their low cost of construction, maintenance and good performance in vibration control.*
The optimization has as main objective to decrease the response in terms of displacement at the top of the analyzed structure, which is obtained through an algorithm performed in MATLAB based on the Central Finite Difference method, optimizing the position and the damping forces of a maximum number of friction dampers.
The results showed that the response in terms of the displacement decrease significantly, over 80%, concluding that the developed method is efficient to obtain the optimum positions and friction forces of the dampers.

Keywords: *Simultaneous optimization, friction dampers, passive control, Firefly Algorithm.*

1. INTRODUCTION

The dynamic loads such as earthquakes can produce structural damage in buildings. For this reason, there are methods to avoid the damage in the structure. These methods have been developed in the last years and consist in the energy dissipation using damper devices. By the way, these devices can be active or passive. The active device changes its properties in function of the structure response and the passive device does not, for these reason, the passive devices are cheaper than the actives, presenting a low cost in the installation and maintenance.

Recently, several researches have been working in damper's optimization methodologies, like the optimization of the location of the dampers in the structures and its parameters. It is possible to find many papers about the optimization of Tuned Mass Dampers, as, for instance, Rakicevic *et al.*, 2012; Mohebbi *et al.*, 2013; Miguel *et al.*, 2013a. On the other hand, few papers about the optimization of friction dampers are found in the literature (e.g., Miguel *et al.*, 2014).

The optimization of energy dissipation systems is an area that has been subjected to changes in the last years. Some researches as Fang *et al.* (2012) and 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 this kind of optimization problem. Some of the salient characteristics of these kinds of algorithms are: (a) they do not require gradient information; (b) if the metaheuristic algorithm is correctly tuned, it does 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.*, 2013b). Thus, note that the optimization of friction dampers is a relatively unexplored subject in the world, and this paper proposes a method for optimization of this kind of passive energy dissipation device.

2. PROBLEM FORMULATION

2.1 The motion equation

The Equation (1) represents the dynamic behavior of a multi-degree of freedom (MDOF) system with friction dampers and subjected to external force, where $\boldsymbol{M}$ and $\boldsymbol{K}$ are the n x n size structural mass and stiffness matrices, respectively, and n is the number of degree of freedoms. $\boldsymbol{C}$ is the damping matrix proportional to $\boldsymbol{M}$ and $\boldsymbol{K}$ matrices. The n-dimensional vector $\boldsymbol{x}$ 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 the n-dimensional vector $\boldsymbol{F_{ex}}$ and $\boldsymbol{F_a}$, respectively.

$$\boldsymbol{M}\ddot{\boldsymbol{x}}(t) + \boldsymbol{C}\dot{\boldsymbol{x}}(t) + \boldsymbol{K}\boldsymbol{x}(t) + \boldsymbol{F}_a = \boldsymbol{F}_{ex} \quad (1)$$

The Equation (2) represents the Coulomb friction force, where μ is the friction coefficient (assumed as constant), $\boldsymbol{N}$ is the normal force vector, *sgn()* is the signal function and $\boldsymbol{v(t)}$ is the relative velocity vector between the ends of the damper.

$$\boldsymbol{F}_a = \mu \boldsymbol{N} sgn(\boldsymbol{v}(t)) \quad (2)$$

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 α_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 *et al.* (2014) and Miguel and Riera (2008). A computational routine based on the finite differences method was developed in MATLAB to solve the Equation 1, determining the dynamic response in terms of displacement of a system with friction dampers.

2.2 Validation of the developed program

The Equation (3) represents the system of Fig. 1, which is in free vibration. For its similarity to Eq. (1), the reader can take the explanation given in Section 2.1. Thus, the system response obtained by the proposed numerical method is compared and validated using ANSYS. The properties of the 3 DOF system implemented to the numerical method validation are presented in the Tab. 1.

$$\boldsymbol{M}\ddot{\boldsymbol{x}}(t) + \boldsymbol{C}\dot{\boldsymbol{x}}(t) + \boldsymbol{K}\boldsymbol{x}(t) + \boldsymbol{F}_a = 0 \quad (3)$$

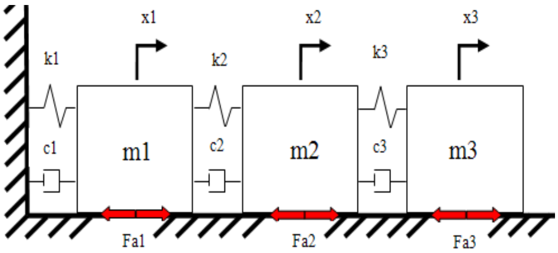

Figure 1. Three DOF system in free vibration with friction damping.

Table 1. Properties of the three DOF system.

Degree of Freedom (i)	Mass (m_i) in kg	Stiffness (k_i) in N/m	Viscous Damping (c_i) in Ns/m	Friction Force(Fa_i) in N	Initial displacement (x_i) in m	Initial Velocity in (m/s)
1	103017.33	4.04e8	6.4513e4	3e5	0.08	0
2	103017.33	4.04e8	6.4513e4	3e5	0.10	0
3	103017.33	4.04e8	6.4513e4	3e5	0.12	0

The response of the system obtained by the developed numerical program 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 program is correct.

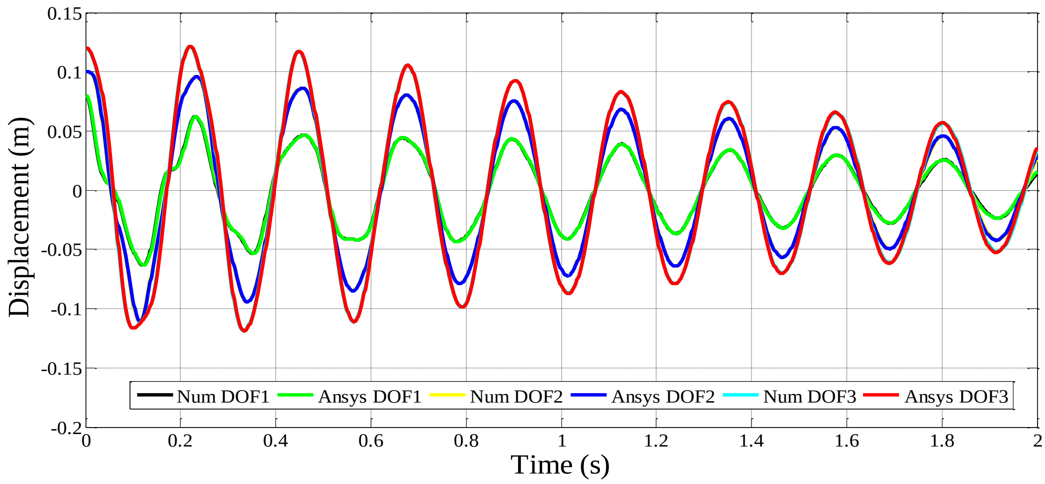

Figure 2. Comparison of response between ANSYS and the proposed numerical method.

2.3 Analyzed structure

A ten story shear building, 3.96m high on each floor and 9.15m wide have been simulated. The structure is represented as lumped mass system as shown in Fig. 3, in which the arrows represent the degrees of freedom of each mass and the properties of the structure is represented in Tab. 2. It is noteworthy that in this research, the damping ratio considered for the first vibration mode and second vibration mode is 0.5 percent.

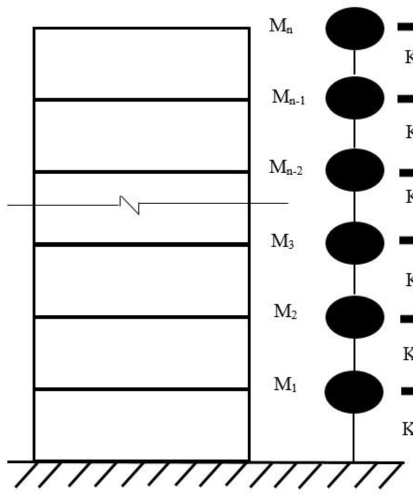

Figure 3. n degree of freedom (DOF) structure represented as lumped mass system.

Table 2. Ten-story mass lumped structure properties.

Story (i)	Mass (m_i) in kg	Stiffness (k_i) em N/m
1-10	360E3	650E6

In order to illustrate the proposed optimization procedure, one dimensional earthquake loading has been simulated and the acceleration component ***A(t)*** are zero mean normal random process simulated in this study by superposition of harmonic waves, as described by Shinozuka and Jan (1972). Equation (4) represents the Spectral Representation Method.

$$\boldsymbol{A}(\boldsymbol{t}) = \sum_{i=1}^{n} \sqrt{2\boldsymbol{S}_{\omega}(f_j)\Delta f_j}\, cos(2\pi f_j t + \phi_j) \tag{4}$$

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 2 π In the other hand, the power spectral density function $\boldsymbol{S_\omega}$ (Eq. (5) and Fig. 4) used in this paper is the proposed by Kanai (1961) and Tajimi (1961) known as the Kanai-Tajimi filter technique.

$$\boldsymbol{S_\omega} = S_0\left[\left(\omega_g^4 + 4\omega_g^2\xi_g^2\omega^2\right)/\left(\left(\omega^2 - \omega_g^2\right)^2 + 4\omega_g^2\xi_g^2\omega^2\right)\right] \tag{5}$$

$$S_0 = \left(0.03\xi_g\right)/\left(\pi\omega_g\left(4\xi_g^2 + 1\right)\right) \tag{6}$$

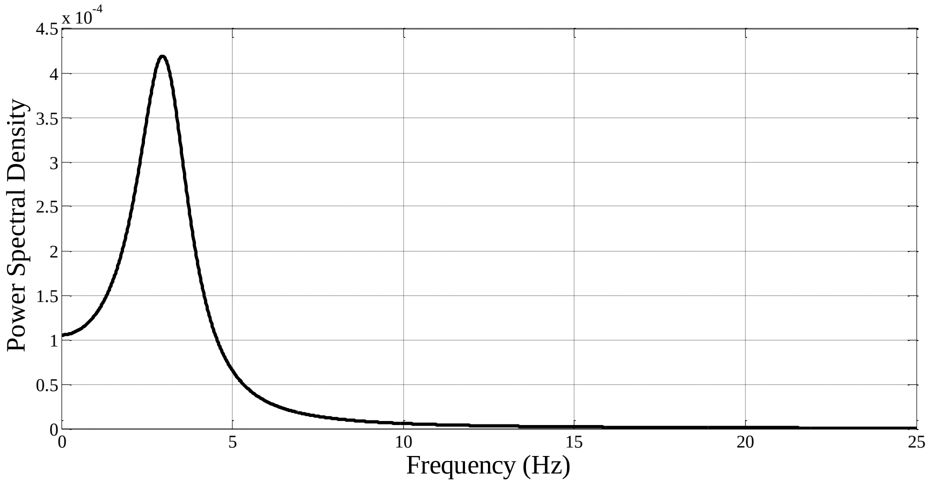

Figure 4. Power Spectral Density Function S_ω of Kanai Tajimi.

In which, S_0 is a constant spectral density and ξ_g and ω_g are the ground damping and frequency, respectively. In this paper, ξ_g =0.3 and ω_g =37.3 (rad/s) have been used for numerical simulations, as suggested by Mohebbi *et al.*, 2013. The time history of the Kanai-Tajimi excitation, with peak ground acceleration (PGA) equal to 0.475g used for the friction damper's optimization, is shown in Fig. 5.

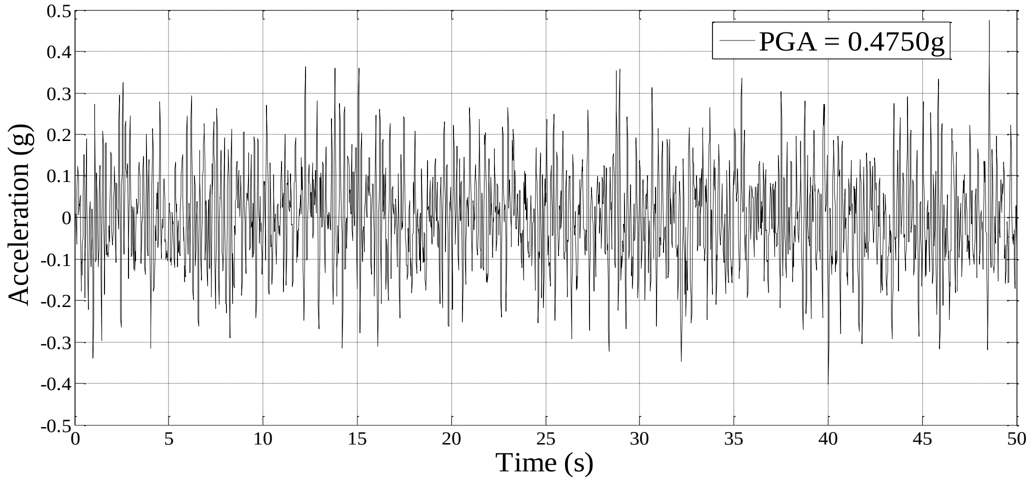

Figure 5. Time History of the Kanai-Tajimi Excitation.

2.4 Friction dampers optimization

In the last years, some researches such as Movaffaghi and Frieberg (2006) and Mousavi and Ghorbani-Tanha (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, the optimization technique has improved linking the computational routine developed in *MATLAB* with the *Firefly Algorithm*, proposed by Yang (2008). The objective function of the simultaneous optimization of friction dampers proposed in this paper is to reduce the maximum displacement at the top of the structure. By the way, the optimization problem considered in this research is complex because there are both discrete and continuous design variables. 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. In 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 five. 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 1500kN-3500kN for Kanai-Tajimi Excitation.

The *Firefly Algorithm* will evaluate the objective function after solving the equation of motion (Eq. (3)) 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. 6.

Firefly Algorithm

Objective function $f(\boldsymbol{x})$, $\quad \boldsymbol{x} = (x_1, ..., x_d)^T$
Generate initial population of fireflies $\boldsymbol{x}_i$ $(i = 1, 2, ..., n)$
Light intensity I_i at $\boldsymbol{x}_i$ is determined by $f(\boldsymbol{x}_i)$
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 $\exp[-\gamma r]$
        Evaluate new solutions and update light intensity
    end for j
end for i
Rank the fireflies and find the current global best $\boldsymbol{g}_*$
end while
Postprocess results and visualization

Figure 6. Firefly Algorithm pseudocode. Source Yang (2008).

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 convergence of the objective function for simulation 1 is presented in Fig 7 showed the efficiency of method when converge in 314 iterations, getting reduce the maximum displacement in 81 % as can been seen in Tab. 4.

Thus, grouping the design variables (positions and friction forces) in vector $\vec{\boldsymbol{x}}$ the optimization problem can be posed as shown in Eq. (7), in which the objective function $Z(\vec{\boldsymbol{x}})$ is minimize the maximum value of the displacement of vector $\left(\overrightarrow{\boldsymbol{Dmax}}\right)$, subjected to number of available positions, maximum number of dampers for each story.

$$\begin{aligned} &\text{Find} && \vec{x} \\ &\text{Minimize} && Z(\vec{x}) = Max\left(\overrightarrow{\boldsymbol{Dmax}}\right) \\ &\text{Subjected to} && \boldsymbol{n_p} \text{ (Number of available positions),} \\ & && \boldsymbol{n_d} \text{ (Maximum number of dampers),} \end{aligned} \tag{7}$$

3. ANALYSING RESULTS

After three simulations, the Firefly Algorithm has converged in the same optimal positions for the five friction dampers and similar friction forces for each one when the ten-story structure is subjected to the Kanai Tajimi Excitation. Additionally, each simulation has obtained similar best objectives as can been seen in Tab. 3.

Table 3. Comparison between the simulations.

Simulation 1		Simulation 2		Simulation 3	
Number of iterations = 314		Number of iterations = 268		Number of iterations = 331	
Best objective = 0.0362 m		Best objective = 0.0368 m		Best objective = 0.0373	
Stories for the optimal location	Optimal friction forces (MN)	Stories for the optimal location	Optimal friction forces (MN)	Stories for the optimal location	Optimal friction forces (MN)
1	3.4878	1	3.4561	1	3.4659
2	3.4174	2	3.3453	2	3.1362
3	3.2613	3	3.4423	3	2.8670
4	3.2434	4	3.3778	4	3.3664
5	2.7198	5	2.9423	5	2.7772

In order to understand the behavior of the structure response after the simultaneous optimization of the five friction dampers, displacement at the top of the structure graphic has been performed as can been seen in the Fig. 8. Table 4 shows the behavior of each response (displacement, velocity and acceleration) for each story when the five dampers are located in its optimal places with optimal forces and how decrease each response in terms of percentage. Thus, it is possible to appreciate that the optimization technique is efficient because in terms of displacement the decrease is over 80%, in terms of velocity is over 75 % and in terms of acceleration is over 50%. In the other hand, 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 and the optimal places for the friction dampers did not change.

Table 4. Comparison of the structure responses with and without friction dampers.

Story	Max. Displacement (m)			Max. Velocity (m/s)			Max. Acceleration (m/s^2)		
	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	0.0340	0.0064	80.9999	0.3272	0.0842	74.2554	7.3982	2.6042	64.7989
2	0.0656	0.0129	80.2647	0.5482	0.1512	72.4214	12.1481	3.8170	68.5788
3	0.0937	0.0176	81.1986	0.6270	0.2046	67.3606	11.9418	5.8755	50.7988
4	0.1196	0.0227	81.0005	0.7269	0.2368	67.4198	11.6632	5.2037	55.3834
5	0.1409	0.0264	81.2489	0.7963	0.2557	67.8879	11.7848	4.6763	60.3187
6	0.1573	0.0294	81.2982	0.9576	0.2306	75.9105	12.2863	5.4193	55.8912
7	0.1713	0.0314	81.6598	1.0839	0.2575	76.2354	11.4819	6.4151	44.1280
8	0.1832	0.0335	81.6958	1.1871	0.2935	75.2747	10.4524	6.0371	42.2419
9	0.1915	0.0350	81.7246	1.3050	0.3116	76.1199	10.6775	4.9954	53.2156
10	0.1959	0.0362	81.5206	1.3837	0.3415	75.3175	16.4595	5.5616	66.2102

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

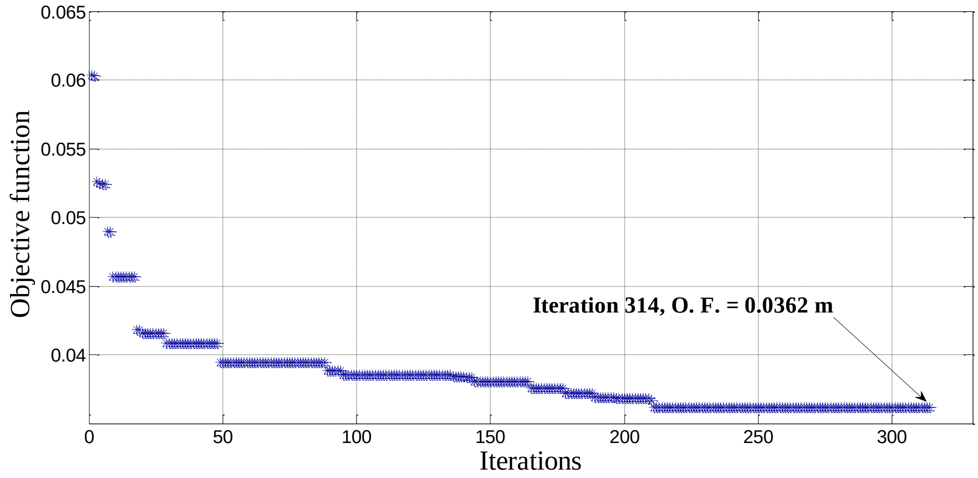

Figure 7. Convergence of the objective function of simulation 1.

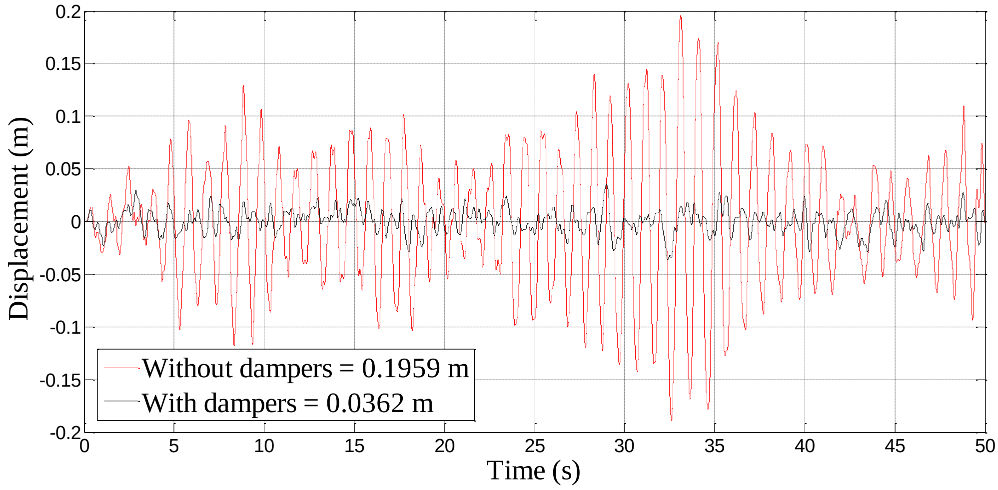

Figure 8. Displacement at the top of the structure under Kanai Tajimi Excitation.

4. CONCLUSIONS

The optimization of passive devices for the seismic control is a new area that has been focus of study for several researchers. The passive dampers highlight for its low cost in maintenance and do not require external energy. For this reason, this research focused in the optimization of friction dampers using a revolutionary metaheuristic optimization technique making these dampers are in the vanguard and stand out from other types of devices. Thus, this paper proposed an optimization methodology for optimum use of friction dampers.

Through the numerical simulations presented, it was concluded the proposed methodology proved to be very effective in reducing the dynamic response, reaching reductions of over 80% in the displacement, over 75% in the velocity and 50% in the acceleration. It is noteworthy that these reductions have been achieved with a limited number of friction dampers due to the fact that these dampers have been optimized, *i.e.*, they are positioned in places where they dissipate more energy and their capacities (frictional forces) are also optimal.

5. AKNOWLEDGEMENTS

The authors acknowledge the financial support of CNPq and CAPES.

6. REFERENCES

Kanai, K. An empirical formula for the spectrum of strong earthquake motions. Bulletin Earthquake Research Institute, University of Tokyo, v. 39, p. 85-95, 1961.

Fang, J. Wang, Q. Wang, S. Wang, Q. Min-max criterion to the optimal design of vibration absorber in a system with Coulomb friction and viscous damping. Nonlinear Dynamics, v. 70, p. 393-400, 2012.

Miguel, LFF. Lopez, RH. Miguel, LFF. Discussion of paper: "Estimating optimum parameters of tuned mass dampers using harmony search." [Eng. Struct. 33 (9) (2011) 2716–2723]. Engineering Structures, v. 54, p. 262-264, 2013a.

Miguel, LFF. Lopez, RH. Miguel, LFF. Multimodal size, shape, and topology optimisation of truss structures using the Firefly algorithm. Advances in Engineering Software, v. 56, p. 23–37, 2013b.

Miguel, LFF. Miguel, LFF. Lopez, RH. Robust Design Optimization of Friction Dampers for Structural Response Control. Structural Control and Health Monitoring, v. 21, n. 9, p. 1240-1251, 2014.

Miguel, LFF. Riera, JD. Controle de vibrações de estruturas utilizando amortecedores por atrito. Revista Internacional de Desastres Naturales, Accidentes e Infraestructura Civil, v. 8, n. 1, p. 57–70, 2008.

Mohebbi, M. Shakeri, K. Ghanbarpour, Y. Majzoub, H. Designing optimal multiple tuned mass dampers using genetic algorithms for mitigating the seismic response of structures. Journal of Vibration and Control, v. 19, p. 605-625, 2013.

Mostaghel, N. Davis, T. Representations of Coulomb friction for dynamic analysis. Earthquake Engineering and Structural Dynamics, v. 26, n. 5, p.541–548, 1997.

Mousavi and Ghorbani-Tanha. Optimum placement and characteristics of velocity-dependent dampers under seismic excitation, v. 11, p. 403-414, 2012.

Rakicevic, ZT. Bogdanovic, A. Jurukovski, D. Nawrotzki, P. Effectiveness of tuned mass damper in the reduction of the seismic response of the structure. Bulletin of Earthquake Engineering, v.10, p. 1049-1073, 2012.

Shinozuka, M. Jan, C. M. Digital simulation of random process and its applications, Journal of Sound and Vibration, v. 25, p. 111-128, 1972.

Tajimi, H. A statistical method of determining the maximum response of a building structure during an earthquake. In Proceceedings of 2nd World Conference in Earthquake Engineering, Tokyo, Japan, P. 781-797, 1960.

Takewaki, I. Tsuji, M. Yoshitomi, S. Adachi, F. Nonlinear optimal oil damper design in seismically controlled muli-story building frame. Soil Dynamic and Earthquake Engineering, v. 44, p.1-13, 2013.

Yang, X S., Nature-inspired metaheuristic algorithms. Luniver Press, 1st Ed., 116p, United Kingdom, 2008.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.