CILAMCE 2017
Florianópolis - Santa Catarina - Brazil

OPTIMIZATION OF INVERTED PENDULUM DAMPER PARAMETERS FOR VIBRATION CONTROL IN TALL BUILDINGS

Pedro Luiz Bernardes Júnior

pedro.bernardes.enc@gmail.com

Programa de Pós Graduação em Integridade de Materiais da Engenharia, Universidade de Brasília

Campus UnB Gama, Área Especial Indústria e Projeção A - 72.444-240, Gama/ DF, Brazil

Gino Bertollucci Colherinhas

ginobertollucci@hotmail.com

Programa de Pós Graduação em Ciências Mecânicas, Universidade de Brasília

Campus Universitário Darcy Ribeiro, Asa Norte - 70.910-900, Brasília/ DF, Brazil

Marcus Vinicius Girão de Morais

Suzana Moreira Avila

mvmorais@unb.br

avilas@unb.br

Programa de Pós Graduação em Integridade de Materiais da Engenharia, Universidade de Brasília

Campus UnB Gama, Área Especial Indústria e Projeção A - 72.444-240, Gama/ DF, Brazil

Abstract. *The constant progress of constructive techniques and civil construction materials, coupled with technological advancement, especially in the field of computational simulations, has allowed the construction of increasingly tall and slender structures. These structures presents high flexibility and vulnerability to dynamic loads actions, such as earthquakes, winds and even occupation by human users or machines. Due to this flexibility, these structures commonly suffer from excessive vibration, which can cause users discomfort or compromise the building safety. One of the most used dampers in building structures are the conventional pendulum tuned mass dampers types, but they have the inconvenience of require a lot of internal space inside the building. In this work, a ten-storey shear-building model is analyzed. It is presented a preliminary set of design parameters for an inverted pendulum tuned mass damper (IPTMD), obtained by a Genetic Algorithm optimization analysis.*

Keywords: *Structural Control, Tuned Mass Damper, Inverted Pendulum, Genetic Algorithm*

1 INTRODUCTION

The advent of increasingly slender and flexible structures has introduced, over time, the need for vibration control devices. The structural control, classified as passive, active, hybrid or semi-Active, is a technique to promote a change on the stiffness and damping properties of a structure and to reduce its response to dynamic loads (Soong & Dargush, 1997).

The tuned mass damper (TMD) is one of the typical passive control devices that can be installed in order to minimize excessive vibrations. When optimally tuned to the resonant mode of interest, a TMD commonly is effective in reducing the dynamic response of the structure because it vibrates out of phase with the main system, transferring energy from the structure to the auxiliary mass and minimizing the main system's vibration.

In order to find a set of optimal parameters for an inverted pendulum tuned mass damper (IPTMD) attached to a reduced model of a tall building, it is performed an optimization analysis using a genetic algorithm toolbox (Colherinhas et al., 2015).

The genetic algorithm (GA) is a technique inspired on the natural selection. In the context of finding the optimal solution to minimize or maximize an objective function, GA presumes that the potential solution of the problem is an individual and can be represented by a set of parameters. According to Man et al. (1996), these parameters are regarded as the genes of a chromosome and can be structured by a string of values in binary form. A fitness value is used to reflect how good the chromosome for solving the problem is, and this value is closely related to its objective value.

In this work an experimental reduced model of a ten storey building was studied, modeled as a shear frame in order to obtain the natural frequencies and modal shapes. Then the structure is reduced to a single degree of freedom system. A two degrees of freedom with the addition of the IPTMD is then analyzed. The aim of this paper is to show the dynamic performance of the experimental high building model with an inverted pendulum tuned mass damper, which will have its parameters obtained through a Genetic Algorithm based search. The damper parameters surveyed are stiffness, damping, length and mass.

2 ANALYTICAL MODEL

2.1 Experimental Reduced Model of a Tall Building

To simulate the behavior of a tall building, a reduced model was assembled. This model consists of ten SAE 1020 steel modules, with Young's Module equals to 2.05×10^{11} and specific weight equals to 7870 Kg/m³. The modules are bolted one by one and each module is set by two plates connected by four columns. Plates and columns have both a thickness of 6,3 mm. The resulting structure, shown in Figure 1, is approximately tall 212 centimeters, with an approximately slenderness ratio of 1:10. All the dimensions of the steel module are shown in Figure 2.

Figure 1. Steel module (left) and experimental reduced model of a tall building assembled (right)

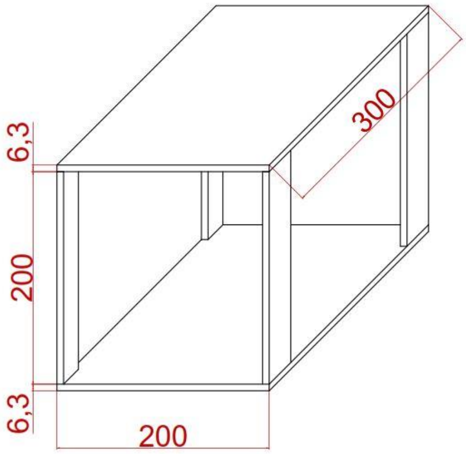

Figure 2. Steel module dimensions (in millimeters)

2.2 Theoretical Model

The physical model presented was modeled as a shear frame with ten degrees of freedom, illustrated in Figure 3. The mass of each floor was considered as the total mass of the plates, bolts and nuts, subtracting the mass relative to the holes. The stiffness of each floor was assumed the sum of all columns stiffness in the considered direction. The properties of mass and stiffness of the structure and the resulting natural frequencies are shown in Tables 1 and 2, respectively. The first five modal shapes are illustrated in Figure 4.

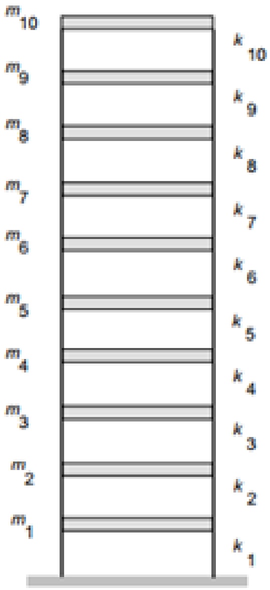

Figure 3. Structure modeled as a Shear Frame

Table 1. Structure's Stiffness and Mass Properties

N	Stiffness k_n (N/m)	Mass m_n (Kg)
1	500901.8720	5.9827
2	592060.4851	6.0086
3	513323.2916	6.0455
4	510294.3134	6.0225
5	502349.2988	6.0224
6	477039.3438	5.9779
7	507729.2016	5.9794
8	481335.9660	6.0016
9	540480.7883	5.9679
10	510765.8977	2.9235

Table 2. Structure's Natural Frequencies

Mode	Natural Frequencies (Hz)
1	7.3488
2	21.6324
3	35.4883
4	48.4065
5	60.6354
6	70.4973
7	79.7474
8	86.3231
9	91.2525
10	92.7778

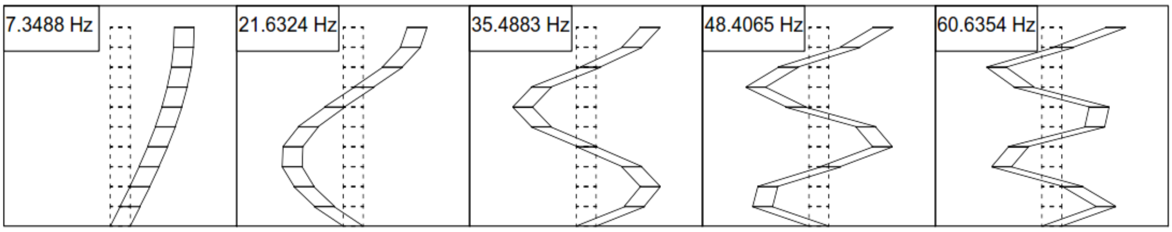

Figure 4. First five modal shapes of the considered structure

2.3 Order Reduction

The TMD is an efficient device in the case of structures that vibrate predominantly around a single mode (Avila, 2002). As the structural response for systems with many degrees of freedom, such as tall buildings, can be obtained through a reduced model using modal analysis (Soong and Dargush, 1997), it is possible to approximate the dynamic response vector y(t), representing it by a single coordinate y_N and a single mode Φ_1.

Proceedings of the XXXVIII Iberian Latin-American Congress on Computational Methods in Engineering
P.O. Faria, R.H. Lopez, L.F.F. Miguel, W.J.S. Gomes, M. Noronha (Editores), ABMEC, Florianópolis, SC, Brazil, November 5-8, 2017.

$$y = \phi_1 \cdot y_N(t) \quad (1)$$

Then, the equation of movement becomes:

$$M_1 \cdot \ddot{y}(t) + C_1 \cdot \dot{y}(t) + K_1 \cdot y(t) = F(t) \quad (2)$$

where $M_1 = \Phi_1^T M \Phi_1$ is the modal mass, $C_1 = M_1 2\xi_1\omega_1^2$ e $K_1 = M_1\omega_1^2$. ξ_1 and ω_1 are the damping ratio and the natural frequency of the mode. With this modal reduction technique and considering $\xi_1 = 0.02$, the equivalent single degree of freedom model is obtained. The modal properties, then, becomes M_1 = 29.5044 Kg; K_1 = 6.2905x104 N/m and C_1 = 54.4936 Ns/m.

2.4 Analytical two degree of freedom system – Main Structure + IPTMD

With the main system reduced to a single degree of freedom model, which corresponds to the mode to be controlled (Soong & Dargush, 1997), the IPTMD is installed. Then it becomes a two degree of freedom (2-DoF) discrete system, illustrated in Fig. 5.

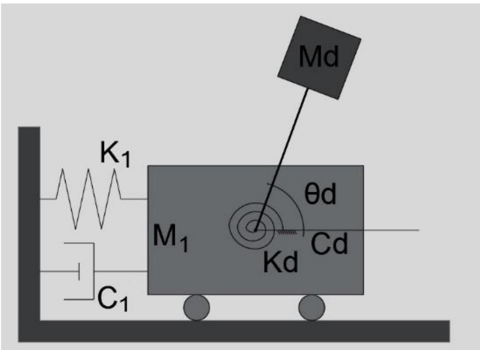

Figure 5. Structure with an IPTMD

The system motion equations considering small displacements is given by:

$$\begin{bmatrix} \frac{\rho L^3}{3} + M_d L^2 & M_d L + \frac{\rho L^2}{2} \\ M_d L + \frac{\rho L^2}{2} & M_1 + M_d + \rho L \end{bmatrix} \cdot \begin{bmatrix} \ddot{\theta} \\ \ddot{u} \end{bmatrix} + \begin{bmatrix} C_d & 0 \\ 0 & C_1 \end{bmatrix} \cdot \begin{bmatrix} \dot{\theta} \\ \dot{u} \end{bmatrix} + \begin{bmatrix} K_d - M_d g L - \frac{\rho g L^2}{2} & 0 \\ 0 & K_1 \end{bmatrix} \cdot \begin{bmatrix} \theta \\ u \end{bmatrix} = \begin{bmatrix} 0 \\ F(t) \end{bmatrix} \quad (3)$$

Where M_1, K_1 e C_1 are the modal mass, stiffness and damping coefficient. M_d, K_d e C_d are the IPTMD's mass, stiffness and damping coefficient. ρ and L are the pendulum bar's linear density and length. By making $F(t)=e^{i\omega t}$, $u(t)=H_u(\omega)e^{i\omega t}$ and $\theta(t)= H_\theta(\omega)e^{i\omega t}$ and replacing in equation (3), it can be obtained:

$$\begin{bmatrix} -\left(\frac{\rho L^3}{3}+M_d L^2\right)\omega^2 + C_d i\omega + \left(K_d - M_d gL - \frac{\rho g L^2}{2}\right) & -\left(M_d L + \frac{\rho L^2}{2}\right)\omega^2 \\ -\left(M_d L + \frac{\rho L^2}{2}\right)\omega^2 & -\left(M_1 + M_d + \rho L\right)\omega^2 + C_1 i\omega + K_1 \end{bmatrix} \cdot \begin{bmatrix} H_\theta(\omega) \\ H_u(\omega) \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \tag{4}$$

Solving the linear system, it is possible to obtain the frequency response functions $H_u(\omega)$ given by Eq. (5):

$$H_u(\omega) = \frac{\omega^2 B_2 + i\omega B_1 + B_0}{\omega^4 A_4 + i\omega^3 A_3 + \omega^2 A_2 + i\omega A_1 + A_0}. \tag{5}$$

where

$B_0 = 6(\rho g L^2 + 2M_d gL - 2K_d)$;

$B_1 = -12C_d$;

$B_2 = 4\left(\rho L^3 + 3M_d L^2\right)$;

$A_0 = 6(-2K_1K_d + K_1 g\rho L^2 + 2K_1M_d gL)$;

$A_1 = 6(-2C_1K_d - 2C_dK_1 + 2C_1M_d gL + C_1\rho L^2 g)$;

$A_2 = 12M_1K_d + 12M_dK_d + 12\rho LK_d + 12M_dK_1L^2 + 4\rho L^3K_1 - 12C_1C_d i^2 - 12M_d{}^2 gL - 6\rho^2L^3 g - 12M_1M_d gL - 6M_1\rho L^2 g - 18M_d\rho L^2 g)$;

$A_3 = 4(3C_dM_1 + 3C_dM_d + 3C_d\rho L + 3C_1M_dL^2 + C_1\rho L^3)$;

$A_4 = -\rho^2L^4 - 12M_1M_dL^2 - 4M_1\rho L^3 - 4M_d\rho L^3$;

3 SENSIBILITY ANALYSIS

The length L, linear density ρ, mass M_d, damping C_d and stiffness K_d defines the pendulum design parameters. Using the same procedure of Colherinhas et. al (2016), a response map was obtained with the response peaks *max($H_u(\omega)$)*values, which are the maximum values of the Frequency Response Functions (FRF), considering different mass ratios $\mu=M_d/M_1$ and different lengths L.

To define the response map the following parameter values were assumed: M_1 = 29.5044 Kg; K_1 = 6.2905x104 N/m and C_1 = 54.4936 Ns/m. K_d and C_d were defined as 5.1988x10^3 N/m and 45.7343 Ns/m, respectively, through the optimal parameters suggested by Den Hartog (1956). The value of ρ is 0.5423, which is the linear density of an aluminum bar with a diameter of 16 millimeters.

Considering these design criteria, the response map shown in Figure 6 was obtained. It is possible to observe a valley on the map. According to Colherinhas et. al (2016), this valley can be interpreted as the points where the combination of μ and L values leads us to an optimal solution. The superior view (Figure 7) shows the curvilinear shape of the possible optimal solutions.

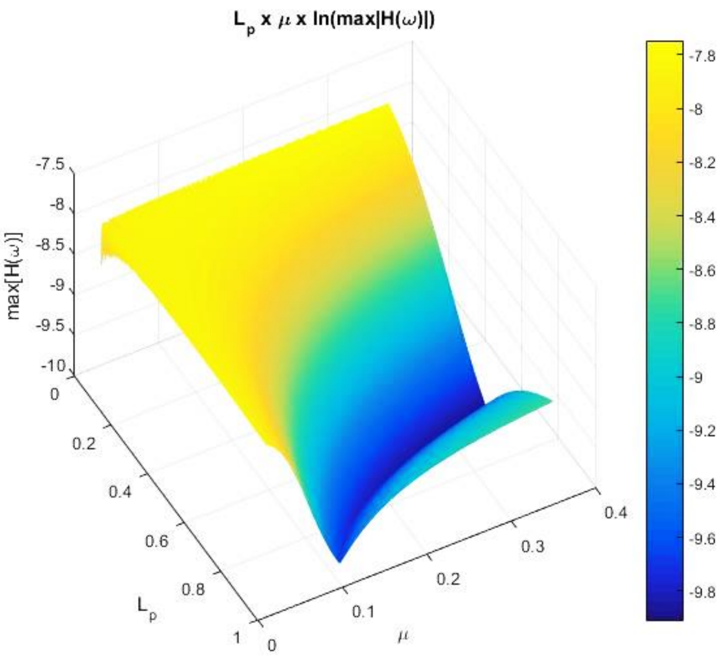

Figure 6. Response map

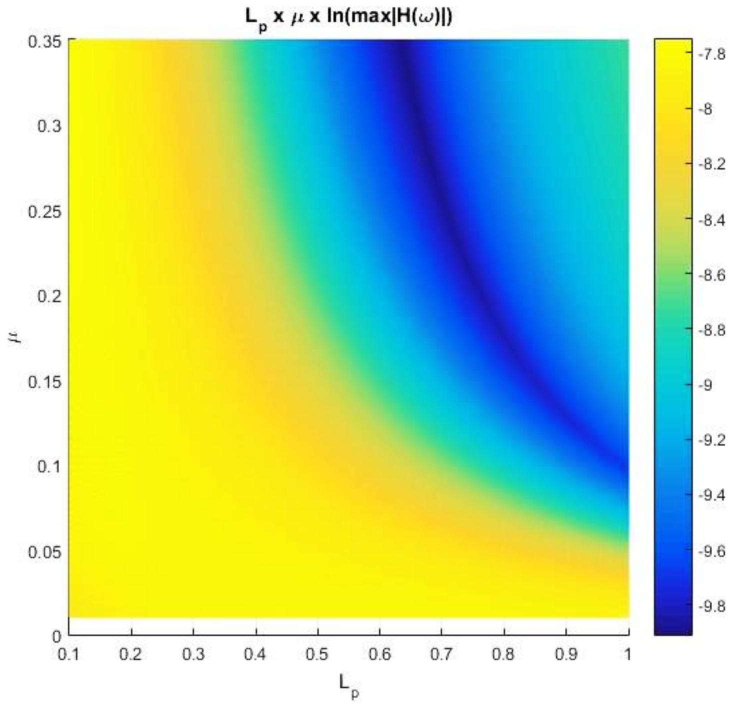

Figure 7. Response map – Top view

4 GENETIC ALGORITHM

An optimization methodology using the GA toolbox (Colherinhas et. al, 2015) was performed. The parameters chosen for optimization were the pendulum length L and the mass ratio μ. As it is a real physical model, there are limitations on the feasible values of L and μ. Then, the initial population C = [L; μ] was created restricting the variables in the following ranges: $0.1 \leq L \leq 1$ m and $0.01 \leq \mu \leq 0.255$. All the other parameters values keeped the same values of section 3.

4.1 Fitness Function

Since the purpose of this optimization is to minimize the frequency response peaks of the model described in section 2.4, the fitness function was defined as the minimization of $H_u(\omega)$, maximizing its inverse.

$$f_{obj} = \frac{1}{H_u(\omega)i} \tag{6}$$

where i=1, 2, … is the chromosome of the population N_i.

4.2 Optimization Results

The Genetic Algorithm toolbox generates a random population from a set of constraints. It occurs at the starting point of GA and in some evolutionary strategies, such as decimation, crossover, and mutation. For this problem, the following set of parameters was used:

- N_{ger} = 150 – number of generations;
- N_{ind} = 200 – number of individuals of the population;
- p_c = 60% – crossover probability;
- p_m = 2% – mutation probability;
- p_{elit} = 2% – elitism probability;
- p_{diz} = 20% – decimation probability;
- N_{diz} = 50 – step of generation for the occurence of decimation.

The selection of individuals is done by the roulette method, where for each chromosome a "slice" is assigned over the circular area of an hypothetical roulette wheel.

According to Colherinhas (2015), the size of this slice is based on the fitness of the chromosome relative to the sum of all others in the population. The roulette wheel is rotated N_{ind} times, where N_{ind} is the number of individuals in the population. Each time the roulette wheel stops, the selected individual is taken to the next generation. These selected individuals will be able to participate of the evolutionary strategies of crossing and mutation. Elitism, mutation, and decimation algorithms maintain or eliminate the respective population percentages for the next generation.

After performing the optimization procedure, the optimal value for the peak response, which was $H_u(\omega) = 9.4229x10^{-06}$ m, was found when L = 0.7013 m and μ = 0.2550. That means a pendulum with a length of 0.70 meters with a mass of 7.52 Kg attached at the end. Figure 8 shows the response of the system when it is coupled with an IPTMD set with these values. It can be observed that the optimum parameter lead to a great response reduction compared to the uncontrolled system. The point that represents this optimal set is located at the curved shape valley of the response map, as expected.

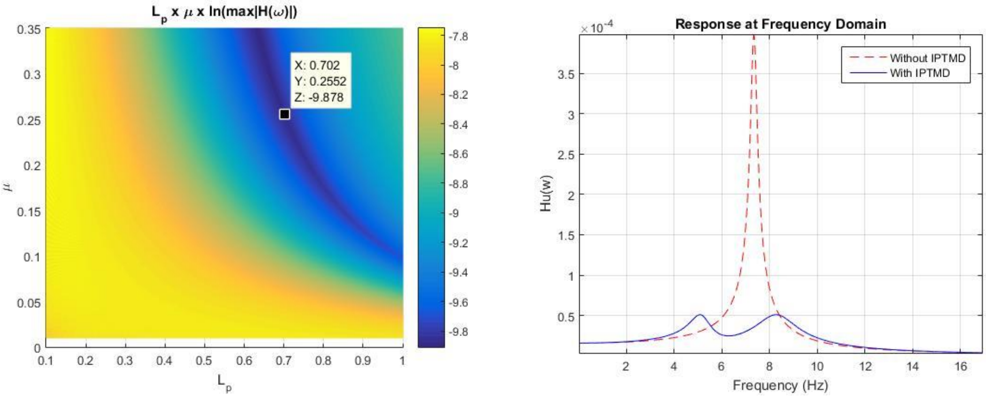

Figure 8. Optimal peak response parameter values (L = 0.7011 m and μ = 0.2550) at Response Map (a) and the equivalent frequency response function (b)

Another optimizations have also been performed. For example, by imposing the upper limit of $\mu \leq 0.10$, the search returns a set of L = 0.9889 m and $\mu = 0.1000$. It is possible to see in Figure 9 that the response of this set, also located at the valley of the response map, is greatly reduced when compared to the uncontrolled system. Those values means a pendulum with a length equal to 0.98 meters and a mass of 2.95 Kg at the top. Despite a smaller mass than the first optimal solution, this solution could not be feasible, due to the problems of buckling and bending that could arise in an aluminium bar with this high length.

In Figure 10, can be observed the response of the returned set when is imposed the upper limit of $\mu \leq 0.20$. The search returns a set of L = 0.7661 m and $\mu = 0.2000$, or 5.9 Kg at the top of the pendulum. At this point, located at the valley of the response map, these optimum parameters also gives a large reduction of the response peak.

For constructive reasons, in order to avoid buckling and bending in the aluminium bar, it was desired to impose the upper limit as $L \leq 0.50$. For this value, the toolbox returned a mass ratio of $\mu = 0.2550$, that means a mass of 7.52 Kg at the top of the pendulum. As can be seen in Figure 11, this point is outside the valley that represents the geometric locus of the optimal solutions in the response map. In fact, the performance on reducing the peak response of this set was not so effective compared to the others. However, this set still gives a substantial reduction and could be considered an efficient solution.

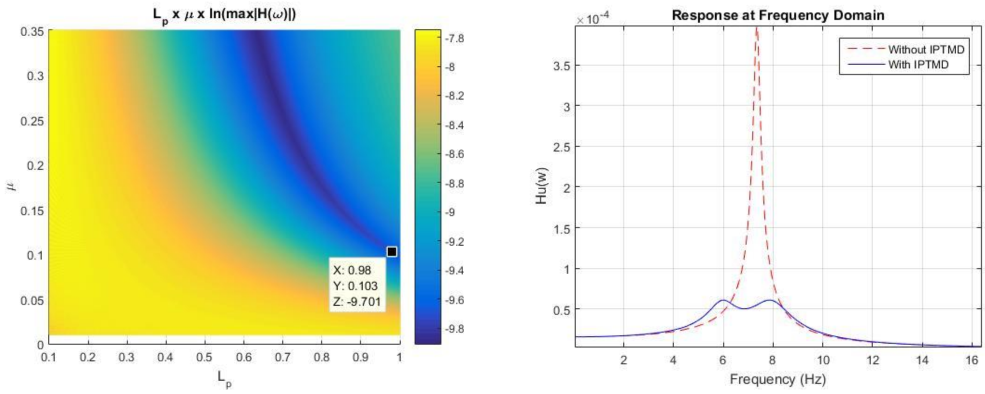

Figure 9. Peak response parameter values (L = 0.9889 m and μ = 0.1000) at Response Map (a) and the equivalent frequency response function (b)

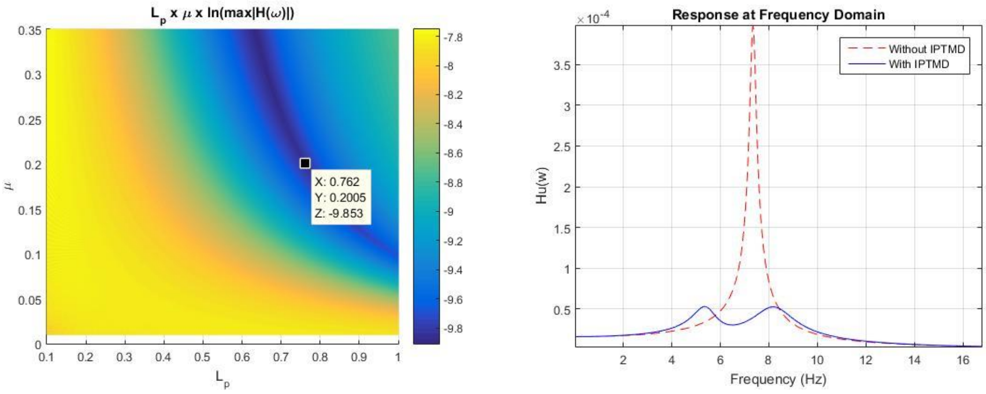

Figure 10. Peak response parameter values (L = 0. 7661 m and μ = 0.2000) at Response Map (a) and the equivalent frequency response function (b)

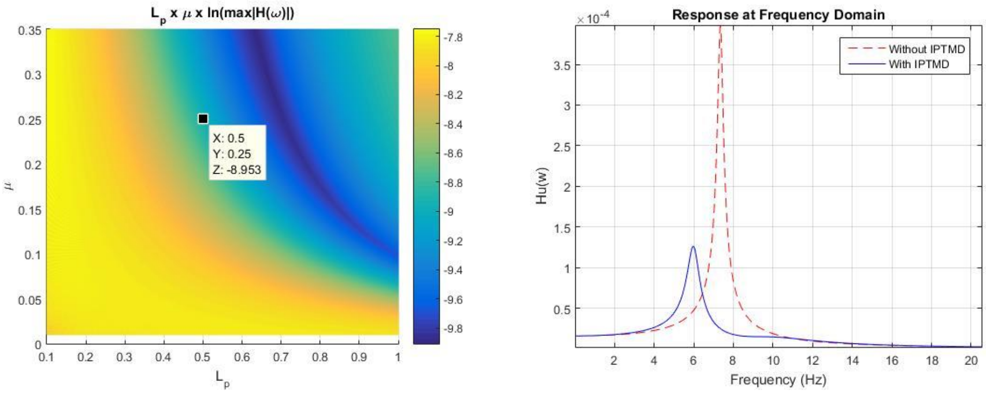

Figure 11. Peak response parameter values (L = 0.5000 m and μ = 0.2550) at Response Map (a) and the equivalent frequency response function (b)

5 CONCLUSIONS

This work presents an optimization of the main parameters values for an Inverted Pendulum Tuned Mass Damper to control the vibrations of a ten degree of freedom shear frame, which is a theoretical modeling of an experimental reduced model of a tall building. It was possible to observe through the peak frequency response that the IPTMD was very effective on reducing the dynamic response of the structure.

The Genetic Algorithm toolbox allowed the search for the optimal IPTMD length and mass ratio after fixing values for stiffness and damping parameters. This search was in accordance with the response map elaborated through the sensibility analysis. The response map shows a surface with a valley, that represents the geometric locus of the optimal solutions for the 2-DoF (Structure + IPTMD) problem. It was possible to confirm that the best performances of IPTMD, found through the G.A. analysis, happens when the parameters are located on the valley.

This GA Toolbox, whose objective was the minimization of the peak response, was efficient in finding the optimal values within the established input limits. In addition, it showed to be a good guideline for the IPTMD design step, considering the future execution of experimental tests on the presented physical model coupled with an inverted pendulum damper.

It was possible to observe that the reduction of the peak response depends on a break even point between the length and the mass at the top of the pendulum and the algorithm results under the constraints confirm it, returning a heavier mass when the length is limited, and returning a higher length when the mass is limited.

For future works, it could be considered to perform a parametric study in order to determine the influence of different values for stiffness and damping properties on the performance of the GA toolbox. Another suggestion is to use different fitness functions to optimize the dynamic response reduction of the system

ACKNOWLEDGEMENTS

This work was supported by the Coordination for the Improvement of Higher Education Personnel (CAPES), the National Council for Scientific and Technological Development (CNPq) and the Federal District Foundation for Research Support (FAPDF).

REFERENCES

Anh, N. D., Matsuhisa, H., Vieta, L. D., Yasuda, M., 2007. Vibration Control of an Inverted Pendulum Type Structure by Passive Mass-Spring-Pendulum Dynamic Vibration Absorber. *Journal of Sound and Vibration*, vol. 307, pp. 187-201

Avila, S. M., 2002. *Controle Híbrido para atenuação de vibrações em edifícios*, Tese de doutorado, Pontíficia Universidade Católica do Rio de Janeiro.

Colherinhas, G. B., 2016. *Ferramenta de Otimização via Algoritmos Genéticos com Aplicações em Engenharia*, Dissertação de Mestrado, Universidade de Brasília.

Colherinhas, G. B., Morais, M. V. G., Shzu, M. A. M., & Ávila, S. M., 2015. Genetic Optimization of Tower Vibrations with Pendulum TMD. *XXXVI Ibero-Latin American Congress on Computational Methods in Engineering.*

Den Hartog, J. P., 1956. *Mechanical Vibrations*. McGraw-Hill.

Deraemaeker, A., Soltani, P., 2016. A short note on equal peak design for the pendulum tuned mass dampers. *J Multi-body Dynamics*

Guimarães, P. V. B., 2016. *Controle Semiativo de Modelo de Pêndulo Invertido para Aerogeradores Off-Shore.* Dissertação de Mestrado, Universidade de Brasília.

Oliveira, F. S., 2012. *Critérios de Projeto para Amortecedor Tipo Pêndulo para Controle de Vibrações em Edifícios Altos*. Dissertação de Mestrado, Universidade de Brasília.

Sherif, A., al-Handasah, D., 2010. Structural Design of Reinforced Concrete Tall Buildings. *Council on Tall Buildings and Urban Habitat Journal*, pp. 34-41.

Soong, T. T., Dargush, G. F., 1997. *Passive Energy Dissipation Systems in Structural Engineering*. John Wiley & Sons.

Tang, K. S., Kwong, S., 1996. Genetic algorithms: Concepts and applications. *IEEE Transactions on Industrial Electronics*, Vol. 43, n. 5, pp. 519-534.

Villaverde, R., Koyama, L. A., 1993. Damped Resonant Appendages to Increase Inherent Damping in Buildings. *Earthquake Engineering and Structural Dynamics*, Vol. 22, pp. 491-507.

Zuluaga, A., L., 2007. *Controle de Vibrações em Edifícios Submetidos à Ação de Cargas Dinâmicas Utilizando Amortecedor de Massa Sintonizado na Forma de Pêndulo*. Dissertação de Mestrado, Universidade de Brasília.