25th ABCM International Congress of Mechanical Engineering
October 20-25, 2019, Uberlândia, MG, Brazil

COB-2019-1484
OPTIMIZATION OF PASSIVE VIBRATION CONTROL SYSTEM APPLIED IN STRUCTURAL MODEL INCORPORATING SMA-SE COIL SPRINGS ASSCIATED WITH TMD

Carlos Heitor de Andrade Lustosa
Federal University of Campina Grande; Avenue Aprígio Veloso, Universitário, Campina Grande, 882/58429-900, PB, Brazil[1].
chdeandrade@gmail.com

Yuri José Oliveira Moraes
Federal University of Paraíba; University City, João Pessoa, SN/58051-900, PB, Brazil[2].
yurijmoraes@gmail.com

Antonio Almeida Silva[1]
antonio.almeida@ufcg.edu.br

Marcelo Cavalcanti Rodrigues[2]
marcelo.labii@gmail.com

Armando Wilmans Nunes[1]
armandowjunior@gmail.com

Marcelio Ronnie Dantas de Sá[1]
marceliojc@hotmail.com

Raimundo Nonato Calazans Duarte[1]
raimundo.duarte@ufcg.edu.br

Abstract. *As cities tend to grow vertically, these buildings become more affected by vibration phenomena. If these new constructions are not well prepared for this type of effort, great damage can be caused, leading to the failure of the structure. This work aims to attenuate the effects of vibration on a simplified structure with three degrees of freedom, and compare the effectiveness of each process, regarding the damping provided to the system. Firstly, a Tuned Mass Damper (TMD) will be added, followed two types of springs, steel and a Shape Memory Alloy (SMA). When dealing with SMA springs, it is also important to analyze the effect that the pre-load of this type of absorber has on the damping. The results indicate that the SMA springs were more effective in most of the cases, with a maximum reduction of 52.4 dB. For the pre-load, it was noted that the springs with a pre-load of 300% were more effective in most cases, especially when the top floor of the structure was analyzed.*

Keywords: *Tuned Mass Damper (TMD), Shape Memory Alloys (SMA), Passive Vibration Control*

1. INTRODUCTION

At the beginning of the study of vibrations, intellectuals focused on understanding the natural events surrounding this phenomenon. Nowadays, vibrations are all around us, being caused by natural events, earthquakes and strong winds, or by artificial inventions, engines and large constructions (Rao, 2011). Depending on the amplitude and frequency of excitation, major damage can be caused to structures that are not properly prepared for this type of effort. In addition, as cities become more vertical, taller buildings are built, requiring more damping, as the larger the building, the stronger the winds that hit it and the more affected they are by vibrations in its surrounding area.

2. METHODOLOGY

2.1 Main Estructure Conception

The first component to be studied was the structure to which the Tuned Mass Damper (TMD) will be attached to and tested. This element will have three degrees of freedom (3 DOF) and should obey the frequency and mass limitations, which will be discussed below. This previous study is of great importance, because if these limitations are not considered, the experimental results obtained will not be real and will have a high error rate.

The limitations mentioned above derive from the limitations of the equipment that will be used during the experimental analysis of the structure, which are the maximum excitation frequency, which must be below 20 Hz, and the maximum supported mass, which is 15 kg. In other words, the natural frequencies to be studied must be less than 20 Hz and the mass of the structure must be less than 15 kg. To guarantee the technical specifications, the structure was initially designed in a computational environment and was analyzed using finite elements. Subsequently, the simulation results were proved by an analytical solution of the differential equation, Eq. (1), where [M], [C] and [K] are the matrices representing mass, damping and stiffness, respectively (Rao, 2011).

$$[M]\ddot{x}(t) + [C]\dot{x}(t) + [K]x(t) = f(t) \tag{1}$$

The method described below was implemented in a Matlab® environment to obtain the natural frequencies and vibration modes of the structure. To obtain the natural frequencies from Eq. 1, it was considered that the body is in free vibration (f (t) = 0), in other words, no external forces acting on the body, and that the damping matrix can be neglected ([C] = 0) with no significant loss. The first step in development is to obtain the inverse stiffness matrix, followed by the multiplication of it by mass matrix, as can be seen in Eq. (2), which is known as the dynamic matrix. From this new matrix, the eigenvalues and eigenvectors matrices are extracted.

$$[D] = [K]^{-1}[M] \tag{2}$$

The eigenvalue matrix is a diagonal matrix and it is from it that the natural frequencies can be obtained through Eq. (3), where (λ_{ii}) represents the coefficients of the eigenvalue matrix. These frequencies obtained directly from the matrix have units of rad/s, simply dividing by 2π transforms the unit to Hz, as already done in Eq. (3). The values obtained by this routine are shown in Tab. 2.

$$f_i = \frac{1}{2\pi\sqrt{\lambda_{ii}}} \tag{3}$$

In order to obtain the results shown in Tab. 2, it was necessary to stipulate some input data, some depending on the materials used and others depending on the geometry. Therefore, the materials of the columns (SAE 304 stainless steel), the floors (aluminum) and the base and angles irons (SAE 1020 steel) were defined. In addition, the screws and nuts used for angle iron-column attachment (M10) and angle iron-floor attachment (M7) were selected, all of which are Allen type screws. These data are of relevance for obtaining the masses on each floor of the structure, which can be found in Tab. 1 below, along with the total mass of the structure. The masses of each floor will be used to compose the mass matrix in Eq. (1).

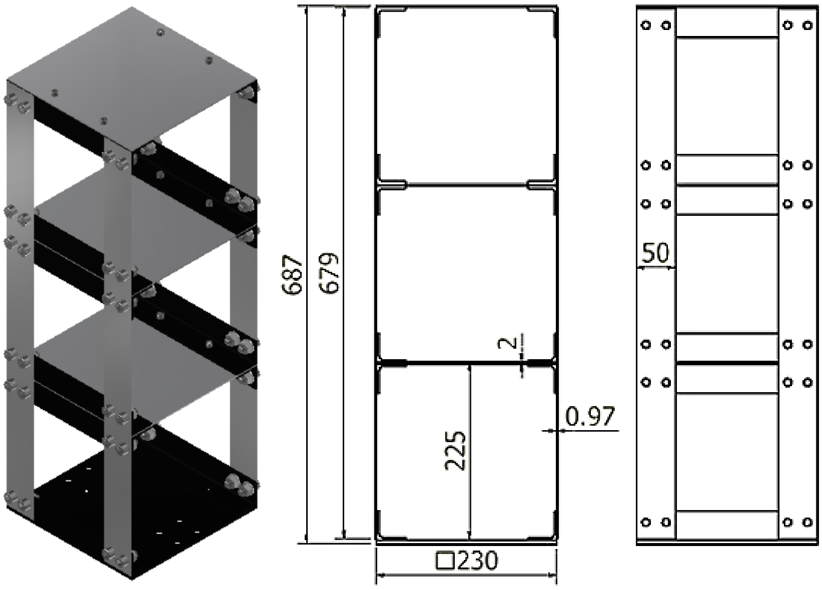
Table 1. Mass per floor of the structure.

Floor	Mass (kg)
Base	3,06
1	2,42
2	2,42
3	1,39
Total	10,33

Another very important parameter for obtaining the natural frequencies is the stiffness of each floor. This stiffness is attained from Eq. (4), where “E” is the modulus of elasticity (Young Modulus) of the material, “L” is the useful length and “I” is the moment of inertia, being all values for the column. These obtained stiffnesses will be employed to compose the mass matrix in Eq. (1).

$$k = \frac{48EI}{L^3} \tag{4}$$

For finite element method simulations to occur, a model must be generated. The software Autodesk Inventor® was used to generate a full-scale model, which is shown in Fig. 1, along with its dimensions. These simulations were performed using the Ansys® software for various length values, until the natural frequency values met the previously mentioned specifications.



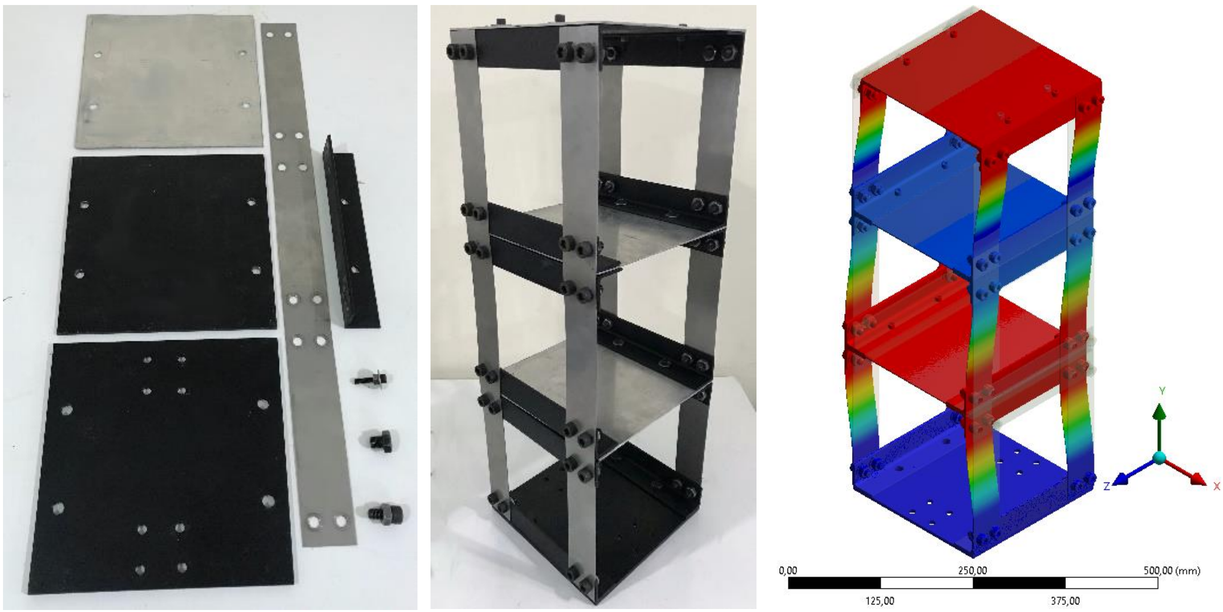
(a) (b)

Figure 1. (a) Structure design. (b) Technical drawing of the structure.

The results of the finite element solution are also shown in Tab. 2 and in Fig. 2 the behavior of the structure at the second natural frequency can be seen. After calculations and simulations showed that the dimensions result in values for natural frequencies within the range specified it the beginning and that the total mass of the structure is also less than the stipulated maximum, the components could be purchased and manufactured. In Fig. 2 are also shown the components used for the assembly of the structure, as well as the structure already assembled.

Table 2. Natural frequencies obtained by the analytical and numerical method.

Natural Frequency	Analytical Method (Hz)	Numerical Method (Hz)	Relative Error
f_1	4,66	4,69	0,6 %
f_2	12,73	13,02	2,3 %
f_3	17,44	18,15	4,1 %



(a) (b) (c)

Figure 2. (a) Main structure components. (b) Assembled structure. (c) Second vibration mode.

2.2 TMD Conception

A tuned mass damper is a device generally composed of a mass, a spring and a damper; however, this type of system has proven to be most effective when the main structure is excited by harmonics or by the wind, while its effectiveness in seismic applications has not been fully proven (Sadek, 1998). One of the disadvantages of using a TMD is that it must be calibrated to a specific frequency and is not useful when an entire range needs to be covered.

After confirming the natural frequencies of the structure, it was possible to concentrate on the design of the pendulum structure and how it would be attached to the main structure. Because of the space between the floors, the TMD needs enough mass for its rod to fit within the given space. The chosen mass is about 20% of the mass of the entire structure, weighing 0.250 kg. The next step is to calculate the length of the rod that will maintain the weight. It was defined that it would have a simple rectangular geometry and would be made of sheet metal with a thickness of 2 mm. In order to calculate this pendulum calibration length, Eq. (5) was obtained by relating the rod geometry to the frequency to which the TMD should be calibrated. In this equation, "L" is the length, "E" is the modulus of elasticity, "b" is the width, "h" is the thickness, "m" is the mass and "fn" is the natural frequency.

$$L = \sqrt[3]{\frac{Ebh^3}{4m(2\pi f_n)^2}} \tag{5}$$

For best results to be obtained, the natural frequencies of the real structure will be used, in other words, the data obtained experimentally, since these results include the dimensional variations due to manufacturing processes and material imperfections, which cause a variation of properties throughout the parts.

It is important to note that the TMD must be firmly attached to the structure so that its base does not vibrate. In addition, the rod must be fixed so that it is parallel to the columns and perpendicular to the floors. In order to comply with these restrictions, two small angles irons were attached to each other and to the bottom of the top floor using screws, and the metal rod was placed between the two, remaining stationary during the tests, as can be seen in Fig. 3.

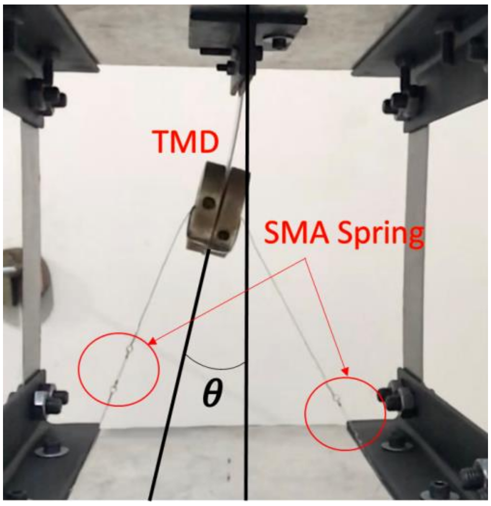


Figure 3. TMD fixed to the top floor with SMA springs.

2.3 Spring Selection

In some cases, even with the help of a TMD, vibration at the new frequencies generated by this device can still damage the structure due to the large amount of energy. One way to mitigate this problem is to change the pendulum rod material to one that is capable of dissipating more energy, such as Shape Memory Alloys (SMAs); however, this solution in full-scale is very costly as these materials are expensive. Another way is to connect springs on either side of the TMD so that some of the energy is dispersed through them. This solution is most plausible in the real world, as springs can be combined in many ways, achieving the required stiffness value.

SMA alloys have two main characteristics which have been extensively studied by scientists around the world, the shape memory and superelasticity effects. Both refer to the return of the element to its initial state, the shape memory effect being caused by the addition of heat to the material, while superelasticity occurs due to load removal (DesRoches, 2004). As in the experiments performed for this study the spring will be at controlled room temperature, the only effect acting on the tests will be the superelasticity.

It is well known that SMA's undergoing micro-constituent transformations have a greater damping effect due to their unique superelasticity feature; however, this damping effect is greatly affected by temperature, frequency and amplitude

(Chang, 2016; Moraes, 2018). To verify this increase in energy dissipation, two springs will be tested, one made of steel and the other made of a nickel-titanium alloy (SMA-SE), an alloy that has superelastic characteristics at the test temperature. Springs selected for analysis are shown in Fig. 4.

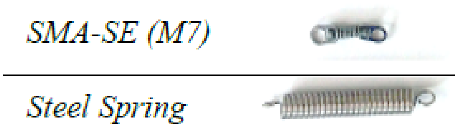
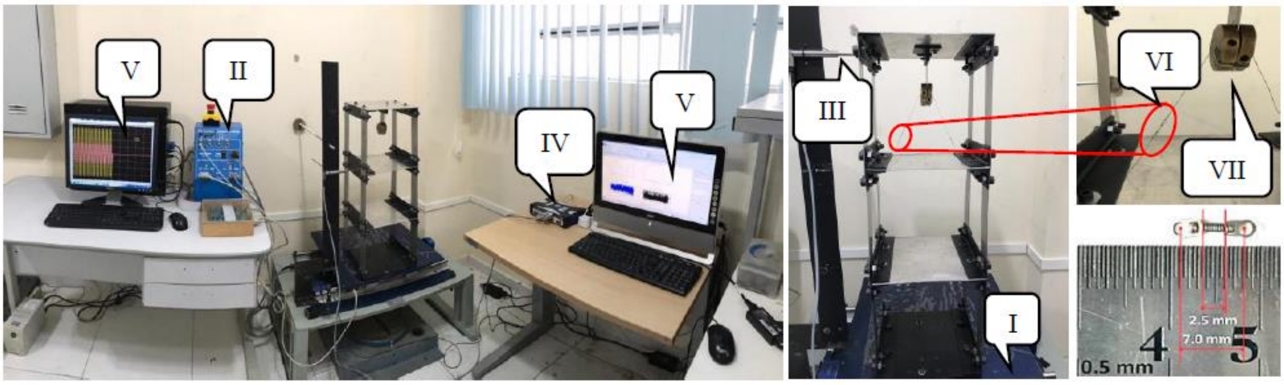


Figure 4. Springs selected for the study.

In this work, springs will be analyzed with a preload, which is measured as an initial percent deformation. This preload is important for the springs to work properly, as during the TMD movement, the springs will enter traction and compression. If this initial load did not exist, the spring coils could come into contact, losing efficiency. On the other hand, this initial deformation cannot be too large as it will cause the spring to fail due to excessive deformation. As the SMA springs under analysis have a maximum deformation of 500%, the springs will be studied with 100% and 300% preload. For the steel spring, only the 100% preload was considered.

2.4 Experimental Procedure

All experimental tests were performed at the Vibration and Instrumentation Laboratory (LVI) with the same data collection equipment, including a Quanser Shake Table II (I), an amplifier (II), inductive displacement sensors (III), an universal data acquisition system (IV), computers (V), coil springs (VI) and TMD (VII). Figure 5 illustrates the configuration along with the identification of each component.



(a) (b) (c)
Figure 5. (a) Configuration used for experimental analysis. (b) Complete structure including TMD and SMA springs. (c) Useful length of SMA spring.

In the experiments, it was necessary to use two computers, because the first (left) is responsible for Shake Table control and the second (right) is responsible for data acquisition. In both, the MATLAB® software was used, in the first, the Simulink tool was used to control the amplitude, frequency band and time of the experiment. While in the second one, the software was used to capture and treat the data. For this, a routine was elaborated, whose work is to calculate the Fast Fourier Transform (FFT) for the input and output data, followed by dividing the output by the input, applying a filter for the elimination of interferences and, finally, plotting the Frequency Response Functions (FRFs) for each experiment.

A very important definition is the input and output data in the experiment. The input data refers to the data obtained by the sensor attached to the Shake Table, while the output data refers to the data obtained by the sensor located on the structure, whichever the floor.

To complete the full spectrum of the experimental procedure, four experiments will be performed: the first with the structure alone, the second with the addition of the TMD, the third with the addition of steel springs and the fourth with the SMA springs. Each test will be performed with data acquisition on all three floors and with the TMD calibrated for each of the three natural frequencies, obtaining FRFs that can be compared later to analyze the change caused by the addition of each component, as well as the effect of the preload on the SMA spring.

The experiment with the structure by itself has two objectives, the first being to obtain the FRFs for the structure, thus defining the maximum energy peaks. The second objective is to obtain the experimental natural frequencies, which are used to design the pendulum rod.

It is important to note that all tests were performed with forced vibration based on a sinusoidal function, keeping the amplitude, frequency range and duration of the tests constant. In addition, to ensure that the extracted results had the lowest fluctuation, all screws were checked and tightened, if necessary, before each experiment. Furthermore, experiments were performed with data acquisition on the three floors of the structure, not at the same time, as to prevent interference from the sensor on the structure.

3. RESULTS AND DISCUSSION

The first step in the experimental process was to obtain the natural frequencies of the structure. To limit the study, it was chosen to work only with the first three natural frequencies of the structure, whose average values are in Tab. 3, corresponding to a maximum variation of up to 4.4%, when compared to the measurements of the other floors , validating the experimental modal analysis. As shown, the highest frequency is below the stipulated maximum value. With the knowledge of natural frequencies, it is possible to calculate the length of the TMD rod using Eq. (5). Rod length values are shown in Tab. 3.

Table 3. Experimentally obtained natural frequencies and respective rod lengths.

Natural Frequency	Average Frequency (Hz)	Rod Length (mm)	TMD Stiffness (N/m)	Rod Mass (g)
f_1	3,73	174	137	25
f_2	11,57	82	1321	10
f_3	16,87	63	2809	08

With these values, it was possible to manufacture the TMDs for each natural frequency, allowing the beginning of the second stage of the experimental process, obtaining the FRFs for the structure with the TMD. This results in the first form of structure vibration control. The efficiency analysis of the control methods will be made from the reduction in transmissibility caused by each one of these methods. Thus, Fig. 6 shows the FRFs for the TMD calibrated for the first natural frequency. As all other experiments, the base of the main structure was fixed to the Shake Table, that is, the structure is always being excited on its base. Considering the input data, it is important to notice that in all experiments, this data is collected by a sensor that is attached to the Shake Table; therefore, having the same displacement as the base of the structure.

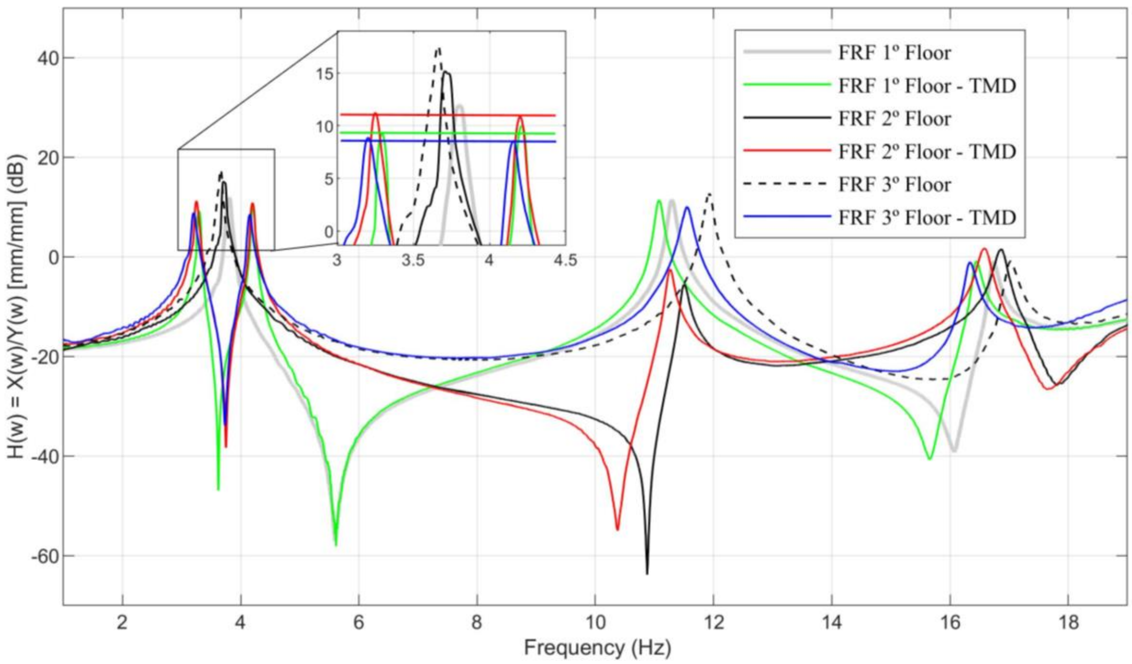


Figure 6. Experimental FRF for TMD calibrated for the first natural frequency.

When comparing the peak of the structure without TMD with the highest anti-resonance peak (reading on the first floor), a reduction of 58.8 dB can be evidenced. When comparing the lateral peaks, whose formation is due to the use of the TMD, there was a maximum reduction of 8.9 dB, a value obtained for reading on the third floor. This initial reduction was approximately 50.5%. The reduction of the lateral peaks becomes important because, as the TMD acts in a small frequency range, the excitation may occur outside the device's direct acting band, that is, in the peak frequencies generated by the addition of the TMD.

Following to the next step, two springs were added to the TMD, one on each side at approximately 45°. Experiments were carried out with 100% preloaded steel springs and SMA springs, with the latter having 100% and 300% preloads. As the TMD rod calibrated for the first frequency is long, this implies a large range of motion, which in turn makes it impossible to use the selected springs, as well as causing a change in the spring clamping angle. Because of these geometric limitations, experiments were performed for the second natural frequency, as it contains more energy than the third.

Performing the appropriate experiments, it can be evidenced that there was control of the structure. When analyzing the anti-resonance frequency, a maximum reduction of 52.4 dB for the first floor, corresponding to the steel springs, can be observed. Similarly, when analyzing adjacent frequencies, there was a maximum reduction of 9.2 dB, equivalent to 80%, when analyzing the peak in the lower frequency (SMA-100%) and 11.7 dB, equivalent to 101.7% when analyzing the peak with the higher frequency (steel).

Similarly, the same experiments were performed with data acquisition on the second floor of the main structure. For the anti-resonance frequency, a maximum reduction of 14.4 dB was obtained with the use of the SMA springs with 100% preload. Unlike previous results for adjacent frequencies, when analyzing the lower frequency, there was a minimum increase of 1.7 dB, corresponding to SMA springs with 300% preload. In the higher frequency analysis, there was a maximum reduction of 7.5 dB, corresponding to the steel coil springs.

Finally, the analysis was performed with data acquisition on the third floor of the main structure, the results of which can be seen in Fig. 7. For the anti-resonance frequency, a maximum reduction of 50.1 dB was obtained, corresponding to the Steel springs. When the adjacent frequencies are observed, similar results are observed to those obtained for the first floor, there was a reduction for both lower and higher frequencies. In the case of the lower, the maximum reduction was 16.7 dB, while in the latter there was a maximum reduction of 14.6 dB, both for the use of 300% offset SMA springs.

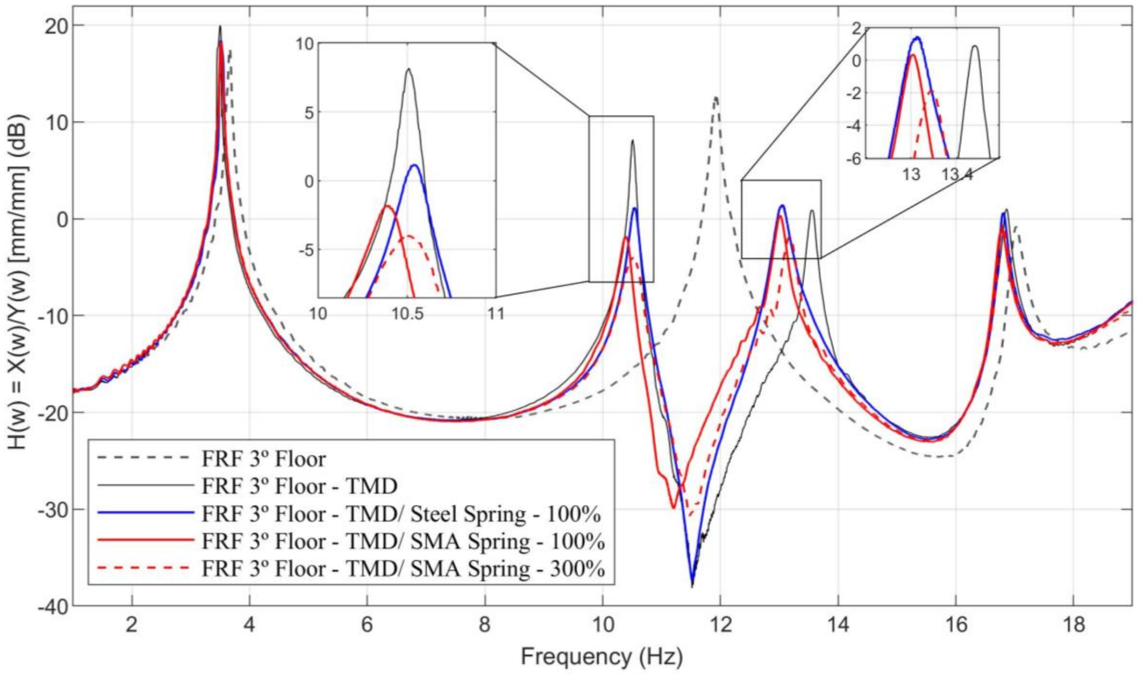


Figure 7. FRFs obtained for the second natural frequency with acquisition on the third floor.

To facilitate the visualization of the results obtained, these are shown in Tab. 4, which illustrates the results obtained for the anti-resonance frequency and for the lower and higher frequencies for each of the studied floors. In the case of the latter frequencies, the best cases are shown, as well as which type of spring was used to obtain this data. All results found in Tab. 4 have unit of dB. As these results show the maximum reduction obtained, the negative signal represents an increase in transmissibility for the respective frequency.

Table 4. Maximum reduction in transmissibility for the second natural frequency.

Floor	Anti-resonance Frequency	Lower Frequency	Best Case	Lower Frequency	Best Case
1°	52,4	9,2	SMA-100%	11,7	Steel
2°	14,4	-1,7	SMA-300%	7,5	Steel
3°	50,1	16,7	SMA-300%	14,6	SMA-300%

4. CONCLUSION

From these analyzes, it can be concluded that passive TMD is an effective method for vibrational control for a structure with three degrees of freedom, provided that the working frequency range is known and small. This fact can be evidenced by the large reduction in transmissibility when analyzing the anti-resonance frequencies, an event that is becomes present by the addition of TMD, which reached 58.8 dB for the first floor. In addition, this device also has the feature of causing a slight reduction in frequencies adjacent to the calibration frequency.

The addition of springs aims to attenuate vibrations at adjacent frequencies, amplifying both the working range of the device and the dissipated energy. Performing a comparative analysis between steel springs and SMA springs, it can be noted that in most cases, more precisely in 67% of these, SMA springs caused a greater reduction in transmissibility at adjacent frequencies, with the maximum reduction being of 52.4 dB. However, further study is needed to understand the zones in which each type of spring is most efficient.

Regarding the preloads, it can be seen that the springs with a preload of 300% caused a slightly greater transmissibility reduction than the 100% springs in most cases studied, more precisely in 75% of the cases. This difference was greater when analyzing the third floor, which is the floor that has the largest displacement in relation to the base. Reductions in the third floor reached 131.5% and 115% for the adjacent lower and higher frequencies, respectively, proving a high efficiency in this last floor.

When thinking about the real case, the results show that the TMD with SMA-300% springs would provide exactly what a building needs. In such a structure, the most critical elements are the top floors, and the study showed that the further from the base, the more efficient the setup with the 300% preload is.

In order to gain a better understanding of this phenomenon, a detailed study of the maximum and minimum deformations that the springs suffer during TMD movement is necessary to obtain more preload values that can be used. In addition, other spring fixation geometries can be studied, as well as the variation in the amount of springs used.

5. ACKNOWLEDGEMENTS

The authors of this paper are grateful for the support provided by CNPq with the Proc. 408131/2018-7 Edital Universal No 28/2018, LVI, LaMMEA, LabII, UFCG and UFPB, who were extremely important for the development of this project.

6. REFERENCES

Chang, S., et al., 2016. "Dampig Characteristics of the Inherent and Intrinsic Internal Friction of $Ti_{50}N_{50-x}Fe_x$ (x=2, 3 and 4) Shape Memory Alloys." *Materials Transactions*, Vol. 57, No. 3, pp. 351-356.

DesRoches, R., et al, 2003. "Cyclic Properties of Superelastic Shape Memory Alloy Wires and Bars." Journal of Structural Engineering, Vol. 130, No. 1, pp. 38-46.

Moraes, Y. J. O., et al., 2018. "Dynamical Analysis Applied to Passive Control of Vibrations in a Structural Model Incorporating SMA-SE Coil Springs." *Advances in Materials Science and Engineering*, Vol. 2018, pp. 1-15.

Rao, S. S., 2011. Mechanical Vibrations. 5^{th} ed., Prentice Hall.

Sadek, F., et al, 1998. "A Method of Estimating the Parameters of Tuned Mass Damper for Seismic Application." Earthquake Engineering & Structural Dynamics, Vol. 26, No. 6, pp. 617-635.

7. RESPONSIBILITY NOTICE

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