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VIBRATION CONTROL OF SLENDER STRUCTURES WITH OPTIMIZED LIQUID COLUMN VIBRATION ABSORBERS

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Abstract. *Liquid Column Vibration Absorbers (LCVA) are devices used to control/reduce low frequency vibrations in slender structures such as buildings, offshore structures, among others. The sources of excitation may be diverse, such as: wind, seismic, unbalance and waves of the sea. In this paper, the performance and effectiveness of a LCVA is investigated. LCVA was designed using nonlinear optimization techniques to control the first vibration mode in a small-scale eight-story building. The scale model of the building represents, without loss generality, slender structures of low frequency. To evaluate the performance of the designed control device, a set of experimental analysis are conducted on the model of the building. These analyses were performed using Frequency Response Functions (FRF) measurements (Inertance), where the excitation was performed with an impact hammer and the response was obtained by an accelerometer. Thus, the effectiveness of the LCVA can be measured based on the reduced frame response presented in the FRF.*

Keywords: *Liquid Column Vibration Absorbers, Vibration Control, Passive Vibration Control, Non-linear optimization techniques*

1. INTRODUCTION

The use of new building materials, development of construction techniques and the application of more efficient structural analysis methods has allowed the construction of lighter and more slender structures. The slenderness of structures is closely related to their flexibility, making them increasingly sensitive to external excitation. In slender structures, the effect of lateral forces such as wind and seismic shocks tend to be low frequency, which can generate resonance conditions. To avoid the damaging effects of these vibrations, the system must be able to effectively control them. Among the possible vibration control techniques, passive control is attractive because it does not require external sources of energy to operate, as well as advantages in terms of reliability, cost-benefit, assembly and simple maintenance.

Among other passive control devices is the Liquid Column Vibration Absorbers (LCVA). This consists of a reservoir of liquid, which is rigidly connected to the structure to be controlled, thus having the ability to dissipate undesired vibrational energy through the movement of the liquid. This kind of absorber is often used for low frequency vibrations. The control device operates optimally when the excitation reaches certain specific parameters, such as in certain wind excitation frequency ranges, which tend to be low, and causes high vibration amplitudes in the structure.

Some of the pioneers to make use of LCVAs in civil engineering structures were Sakai and Takeda (1989). Balendra et al. (1995) studied the effectiveness of a LCVA for the control of tower vibration. Chang and Hsu (1997) investigated the performance of a LCVA for wind driven vibration control of a building. Jin et al. (2007) conducted a numerical and experimental study on LCVAs to control the seismic response of an offshore platform. Al-Saif et al. (2011) proposed a modified version of the LCVA applicable in the vibration control of structures subjected to low frequency vibrations. Shad et al. (2013) conducted a numerical and experimental study to evaluate the effectiveness of a LCVA coupled to a scaled steel structure when subjected to seismic and harmonic loading. Altunisik et al. (2017) studied the performance of LCVAs installed in a prototype of a steel structure exposed to soil movements with different excitation directions.

This paper presents the results of experimental analyses to evaluate the performance of a LCVA applied in a scale model of an eight-story building. Measurements were made based on the reduction of the structure response through Frequency Response (FRF) measurements.

2. LIQUID COLUMN VIBRATION ABSORBERS (LCVA)

In slender structures, the first natural frequencies are usually low (order of one Hz). For this type of structure, the LCVA is among the most used control devices, because, due to their dynamic characteristics, these devices work in low frequency. There are several versions of the LCVA, and the most common consisting of: U-shaped, V-shaped or circular reservoir.

When a structure begins to vibrate, the LCVA is excited by the movement of the structure. As the operation of LCVA consists of the liquid mass oscillation in the reservoir, it is fundamental that the frequency of this movement be in tune with the natural frequency of the structure (Chaiviriyawong et al. 2008).

A LCVA, when compared with other vibration control devices in slender structures, proves to be a very interesting solution in terms of economics and simplicity of installation and maintenance (Pestana, 2012).

The Fig. 1 shows a schematic representation of the control device.

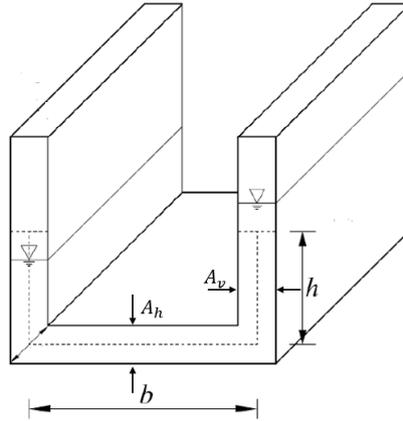


Figure 1. Schematic representation of a Liquid Column Vibration Absorbers (LCVA).

Sakai and Takeda (1989). have presented fundamental theory to describe the motion of a LCVA, as well as allowing simple calculations of the natural frequency of the liquid column. This theory can be derived using a model of a simple U-tube with a constant rectangular cross-section, in which the motion of the liquid contained inside a LCVA is assumed to be unsteady and nonuniform. The natural frequency of a LCVA can be calculated using Eq. (1), and can be seen to be dependent on the effective length (L_e) of the liquid column and gravitational acceleration, whereas the LCVA mass is equal to the total mass of liquid contained in the passive control device $m = m_l$

$$\Omega_{LCVA} = \frac{1}{2\pi} \sqrt{\frac{2g}{L_e}} \quad (1)$$

The effective length (L_e) is given by Eq. 2:

$$L_e = \left(\frac{A_v}{A_h}\right) b + 2h \quad (2)$$

where A_v and A_h are the vertical and horizontal cross-sections of LCVA, respectively, b is the length of the horizontal column and h the height of the vertical column as shown in Fig. 1

The natural frequency of LCVA Eq. (1) is of considerable importance to the project, because it will provide primordial information that will be used in subsequent numerical analysis.

3. PRIMARY SYSTEM

The physical model of the primary system for analysis is an eight-story scale building, as can be seen in Fig. 2. The scale model of the building represents a slender low frequency structures to be controlled by LCVA, which has the following characteristics:

- Its base is composed of a concrete block simulating the building foundation;
- Support beams are corrugated steel bars;
- Steel sheets are equivalent to the slabs of each floor.

Table 1 shows the dimensions of each part that comprises the model building.

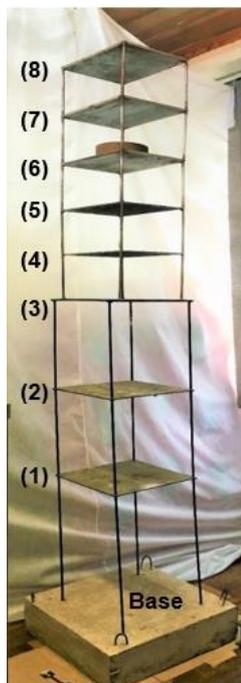


Figure 2. Physical model of the eight-story slender building.

Table 1. Physical dimensions of the eight-story slender building

Item	Length (mm)	Width (mm)	Thickness (mm)
Base	600	600	150
Slab 1	400	400	4,5
Slab 2	400	400	4,5
Slab 3	400	400	9,5
Slab 4	400	300	5,3
Slab 5	400	300	5,3
Slab 6	400	300	10
Slab 7	400	300	10
Slab 8	400	300	10
Large Pillars	400	Diameter = 9,8	-
Minor Pillars	200	Diameter = 9,8	-

4. LIQUID COLUMN VIBRATION ABSORBERS DESIGN

For LCVA design, firstly, the modal parameters of the primary system are obtained. Thus, the natural frequencies and their respective modes of vibration are initially obtained, using a finite element model with the use of ANSYS software. These parameters are validated through an experimental analysis performed at the Laboratory of Vibrations and Sound of UFPR (LAVIBS).

With the model of the primary system validated, following the methodology based on the concept of generalized equivalent parameters (GEP) (Espíndola e Silva, 1992), nonlinear optimization techniques (NLOT) are used to find the ideal parameters of the damper, so that effective vibration control is achieved. NLOTs are applied using the software “LAVIBS-ND”, developed by the students of the Vibration and Sound Group (GVIBS) of the Federal University of Paraná (UFPR), with has numerical codes implemented in FORTRAN language and JAVA graphical interface. The software has 5 types of absorbers, among which is the LCVA. The Fig. 3 shows one of the software screens “LAVIBS-ND”.

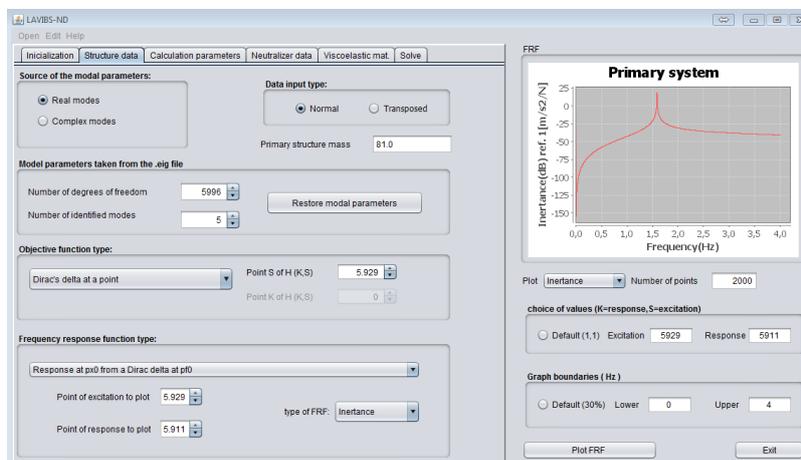


Figure 3. Screen optimization software "LAVIBS-ND"

The software is based on input data such as: primary system modal parameters, frequency range for control, quantity and position of absorber. The output are the optimal parameters (optimal frequency, optimal mass and optimal damping) for the control device design. The concern here is the control of a small frequency range, where the first mode is predominant as the most important mode to be controlled in slender low frequency structures by LCVA. The input data were obtained through a modal analysis made in ANSYS Workbench. In this model, the mode shapes were considered as one-dimensional, since in this work the optimal LCVA design considers the transverse excitation only, on the “X” axis.

With the modal parameters of the primary system determined, an optimization method, based in genetic algorithms, was performed (Bavastrri et al., 2007). To proceed with the optimization, the software requires the prior definition of the quantity and modal position of the absorbers. It was established the design of a single absorber positioned at the top of the structure. The choice of the position of the absorber was made, considering that the top of the building has the largest displacement for first mode of vibration. Thereby, it will increase the efficiency LCVA, because this is the mode to be controlled. Thus, with all parameters determined, it is possible to send the data to the FORTRAN algorithm to perform the calculations. And when completed, the “LAVIBS-ND” software generates an output file which contains the optimum absorber parameters.

With the optimum parameters of the damper determined, it is possible to calculate analytically the physical parameters (dimensions and shape) of the LCVA that satisfies the obtained results. For the design of the LCVA, we chose the box geometry in “U” shape. Such geometry is composed of two vertical columns connected by a horizontal passage, filled to a certain level with liquid. The liquid chosen to compose the control device was water. Thus, with the predefined geometry, some algebraic manipulations (from Eq. 1) were performed to determine the dimensions in order to satisfy the parameters obtained via NLOT. The designed device and its dimensions (in mm) can be seen in Fig. 4.

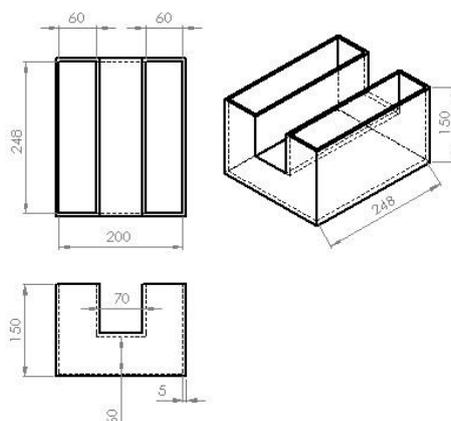


Figure 4. Model and dimensions of the designed LCVA.

The optimum results obtained via NLOT for the LCVA design were:

- Optimal natural frequency: 1.58 Hz;
- Optimal mass: 3.56 kg; and
- Optimal damping ratio: 0.13.

Thereby, the LCVA was built in acrylic, to enable the visualization of the liquid movement during the experimental measurements. The constructed device can be seen in Fig. 5.



Figure 5. Liquid Column Vibration Absorber.

After construction, to control device characterization, experimental analysis were performed in order to obtain the Frequency Response Function (FRF) curves and thus verify if the projected dimensions led to the natural frequency obtained via NLOT to control the system first mode of vibration. For this, a power amplifier, a piezoelectric accelerometer, an electromagnetic shaker, a load cell, a signal analyzer and a computer were used as shown in Fig. 6.

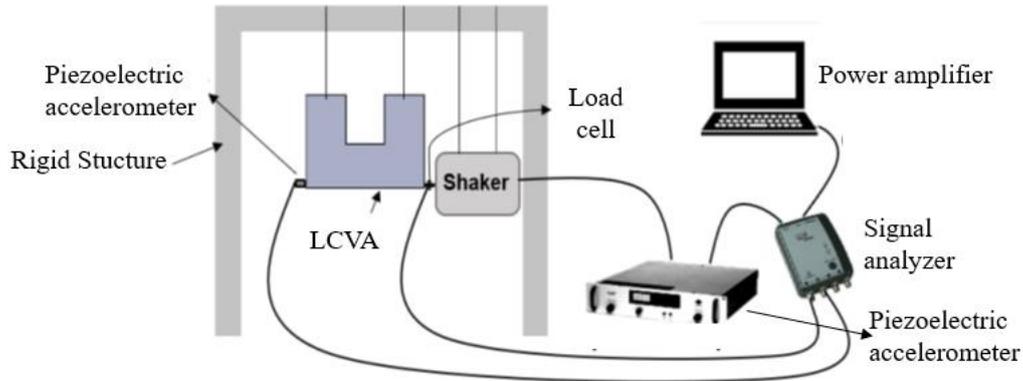


Figure 6. LCVA Measurement System Configuration.

The LCVA was connected to the shaker, together with a load cell (model 8230-002, Bruel & Kjaer). The load cell was interlocked with a screw to ensure that shaker oscillation was transmitted in phase to the LCVA. On the opposite side of the projected control system, regarding the excitation direction, a piezoelectric accelerometer (model 393A03, PCB Piezotronics) was installed to determine the dynamic mass on the base of the system. The dynamic mass corresponds to the ratio between excitation and acceleration response. Although the useful range of the shaker occurs above 2 Hz, it can operate in frequencies below. In this case, as it was used to obtain a FRF, it was enough that the shaker could maintain, in the interest frequency range (between 1 and 5 Hz), a constant force, which was proved experimentally possible. The accelerometer and load cell information was obtained by signal analyzer PHOTON II for further analysis of the results.

4.1 Experimental arrangement

In order to verify its effectiveness for controlling the first mode of vibration on the “X” direction of the structure, experimental measurements of frequency response function (Inertance), were performed, comparing the primary system response with and without LCVA.

The experimental test, as shown in Fig. 7, was carried out by applying a mechanical impulse to the primary system with an impact hammer (model 086C04), and measuring the response with a piezoelectric accelerometer fixed to the primary system (model 393A03), both from the PCB Piezotronics. The obtained signal is then digitized by PHOTON II data acquisition system (LDS Dactron). The modal data were extracted using the RT Pro Photon software in a portable computer, which generates the Frequency Response Functions.

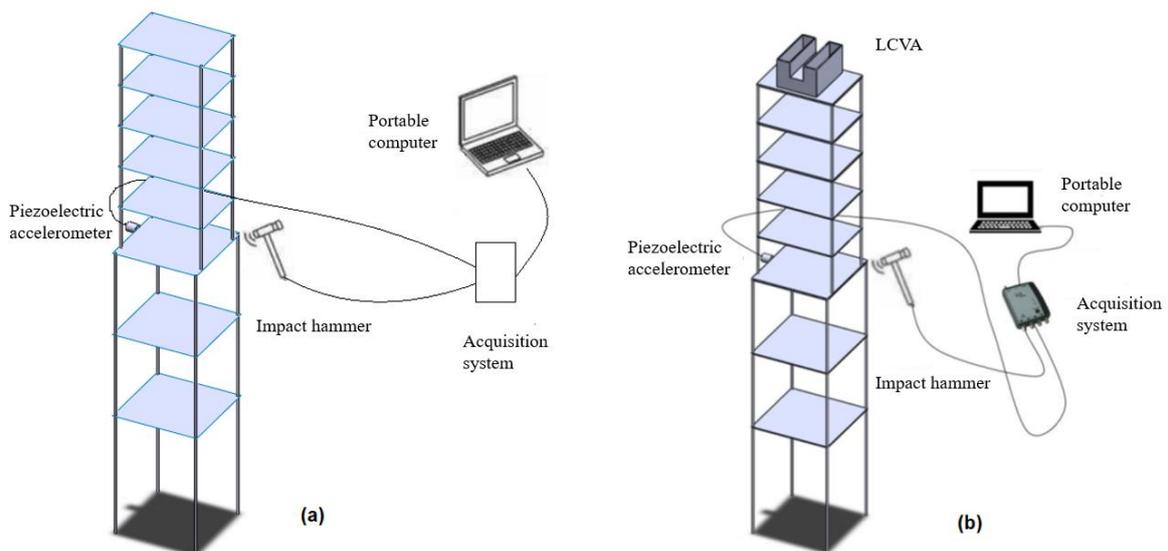


Figure 7. Schematic representation of the Frequency Response Function. (a) primary system (b) composite system.

The Fig. 8 shows how RT Pro Photon software generates the obtained signal. On the left side of the screen you can see the input (excitation) and output (response) signals in the time domain; and in the middle of the screen you can check the FRF curves, where the graph above shows the magnitude of the signal in dB and the below shows its phase.

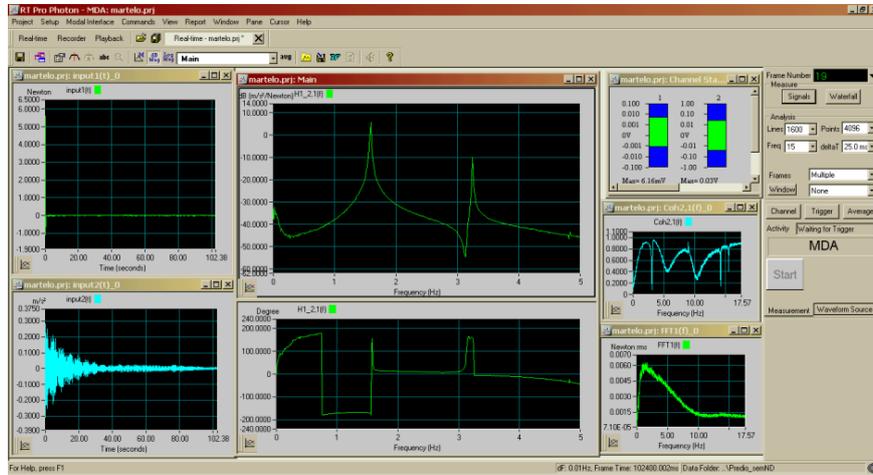


Figure 8. RT Pro Photon software screen.

For primary system analysis and composite system analysis, the position for excitation and response were the same. As shown in Fig. 7, the excitation and response were applied on Slab 3, in a way that the sensors were aligned, allowing an approximation of one unidirectional experimental test.

5. RESULTS

5.1 LCVA analysis

With the LCVA built, the experimental analysis was performed in order to obtain the curves of dynamic mass on the base of the device. The result obtained can be seen in Fig. 9.

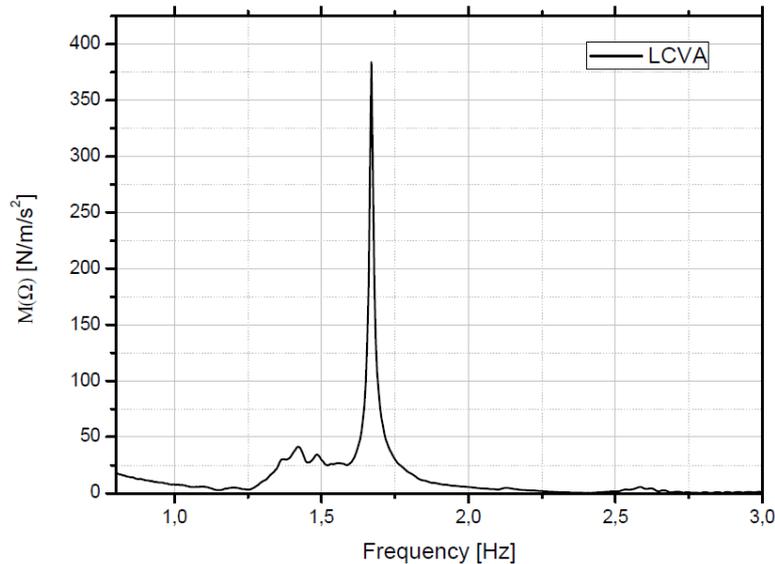


Figure 9. Dynamic mass at LCVA base

It is possible to observe in Fig. 9 that the resonant frequency peak has a value around 1.6 Hz, which coincides with the value obtained via NLOT. The dynamic mass (FRF) provides an idea of the difficulty with which the structure can be moved. This means that for the peak frequency, the behavior of the absorber will oppose the response of the primary system. This effect is what results in the vibration control of the structure.

It can also be observed in Fig. 9 a peak before the resonant frequency. This peak may be related to the rigid body frequencies of the system due to the way the LCVA was positioned during the experimental analysis.

5.2 Coupled System Analysis

In order to evaluate the effectiveness of the LCVA designed to reduce the vibration amplitude of the eight-story building in scale, the inertance curves obtained by the experimental analysis of the composite system were compared with the response obtained by the primary system analysis. The effectiveness of the LCVA can be proven according to Fig. 10, where the results of the building with and without the absorber are presented.

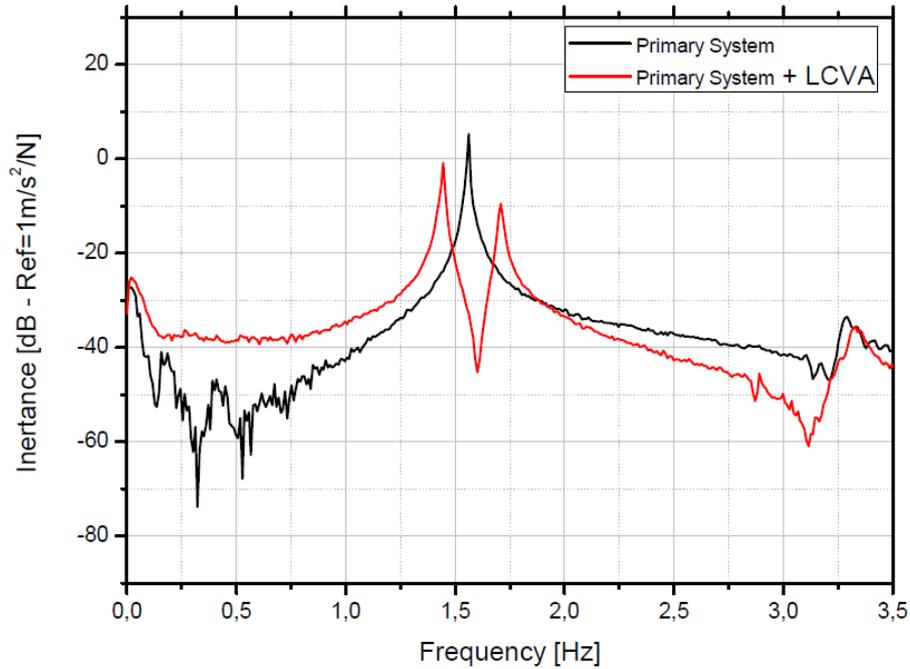


Figure 10. FRF of the primary system with and without the experimentally obtained LCVA.

In Fig. 10, the black curve represents the primary system response without the control device, while the red curve represents the primary system (building) response with the LCVA attached to the top of the frame. In Tab.2 it is possible to verify the efficiency in reducing the amplitude obtained by coupling the LCVA to the eight-story scale building.

Table 2. Efficiency of the LCVA coupled to slender building experimentally analyzed.

	Natural Frequency [Hz]	Amplitude [dB]	Reduction [dB]
Primary system without LCVA	1,58	5,37	-
Primary system with LCVA	1,445	-0,78	6,15 dB
	1,58	-32,7	38,07 dB
	1,708	-9,47	14,84 dB

The first peak generated in the composite system analysis corresponding to a frequency of 1.445 Hz, which occurs when the displacement of the building and the liquid that makes up the absorber are in the same phase, at such frequency a reduction of 6.15 dB is noted. Already the second peak of the composite system, corresponding to the frequency 1.708 Hz, which occurs when the liquid movement and the building displacement are with a phase lagged in 180 degrees. In this frequency, a reduction of approximately 15 dB can be observed. These two peaks appear because when coupling the LCVA to the system, the configuration of the mode to be controlled changes, creating an additional degree of freedom. These two modes can be reduced if it is possible to add damping in the LCVA. However, this possibility was not approached in this paper.

As the LCVA has low damping, when optimizing for the 1st mode of the primary structure, the reduction reached 38.07 dB for this mode. This proves that LCVA as a great device for vibration control in slender structures, considering a narrow frequency range.

6. CONCLUSION

In this paper, the performance and effectiveness of a LCVA, designed using non-linear optimization techniques, to control the first mode of vibration in a small-scale eight-story building was investigated. For the LCVA design, a specific optimization is performed through the software "LAVIBS-ND", using the modal parameters of the primary system identified by numerical analysis using ANSYS software. The aim here is to reduce the response of the primary system to the choice of optimal parameters of the absorber. With the results obtained through NLOT it was possible to size the ND in order to satisfy the optimal parameters found. With the defined dimensions, the control device was constructed in acrylic for later analysis of its effectiveness.

The effectiveness of the LCVA verified from measurements of inertance curves of the primary system without and with the designed device coupled to the top of the structure.

Significant reduction in amplitude was noted when the LCVA was introduced into the eight-story low-scale building. This reduction represents approximately 40 dB, thus showing an effective behavior for the control of vibration for the frequency in question.

The results obtained for the LCVA were shown to be a promising device for passive vibration control, being an economic option for lean buildings.

7. REFERENCES

- Altunişik, A. C.; Yetişken, A.; Kahya, V., 2017. "Experimental study on control performance of tuned liquid column dampers considering different excitation directions". *Mechanical Systems and Signal Processing*, Vol. 102.
- Al-Saif, K.A.; Aldakkan, K.A.; Foda, K.A., 2011. "Modified liquid column damper for vibration control of structures". *International Journal of Mechanical Sciences*, Vol. 53.
- Balendra, T.; Wang, C. M.; Cheong, H. F., 1995. "Effectiveness of Tuned Liquid Column Dampers for Vibration Control of towers". *Engineering Structures*, Vol. 17, n. 9.
- Bavastri, C. A.; Doubrawa, F.J.; Espíndola, J. J.; Lopes, E. M. O.; Venancio, H. W., 2007. "Modelo geral de neutralizadores dinâmicos para controle passivo de vibrações e ruído: Parâmetros equivalentes generalizados". *XXVII Cilamce - Iberian Latin American Congress on Computational Methods in Engineering*.
- Chaiviriyawong, P., Limkatanyu, S. e Pinkaew, T. "Simulations of characteristics of tuned liquid column damper using an elliptical flow path estimation method". *The 14th World Conference on Earthquake Engineering, 2008*.
- Chang, C.C.; Hsu, C.T., 1997. "Control performance of liquid column vibration absorbers". *Engineering Structures*.
- Dimarogonas, A., 1996. *Vibration for Engineers*. Prentice-Hall, New Jersey, 2nd edition.
- Espíndola, J. J.; Silva, H. P., 1992. "Modal Reduction of Vibration by Dynamic Neutralizers: A General Approach". *Proceedings of 10th International Modal Analysis Conference*.
- Jin, Q., Li, X., Sun, N., Zhou, J., Guan, J., 2007. "Experimental and numerical study on tuned liquid dampers for controlling earthquake response of jacket offshore platform". *Marine Structures*.
- Pestana, I. G. Controle de vibrações em engenharia civil – Amortecedor de Colunas de Líquido Sintonizado. Dissertação (mestrado) – *Universidade Nova de Lisboa, 2012*.
- Sakai, F.; Takeda, S., 1989. "Tuned liquid column damper new type device for suppression of building vibrations". *Proceedings of International Conference on High Rise Buildings*.
- Shad, H.; Adnan, A. B.; Behbahani, H. P. Performance evaluation of tuned liquid dampers on response of a SDOF system under earthquake excitation and harmonic load. *Research Journal of Applied Sciences, Engineering and Technology, 2013*.

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