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EXPERIMENTAL STUDY OF AN INVERTED PENDULUM TUNED MASS DAMPER

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Abstract. *The constant advance in the materials and techniques of civil construction, especially with the advent of the personal computer in the design of structures, allowed the appearance of gradually taller buildings. This resulted in an increase in the slenderness and flexibility of structures, also increasing the vulnerability of these structures to dynamic actions such as winds and earthquakes. In view of this, the vibration control appears as a subject of great importance for structural engineering. One of the passive structural control devices is the Tuned Mass Damper (TMD), which promotes the transference of energy between the main structure and an auxiliary mass. One of the TMD most used in building structures is the conventional pendulum type, but this one still has some drawbacks, such as the large space it occupies inside the building. In this work, a scale model of a 10-storey building is controlled by an Inverted Pendulum Tuned Mass Damper (IPTMD). The IPTMD modal parameters, obtained experimentally by video motion capture analysis, are used as the definition basis for main design parameters.*

Keywords: Structural Control, Tuned Mass Damper, Inverted Pendulum

1. INTRODUCTION

The advent of increasingly slender and flexible structures has imposed the need for vibration control devices over the time. A typical passive control device is the Tuned Mass Damper (TMD) (Carmona et al, 2017) tuned to a specific frequency to vibrate out of phase with the main system. This transfers energy between them reducing the response of the main system. This passive control device has been studied by many researchers in literature. (Avila, 2002; Ghassempour et al, 2019; Elias et al, 2016; Garrido et al, 2013)

A common TMD geometry is a simple pendulum (Oliveira et al, 2014), this device has been successfully applied in the passive control of wind-induced vibrations of high structures (Deraemaeker and Soltani, 2016). However, it has drawback of requiring large internal space inside the building. Thus, inverted pendulum appears as a possible adequate alternative (Guimarães et al, 2014). On the other hand, according to Anh et al. (2007), studying and designing an inverted pendulum system is a great challenge compared to simple pendulum due to its stability. While the simple pendulum is stable, the inverted one is unstable.

This work presents an experimental model of TMD Inverted Pendulum (IPTMD), built to control a 10-storey building scale model. The scale model is composed by a three-dimensional steel frame. The IPTMD modal parameters, obtained experimentally by video motion capture analysis, are used as the definition basis for main design parameters.

2. SCALE MODEL OF MAIN STRUCTURE

2.1 Experimental Scale Model of Tall Building

To simulate the dynamic behavior of a tall building experimentally, a scale model was constructed (Bernardes Junior et al., 2017). This model consists of ten steel SAE 1020 modules. Each module is composed of two plates connected to each other by four columns. All plates and columns having a thickness of 6.3 mm. And Fig. 1 shows the main dimensions.

Figure 2 show the scale model assembly attached at a fixed base. The resulting structure is approximately 2.12 meters high and has an approximate slenderness ratio of 1:10.

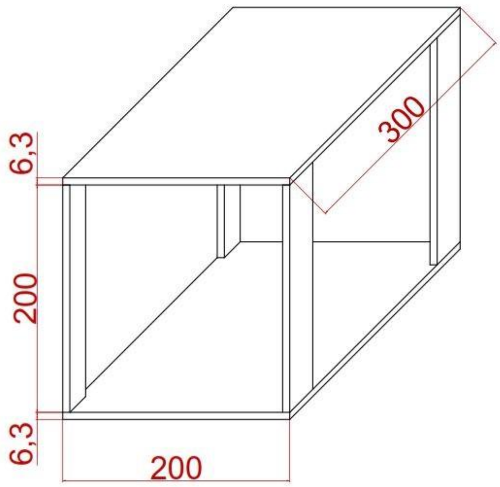


Figure 1. Isometric view and main dimensions (mm) of Steel Module

Figure 2. Ten-Story Building Scale Model

2.2 Experimental Modal Analysis

A modal test was carried out with an impact hammer test and two accelerometers (a reference and a measurement accelerometer). Both shear piezoelectric accelerometers have a sensitivity of 10 mV/g. The structure was excited with an impulse always in the same place, at half height. The reference accelerometer was also positioned at half height, while the measurement accelerometer was positioned at the top of the structure. The signals were acquired in the time domain by an acquisition system and registered with LabView software. Table 1 presents the first two natural frequencies identified, illustrated at Figure 3.

Table 1 – Natural Frequencies.

Mode	Frequency (Hz)
1	4.04
2	12.15

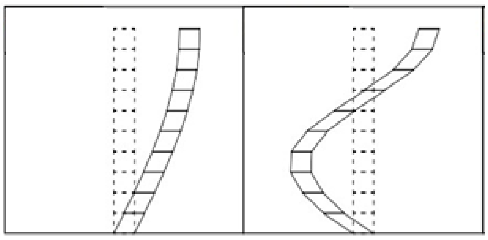


Figure 3. First two vibration modes: 4.04 Hz (left) and 12.15 Hz (right)

3. NUMERICAL MODEL

The physical model presented was modeled, in its lower stiffness direction, as a shear-frame frame with ten degrees of freedom. The mass of each floor was considered as the total mass of the plates, screws and nuts, subtracting the mass of the holes. The stiffness of each floor was assumed to be the sum of the stiffness of all the columns of the floor, in the direction considered. The motion equation of this system is given by

$$\boldsymbol{M}\ddot{\boldsymbol{y}}(t) + \boldsymbol{C}\dot{\boldsymbol{y}}(t) + \boldsymbol{K}\boldsymbol{y}(t) = \boldsymbol{F}(t) \tag{1}$$

where $\boldsymbol{M}$ is the mass matrix, $\boldsymbol{C}$ is the damping matrix, $\boldsymbol{K}$ is the stiffness matrix, $\boldsymbol{F}$(t) is the dynamic force vector and $\boldsymbol{y}$(t) is the displacement vector of the structure.

However, the response of systems with many degrees of freedom, such as tall buildings, can be obtained through a reduced model using the modal reduction technique (Soong and Dargush, 1997). Considering a structural damping ratio of $\xi_1 = 0.004$, the properties of the reduced one degree of freedom model are given : $M_1 = 33.5559$ kg, $K_1 = 2.1513\text{x}10^4$ N/m and $C_1 = 6.7971$ Ns/m.

The tuned mass damper studied in this work is characterized by a rigid bar with linear mass density ρ and length L, coupled at one end to the main structure with stiffness K_d and damping coefficient C_d. A mass M_d is concentrated at the other end of the bar (Figure 4).

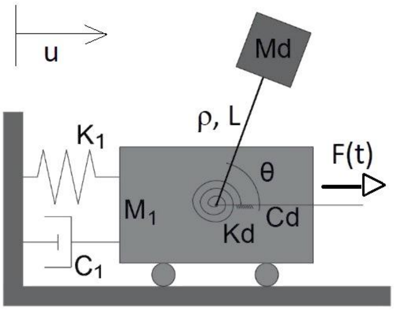


Figure 4. One degree of freedom main system with an IPTMD attached

It is considered that the angular amplitude is maintained within the regime of small displacements, to guarantee the linear behavior of the model. In addition, the vibration of the system is considered in only two dimensions. The matrix motion equation is given by

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

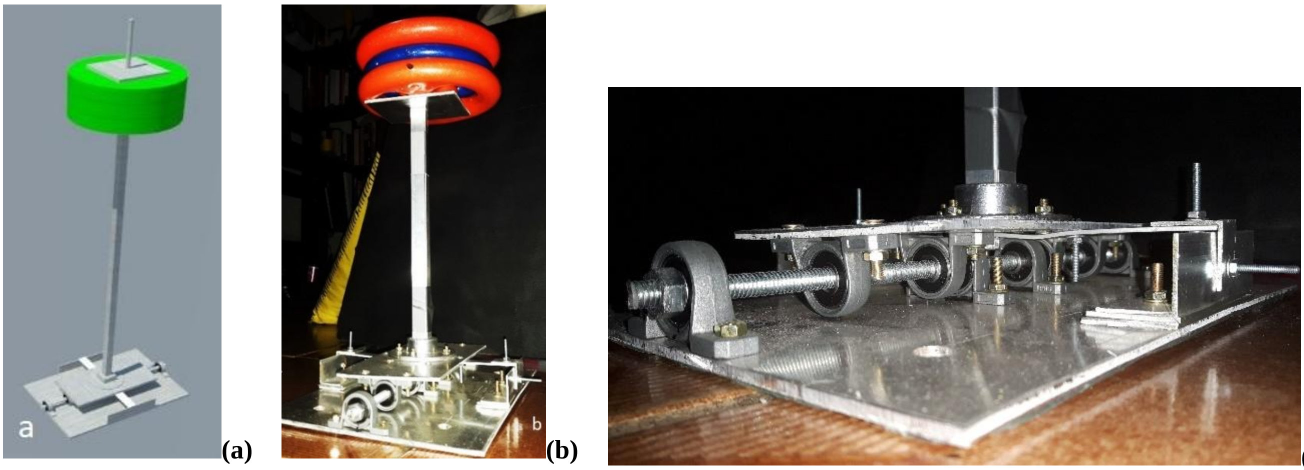
Where u and θ are the modal and angular displacements and F(t) is the dynamic excitation applied to the main system.

4. EXPERIMENTAL MODEL OF INVERTED PENDULUM TMD

4.1 Model Construction

The experimental Inverted Pendulum TMD (IPTMD) device was built in extrude aluminum sections, aluminum laminated plates, bearings, steel threaded rods and steel cast weights (Figs. 5a and 5b). Then, the mass M_d is defined partially as the body at top of bar, with length L, oscillating about the rod.

The angular displacement of the pendulum is obtained by installing an aluminum plate under the pendulum, transverse to the axis of rotation and fixed to the two lateral supports at the base (Fig. 5c). It is also this plate that is primarily responsible for the pendulum stiffness K_d. Thus, when changing this plate for others with different characteristics, it is possible to change this important IPTMD parameter.



(a) **(b)** **(c)**

Figure 5 – IPTMD in a CAD model (a), experimental (b) and detail of support (c).

4.2 Experimental Determination of IPTMD Parameters

The main design parameters of IPTMD are the bar length L and the mass ratio μ. In order to obtain these parameters, it is first necessary to know the stiffness K_d and the damping ratio ξ_d of the device. To identify these dynamic properties experimentally, it is used video motion acquiring techniques. The mass at the top M_d was varied from 1 to 6 kg, exciting the pendulum with an initial angular displacement (free vibration), while its movement was captured by a DSLR camera at the frequency of 30 frames per second. This procedure was repeated 5 times for each value of mass M_d. Using a fixed point in the video, within the the software *CvMob*, it was possible to capture the trajectory of this point (Fig. 6).

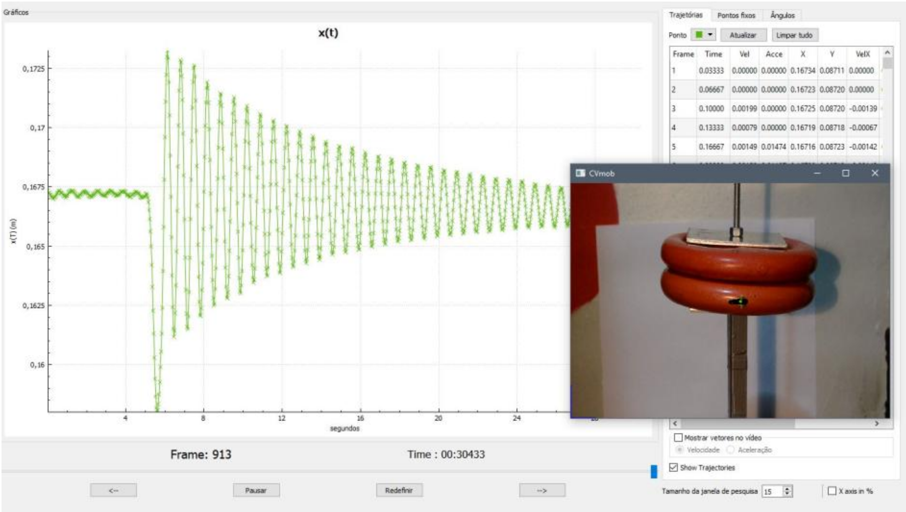


Figure 6 – Capture of the trajectory registered in the video.

Through CurveFit Toolbox (Matlab 2015), it was possible to adjust the captured displacement time history to a damped sinusoid:

$$y(t) = ae^{-bt}\sin(ct+d)+e \tag{3}$$

where

$$\omega_d{}^2 = c^2 + b^2 \tag{4}$$

$$\xi_d = \frac{b}{\omega_d} \tag{5}$$

and

$$K_d = \frac{2\omega_d{}^2 L^2 (3M_d + \rho L) + gL(6M_d + 3\rho L)}{6} \tag{6}$$

Equation (6) was given by Anh et al (2007) where ω_d is the natural frequency of the pendulum and ξ_d is the pendulum damping ratio. This procedure is illustrated in Fig. 7. The average values of K_d and ξ_d for each M_d value are shown in Table 2.

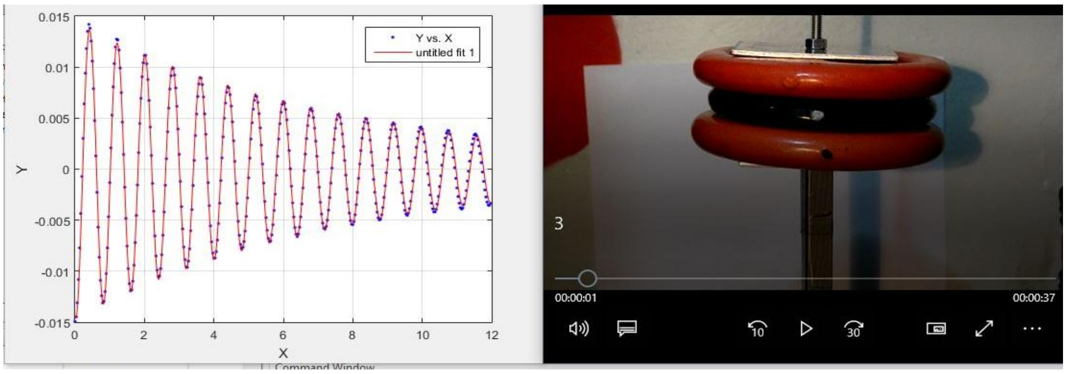


Figure 7 – Fit of trajectory with CurveFit Toolbox/Matlab

Table 2 – Experimental Stiffness K_d and Damping Factor ξ_d of IPTMD device.

	1 Kg	2 Kg	3 Kg	4 Kg	5 Kg	6 Kg	Average
Kd (N/m)	179.76	214.23	208.3	218.53	208.39	208.43	206.2
ξd	0.012	0.012	0.013	0.014	0.264	0.015	0.055

4.3 Search for the IPTM design parameters

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

To define the response map, shown in Figure 8, K_d and C_d were fixed from the values previously shown in Table 2, being 206.28 N / m and 1.29 Ns / m, respectively. It is possible to observe a valley on the map. According to Colherinhas et. (2016), this value can be interpreted as corresponding to the points where the combination of values μ and *L* results in a solution with the lowest values of response peaks. It is possible to observe a curve in the top view of the generated surface (Figure 9).

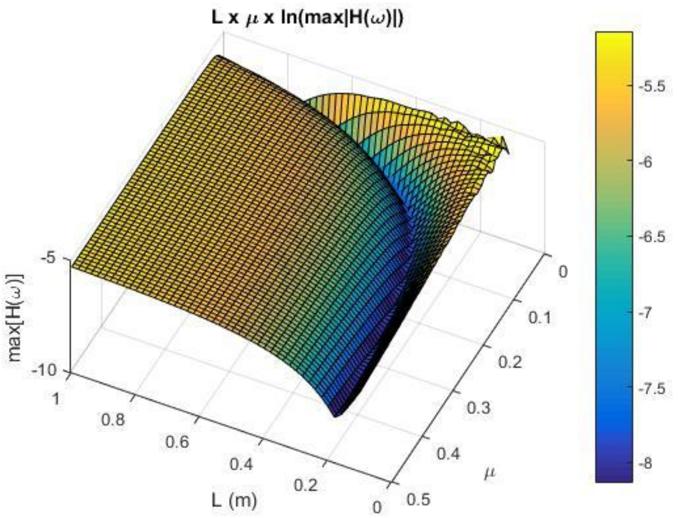


Figure 8 Map of the Frequency Response Functions as a function of *L* and μ

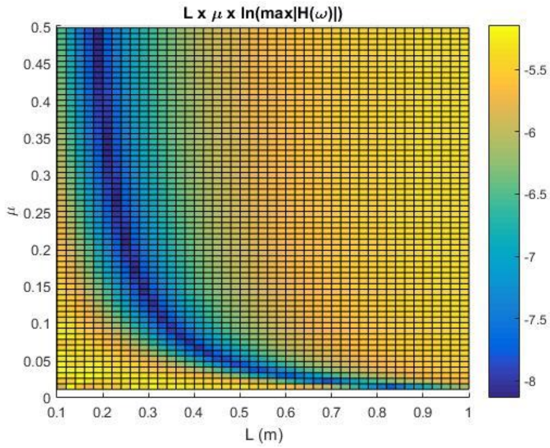


Figure 9 – Response Map in function of μ and L

Due to the constructive limitations existing in a real physical model, there are limitations in the values of *L* and μ feasible in practice. To avoid buckling and bending of the pendulum rod, it was desired to impose the upper limit L ≤ 0.50 and μ = 0.15. A point in the valley response map was chosen *L*=0,28 m and μ = 0,145 (M_d = 4,87 Kg). Figure 9 shows the numerical frequency response of the system with and without control, where it can be verified a considerably good performance of the IPTMD on reducing the main system dynamic response. So the experimental IPTMD was set with the following parameters: M_d = 5 Kg and L = 0,3 m.

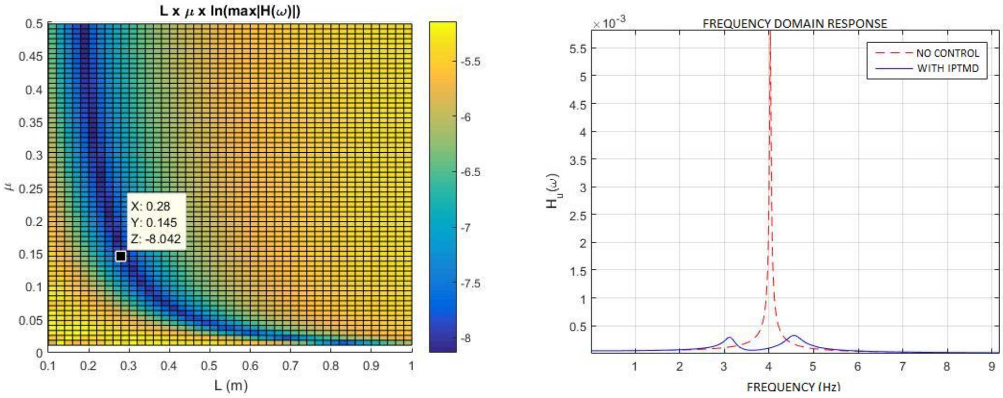


Figure 9 - Parameter values (L = 0.28 m and μ = 0.145) on the Response Map (a) and the equivalent frequency response function (b)

5. CONCLUSIONS

In this work, an Inverted Pendulum Tuned Mass Damper was built to control the dynamic response of a reduced, pre-assembled experimental model to simulate the behavior of a tall building. The physical characteristics (natural frequency, stiffness and damping ratio) were satisfactorily determined experimentally through video analysis. With these data, it was possible to define the main parameters of the TMD using response map technique. With the IPTMD parameters set up in a future work it will be tested experimentally on the scale model of a tall building.

6. ACKNOWLEDGEMENTS

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