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A COMPARATIVE ANALYSIS OF TLCD EQUIPPED SHEAR BUILDINGS UNDER DYNAMIC LOADS

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Abstract. *Brazilian cities are living a process of intense vertical growth due to the necessity of increasing the efficiency of use of the urban spaces. Tied to this necessity is the rapid development of new materials and technologies, especially when it comes to quality and resistance. These factors permitted the construction of slender buildings, which are susceptible to dynamic loads. This study targets the behavior of shear buildings equipped with tuned liquid column dampers (TLCD) which attenuates dynamic load induced vibration. Shear buildings are a frame model in which the horizontal elements are considered to be much stiffer than the vertical elements. This consideration allows us to neglect the rotational degrees of freedom in every story, making the analysis of the structure simpler. Furthermore, this model considers that the mass is lumped in the horizontal elements. TLCDs are a passive damping system used in tall buildings. This kind of damper has proven to be very efficient, being an excellent alternative to mass dampers. A linear dynamic analysis of the structure-damper system is made using the software DynaPy, developed in the research process. The software solves the equations of motion through numeric integration using the central differences method. Thus, the main objective is to compare the dynamic response of structures with and without TLCDs.*

Keywords: *TLCD, Structure Dynamics, DynaPy, Numeric Integration*

1 INTRODUCTION

Since the XIX century, urbanization, population growth and the increasing land price in big cities have pushed civil engineering towards the construction of tall and slender buildings. However, that also created the necessity of studying new mechanisms for attenuation of earthquake and wind induced vibrations. Many vibration control systems were developed since then, including the Tuned Liquid Dampers (TLD).

Tuned Liquid Dampers are built to counterbalance the structure movement, using a liquid mass to transfer inertial forces to the structure. This system has to be tuned to the building natural frequency in order to yield satisfactory results. There are two main categories of TLDs: Tuned Sloshing Dampers (TSD) and Tuned Liquid Column Dampers (TLCD). The first uses a big liquid container that produces sloshing movement when excited, which causes some head loss. The second typically has a tube shaped container and do not produce a significant sloshing movement. In this case, the head loss is caused by the movement of the fluid inside the tube and through valves and other local components.

Tuned Liquid Column Dampers are very versatile and have many different variations. The basic model is a U-shaped tube with both ends open and a valve in the middle of the tube or some other local head loss inducing mechanism. One way to modify its natural frequency is to attach pressurized air tanks to both ends, making it a Pressurized Tuned Liquid Column Damper (PTLCD).

A computer program, named DynaPy, was developed to model and simulate different structures and dampers under any type of excitation. The theoretical foundation for building the software can be found in many books and papers. The formulations and solutions of the equations of motion can be found on Belvins (1990), Chopra (1995), Clough (2003), French (2001), Nadauscher (1994), Pedroso (2000, 2003, 2005), Tedesco (1999). The TLCD model can be found on Baleandra (1997), Freitas (2016, 2017), Gao (1996), Kenny (2013), Pedroso(1992), Pestana (2012), Shum (2007).

The objectives of this research were to model different structures equipped with properly designed TLCDs using the software DynaPy, simulate the dynamic response of this system to base excitation loads and compare the results with and without the TLCD.

2 METHODOLOGY

The system studied in this research is a multi-story shear building with a PTLCD installed on the last story. Each story on the shear building has one horizontal degree of freedom x_{si} and the PTLCD has one vertical degree of freedom x_f. The structure parameters are the mass m_{si}, damping ration ξ_{si} and stiffness k_{si} of each story. The PTLCD parameters are the tube diameter D, water height h, tube length b, total fluid length L, gas tank height Z, gas pressure P, tube Area A and valve area A_c. Figure 1 shows the geometric parameters of the structure-PTLCD system.

Using these parameters, the system equations of motion are deduced and written in the coupled format. Then, the central differences method is used to solve the equation of motions. The entire process of modeling, assembling the matrices and solving the equations is done through the software DynaPy, which also plots the results obtained.

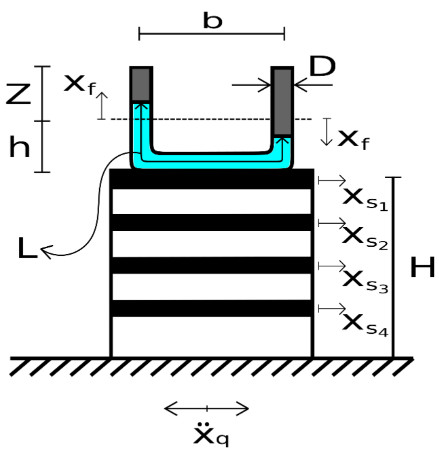

Figure 1: Geometric parameters of the structure-PTLCD system

3 EQUATIONS OF MOTION

3.1 Structure Modeling

Modeling of the structure is very simple and based on few parameters. The mass m_{si} of each story is estimated for each case, while the stiffness is calculated as shown in Eq. (1), in which E is the elasticity module, I is the moment of inertia and H is the height of the column.

$$k_s = \frac{24EI}{H^3}. \tag{1}$$

The story damping is calculated based on the structure natural frequency ω, it's damping ratio ξ and the story mass m_{si}, as shown in Eq. (2)

$$c_s = 2m_{si}\omega\xi_s. \tag{2}$$

3.2 PTLCD Modeling

Modeling of the PTLCD is a little more complicated and involves many different variables. The PTLCD mass m_f can be obtained by multiplying its volume by the fluid specific mass ρ_f, as shown in Eq. (3).

$$m_f = \frac{\pi D^2}{4} L\rho_f \tag{3}$$

The PTLCD stiffness has two parts, as seen on Eq. (4). The first part comes from the fluid vibration natural frequency, while the second part comes from the compressed air tank stiffness (Freitas, 2017).

$$k_f = \frac{\pi D^2 \rho_f g}{2} + 1.4\frac{P}{z}\frac{\pi D^2}{2} \tag{4}$$

Finally, the PTLCD damping also has two parts, as shown in Eq. (5). The first comes from the distributed head loss, which is dependent on the friction factor f, due to the fluid movement inside the tube and the second comes from the local head loss due to the fluid passage through the valve (Freitas, 2017).

$$c_f = \left[\frac{\pi L D \rho_f}{8} f|\dot{x}_f|\right] + \left[\frac{\rho_f A}{2}\left(\frac{A}{A_c} - 1\right)^2 |\dot{x}_f|\right] \tag{5}$$

3.3 Earthquake Modeling

The earthquake doesn't apply a force directly to the structure. It actually applies an acceleration $\ddot{x}_q$ to its base, which multiplied by the story mass m_{si} equals to an effective force f_{qi}, as shown in Eq. (6)

$$f_{qi} = \ddot{x}_q m_{si} \tag{6}$$

3.4 Coupled Equation of Motion

The equation of motion can be written in its classic form, shown in Eq. (7), in which the capital letters M, C and K represent the mass, damping and stiffness matrices, respectively, while the capital letters $\ddot{X}$, $\dot{X}$, X and F represent the acceleration, velocity, displacement and force vectors, respectively, which are dependent on the time t. This matrix equation can be separated into two parts, the structure and the PTLCD degrees of freedom, as shown in Eq. (8). The sub-matrices in each this equation are detailed on Eq. (9), Eq. (10), Eq. (11) and Eq. (12).

$$M\ddot{X}(t) + C\dot{X}(t) + KX(t) = F(t) \tag{7}$$

$$\begin{bmatrix} M_s & M_{cp} \\ M_{cp} & m_f \end{bmatrix} \begin{Bmatrix} \ddot{X}_s(t) \\ \ddot{X}_f(t) \end{Bmatrix} + \begin{bmatrix} C_s & 0 \\ 0 & c_f \end{bmatrix} \begin{Bmatrix} \dot{X}_s(t) \\ \dot{X}_f(t) \end{Bmatrix} + \begin{bmatrix} K_s & 0 \\ 0 & k_f \end{bmatrix} \begin{Bmatrix} X_s(t) \\ X_f(t) \end{Bmatrix} = \begin{Bmatrix} F_q(t) \\ 0 \end{Bmatrix} \tag{8}$$

$$[M_s] = \begin{bmatrix} m_{s1} & 0 & \cdots & 0 \\ 0 & m_{s2} & \cdots & 0 \\ \vdots & \ddots & \ddots & 0 \\ 0 & 0 & 0 & m_{sn} + m_f \end{bmatrix} \tag{9}$$

$$[C_s] = \begin{bmatrix} c_{s1} & 0 & \cdots & 0 \\ 0 & c_{s2} & \cdots & 0 \\ \vdots & \ddots & \ddots & 0 \\ 0 & 0 & 0 & c_{sn} \end{bmatrix} \tag{10}$$

$$[K_s] = \begin{bmatrix} k_{s1}+k_{s2} & -k_{s2} & 0 & \cdots & 0 \\ -k_{s2} & k_{s2}+k_{s3} & -k_{s3} & \cdots & 0 \\ 0 & -k_{s3} & \ddots & \ddots & 0 \\ \vdots & \ddots & \ddots & k_{sn-1}+k_{sn} & -k_{sn} \\ 0 & 0 & 0 & -k_{sn} & k_{sn} \end{bmatrix} \tag{11}$$

$$[M_{cp}] = \begin{bmatrix} 0 \\ \vdots \\ 0 \\ \frac{b}{L}m_f \end{bmatrix} \tag{12}$$

4 METHOD OF SOLUTION

4.1 Central Differences Method

During the research process, the software DynaPy was developed. This program is capable of taking the structure, TLCD and excitation parameters, assembling the mass, stiffness, damping and force matrices and solving the equation of motion. The equation of motion is solved step by step using the central differences method, as shown in Eq. (13) (Tedesco et al., 1999). Using this method it is possible to calculate the the displacement X_{i+i} one step ahead given that the displacement on the current (X_i) and previous (X_{i-i}) iterations are known. The distance between two steps is the time Δt. After solving the equation, the software post-process the results generating plots.

$$X_{i+1} = \left(\frac{M}{\Delta t^2} + \frac{C}{2\Delta t}\right)^{-1} \left[F - \left(K - \frac{2M}{\Delta t^2}\right)X_i - \left(\frac{M}{\Delta t^2} - \frac{C}{2\Delta t}\right)X_{i-1}\right] \tag{13}$$

4.2 Nonlinearity Treatment

As seen on Eq. (5), the PTLCD damping coefficient is dependent on the fluid velocity. That makes the damping matrix C nonlinear and, consequentially, the equation of motion is nonlinear. In order to be able to use the algorithm described on Eq. (13) directly, the damping matrix must be linearized. That was achieved by approximating the instant velocity $\dot{x}_f$ on the iteration i by its value on the iteration $i-2$, which can be calculated numerically at each step using the central differences method. As long as the time step used between iterations is small enough, this linearization method is guaranteed to converge to the exact solution.

5 DYNAPY OVERVIEW

DynaPy is a structure dynamics modeling and simulation software that can be used to study simple two-dimensional structures. The software was developed in Python as part of this research process in order to give the researchers the ability to make many simulations in a short amount of time and gather all sorts of results, according to the researcher's need.

In the current version, this software supports shear building structures, TLCDs, PTLCDs, harmonic excitations and generic excitations. The processing is made using central differences methods only, but other methods will be implemented in the future. The post-processing options include displacement vs. time, velocity vs. time, acceleration vs. time, displacement vs. velocity, dynamic amplification factor vs. frequency ratio and maximum displacement vs. frequency ratio plots. Figure 2 shows the dynamic response plots screen with the ”displacement vs. time” plot option selected.

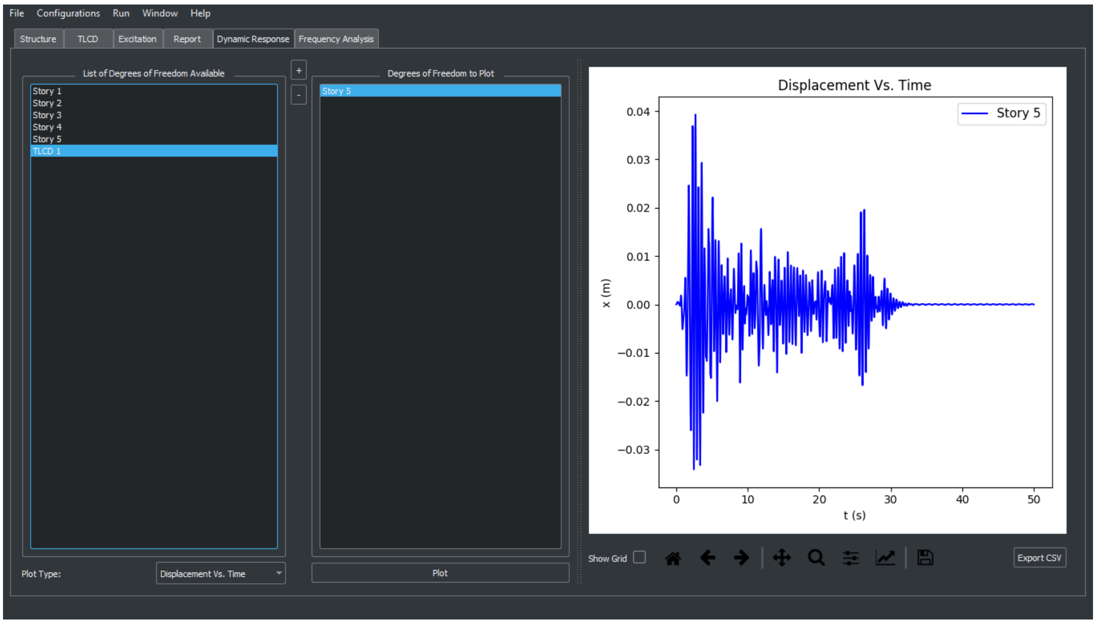

Figure 2: DynaPy dynamic response screen

6 RESULTS

6.1 Response to Harmonic Excitation

In order to visualize the effect of the TLCD on the building, a 5-story building equipped with a PTLCD was modeled on DynaPy. Each story in the building was 3 m high, had 10 t of mass and columns made of reinforced concrete with a square cross section with 35 cm sides. The building damping ratio was set to 2%. The PTLCD had 30 cm of diameter, 100 cm of water height, 1000 cm of length, 40 cm, of gas height, 3.69 atm of gas pressure and its valve opening was set to 51% of the cross section area. A harmonic excitation with 5 m/s^2 amplitude and 14.84 rad/s frequency, which corresponds to the building natural frequency, was applied to the base.

Figure 3 shows the comparison between the dynamic response of the last story with and without the PTLCD. It was found that the use of the damping system reduced the maximum displacement by 45%, while the displacement in the steady state was reduced by about 80%. The shape of the response is also changed, reaching the maximum displacement much earlier and reducing the amplitude of displacements to a steady value afterward. The mass of the PTLCD represents only 1.7% of the total mass of the structure, but that is enough to provide a satisfactory damping.

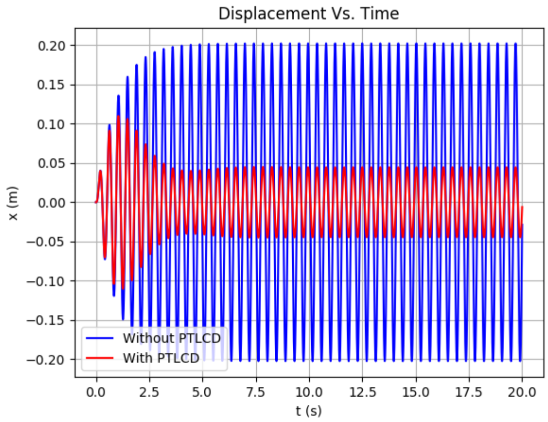

Figure 3: Dynamic response of a 5-story building under harmonic excitation with and without PTLCD

6.2 Response to El Centro Earthquake

A more realistic simulation was done by applying the El Centro earthquake to a 10-story building equipped with a PTLCD. Each story in the building was 3 m high, had 12 t of mass and columns made of reinforced concrete with a square cross section with 35 cm sides. The building damping ratio was set to 2%. The PTLCD had 50 cm of diameter, 200 cm of water height, 1000 cm of length, 100 cm, of gas height, 2.375 atm of gas pressure and its valve opening was set to 20% of the cross section area. The natural frequency of the building is 7.04 rad/s.

Figure 4 shows the comparison between the dynamic response of the last story with and without the PTLCD. Once again, the use of the damping system greatly reduced the amplitude of vibration. The maximum displacement was reduced by 45%, and in most of the time, the response with the PTLCD is significantly smaller than the one without the PTLCD. The mass of the PTLCD, in this case, represents about 2.0% of the total mass of the structure.

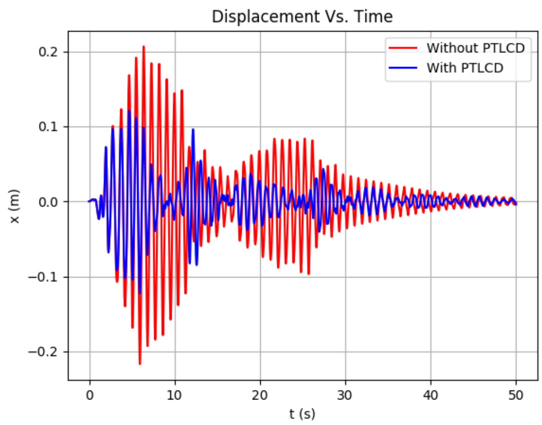

Figure 4: Dynamic response of a 10-story building under El Centro earthquake with and without PTLCD

7 CONCLUSIONS

The simulations showed that the implementation of TLCDs on shear buildings can be a very effective vibration control system. With less than 2.0% additional mass it was possible to achieve about 45% reduction in the maximum displacement in both cases.

In the harmonic excitation case, it can be seen that the PTLCD takes some time to fully activate and work with maximum efficiency. That can be noticed by the fact that the steady state response is much smaller than the maximum response, which happens some seconds before reaching steady state. This happens because the fluid starts with zero displacement and zero velocity and has to reach maximum displacement vibration in order to efficiently counterbalance the structure vibration.

On the other hand, the El Centro case showed that this vibration control system is also capable of yielding good results for non-harmonic excitations, like earthquakes. However, it must be noted that the main frequencies of the earthquake spectrum must match the frequency to which the TLCD was tuned in order to achieve good results. Also, the TLCD will be more effective on structures with natural frequency in the range of the main frequencies of the earthquake spectrum.

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