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STUDY OF VIBRATION CONTROL USING TLCDS AND PERFORMED BY THE SOFTWARE DYNAPY IN A VISUAL WAY

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Abstract. The problem of scarce construction area in highly populated cities of the world has led to the use of tall buildings in the modern era. They provide a way to allocate more space for homes and the commerce, increasing density in major cities. However, this type of structure is more susceptible to vibration problems caused by winds and earthquakes. Tall building designers need to address this liability carefully, since even small vibrations can cause extreme nuisance and discomfort to the inhabitants of the building. One way to reduce the vibrations in a building is to use damper mechanisms, such as a Tuned Liquid Column Damper (TLCD). This damper is a passive device that works by absorbing a portion of the building's oscillation energy, thanks to the relative movement between them. The energy is mainly dissipated due to local pressure losses, such as the ones that occur when a fluid is forced to pass through orifices. The effectiveness of a damper in a dynamically excited structure can be computed by comparing its undamped response to the dampened response. In order to obtain these responses, a numerical study of shear buildings equipped with TLCDs is done using DynaPy, an open source software developed in the Python programming language. New features have been incorporated into DynaPy, allowing the user to visualize and better understand the steps performed by the program to obtain the dynamic response of the system.

Keywords: Vibration control, Shear building, TLCD, Python, DynaPy

1 Introduction

Since the XIX century, urbanization, population growth and the increasing land price in major 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's 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 used to create the software can be found in many books and papers. The formulations and solutions of the equations of motion can be found in Blevins [1], Chopra [2], Clough [3], French [4], Nadauscher [5], Pedroso [6-8], Tedesco [9]. The TLCD model can be found in Baleandra [10], Freitas [11-12], Gao et al [13], Kenny [14], Pedroso [15], Pestana [16], Shum et al [17]. DynaPy allows their users to simulate structure-TLCD systems, obtain its dynamic response to base excitation loads and compare the results with and without the TLCD. It is also possible to use a PTLCD instead of a TLCD.

Many studies have been performed on TLCDs and PTLCDs. Baleandra et al [18] studied the efficiency of TLCDs in the vibration control of many structures under random wind action. Optimization studies for many TLCD parameters were made by Gao et al [13] and Kenny [14]. Sousa [19] compares the efficiency between different types of dampers that use liquid to dissipate the vibration energy of the structure.

Hochrainer and Ziegler [20] studied the incorporation of a sealed pressurized gas chamber to the both ends of the Liquid Column Damper. Shum et al [17] studied the use of multiple PTLCDs in the reduction of vibration in long span cable-stayed bridges. Pestana [16] evaluates the efficiency of a TLD system in a reduced-scale frame and compares the results with a numerical simulation.

Gur et al. [21] evaluate the efficiency of a TLCD that had its orifice substituted by a metal ball that was free to move inside the horizontal portion of the tube, called a Tuned Liquid Column Ball Damper (TLCBD). Bigdeli and Kim [22] compare the performance between different types of the most used passive control devices by performing an experimental study. The vibration control using a Liquid Column Damper containing embossments on its inside walls was analyzed by Park et al. [23]

Freitas [12] coded the software DynaPy to assist in the numerical study that evaluates the efficiency of TLCDs in structures modelled using the shear building theory. Multiple dampers are tested, as well as the incorporation of a pressurized chamber in the vertical portion of the TLCD. Mendes [24] studies the use of multiple PTLCDs in reducing the vibration caused by a seismic excitation in various system models utilizing soil-structure interaction. The interaction between the soil, the foundation, the structure and the PTCLDs is considered in many of them.

The objective of this work is to create a new feature for DynaPy, so that it becomes easier for its users to understand how the dynamic response of the system is obtained. This is done by adding a new mode to the run tab, called Step-by-Step Mode, that can only be accessed after an initial case has been run and all the data is generated and stored by DynaPy. This mode contains many interactive elements, such as dynamic tables and figures that change when buttons are pressed, different options to plot graphs and visualize the results. With this new interactive tool, the study of structure dynamics and vibration control becomes more visual and also more interesting.

2 Structure-PTLCD System

The system studied in this work 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 for each story are the mass m_{si}, a damping ratio ξ_s and the stiffness k_{si}. The PTLCD parameters are the tube diameter D, water height h, tube width 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 equations of motion of the system are deduced and written in the coupled format. Then, the central difference method is utilized to solve them. The entire process of modelling, assembling the matrices and solving the equations is done through the software DynaPy, which also plots the results obtained.

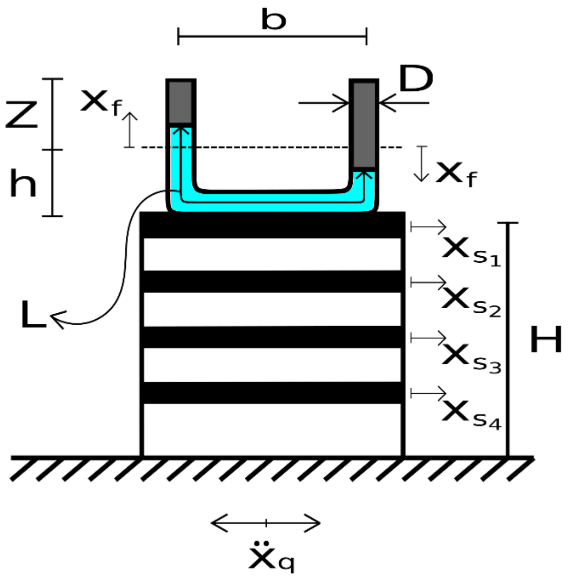

Figure 1. Geometric parameters of the structure-PTLCD system

3 Equations of Motion

3.1 Structure Modelling

Modelling of the structure is very simple and based on few parameters. The mass of each story m_{si}, is estimated for each case, while the stiffness is calculated considering a fixed-fixed column as shown in Eq. (1), in which E_i is the modulus of elasticity, I_i is the moment of inertia and H_i is the height of the columns for each story.

$$k_{si} = \frac{24E_iI_i}{H_i^3} \tag{1}$$

The story damping c_{si} is calculated based on the structure's first natural frequency ω, a damping ratio ξ_s, which is shared by all stories, and the story mass m_{si}, as shown in Eq. (2).

$$c_{si} = 2m_{si}\omega\xi_s \tag{2}$$

3.2 PTLCD Modelling

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 k_f has two terms, as seen in Eq. (4). The first one is an equivalent stiffness obtained from the natural frequency of vibration of the fluid, while the second one comes from the compressed air tank stiffness [12].

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

Finally, the PTLCD damping c_f also has two terms, as shown in Eq. (5). The first term comes from the distributed head loss, which is dependent on the friction factor f, due to the fluid movement inside the tube. The second term comes from the local head loss that occurs due to the passage of fluid with velocity $\dot{x}_f$ through a valve of area A_c [12].

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

3.3 Seismic Excitation Modelling

A seismic excitation doesn't apply a force directly to the structure. Instead, it applies an acceleration $\ddot{x}_q$ to its base, which multiplied by the story mass m_{si} equals to an effective force f_{qi}, shown by Eq. (6).

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

Additionally, the effective force generated on the fluid f_f is given by Eq. (7) [24].

$$f_f = -\frac{b}{L} m_f \ddot{x}_q \tag{7}$$

3.4 Coupled Equation of Motion

The equation of motion can be written in its classic form, shown in Eq. (8). In this equation, the capital letters M, C and K represent the mass, damping and stiffness matrices, respectively. 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 the structure and the PTLCD degrees of freedom, as shown in Eq. (9). The submatrices and subvectors in each equation are detailed in Eq. (10), Eq. (11), Eq. (12), Eq. (13) and Eq. (14).

$$M\ddot{X}(t) + C\dot{X}(t) + KX(t) = F(t) \tag{8}$$

$$\begin{bmatrix} M_s & M_{cp} \\ M_{pc} & m_f \end{bmatrix} \begin{Bmatrix} \ddot{X}_s(t) \\ \ddot{X}_f(t) \end{Bmatrix} + \begin{bmatrix} C_s & 0 \\ 0 & c_f \end{bmatrix} \begin{Bmatrix} \dot{X}_s(t) \\ \dot{X}_f(t) \end{Bmatrix} + \begin{bmatrix} K_s & 0 \\ 0 & k_f \end{bmatrix} \begin{Bmatrix} X_s(t) \\ X_f(t) \end{Bmatrix} = \begin{Bmatrix} F_q(t) \\ f_f(t) \end{Bmatrix} \tag{9}$$

$$[M_s] = \begin{bmatrix} m_{s1} & 0 & \cdots & 0 \\ 0 & m_{s2} & \cdots & 0 \\ \vdots & \ddots & \ddots & 0 \\ 0 & 0 & 0 & m_{sn} + m_f \end{bmatrix} \tag{10}$$

$$[C_s] = \begin{bmatrix} c_{s1} & 0 & \cdots & 0 \\ 0 & c_{s2} & \cdots & 0 \\ \vdots & \ddots & \ddots & 0 \\ 0 & 0 & 0 & c_{sn} \end{bmatrix} \tag{11}$$

$$[K_s] = \begin{bmatrix} k_{s1} + k_{s2} & -k_{s2} & 0 & \cdots & 0 \\ -k_{s2} & k_{s2} + k_{s3} & -k_{s3} & \cdots & 0 \\ 0 & -k_{s3} & \ddots & \ddots & 0 \\ \vdots & \ddots & \ddots & k_{sn-1} + k_{sn} & -k_{sn} \\ 0 & 0 & 0 & -k_{sn} & k_{sn} \end{bmatrix} \tag{12}$$

$$[M_{cp}] = \begin{bmatrix} 0 \\ \vdots \\ 0 \\ \frac{b}{L} m_f \end{bmatrix} \tag{13}$$

$$[M_{pc}] = [M_{cp}]^T \tag{14}$$

4 Method of Solution

4.1 Central Difference Method

To solve the equation of motion and find the structure response, the software DynaPy was utilized. 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 difference method, as shown in Eq. (15) [9].

$$X_{i+1} = \left(\frac{M}{\Delta t^2} + \frac{C}{2\Delta t}\right)^{-1} \left[F_i - \left(K - \frac{2M}{\Delta t^2}\right) X_i - \left(\frac{M}{\Delta t^2} - \frac{C}{2\Delta t}\right) X_{i-1}\right] \tag{15}$$

Using this method, it is possible to calculate the displacement X_{i+1} one step ahead given that the current external force F_i and the displacement on the current and previous iterations are known (X_i and X_{i-1} respectively). The distance between two steps is the time Δt. To evaluate X_{i-1} at time t = 0, Eq. (16) and Eq. (17) are used together with the initial conditions [9].

$$\ddot{X}_0 = \frac{1}{m} [F_0 - C\dot{X}_0 - KX_0] \tag{16}$$

$$X_{-1} = X_0 - \dot{X}_0 \Delta t + \frac{\ddot{X}_0 (\Delta t)^2}{2} \tag{17}$$

With the displacements at various time steps, the central difference method can be used to approximate the velocity and the acceleration, given by Eq. (18) and Eq. (19). After solving for them, the dynamic response of the structure is determined and can be visualized by plotting the results.

$$\dot{X}_i = \frac{X_{i+1} - X_{i-1}}{2\Delta t} \tag{18}$$

$$\ddot{X}_i = \frac{X_{i+1} - 2X_i + X_{i-1}}{\Delta t^2} \tag{19}$$

4.2 Nonlinearity Treatment

As seen in Eq. (5), the PTLCD damping coefficient is dependent on the fluid velocity. This causes the damping matrix C to be nonlinear and, consequentially, the equation of motion is also nonlinear. In order to be able to use the algorithm described by Eq. (15) directly, the damping matrix must be linearized. This is 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 difference 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 Computational Aspects

5.1 An Overview of DynaPy

The program used in this work is called DynaPy, a structure dynamics modelling and simulation software that can be used to study simple two-dimensional structures. It allows its users to run many simulations in a short amount of time and gather all sorts of results, according to their need. In the current version, this software supports shear building structures, TLCDs, PTLCDs, harmonic excitations and generic excitations.

DynaPy is based on the Python programming language, which is free, open source and widely disseminated, having a large and active community. This enables the creation of many libraries and packages for all kinds of uses and situations. The two most important and fundamental to DynaPy are called Numpy [25] and Matplotlib [26]. The first is a numeric library containing all kinds of programming functions responsible for handling equations, linear systems, matrices, vectors and many more. The second is a graphical library for 2D and 3D plotting. By utilizing both of them, it is possible to perform numerical analyzes and do the post-processing with ease.

The program is composed of three main parts - pre-processing, processing and post-processing. In the first, the user inputs the data by interacting with a graphical interface. This involves geometric parameters of the structure and the TLCD, as well as physical parameters, such as the structure mass and the modulus of elasticity. Other input parameters include the duration and time step of the analysis, boundary conditions and seismic characteristics.

Next, at the beginning of the processing step, the software calculates every other property necessary for solving the problem. Then, it assembles the system mass, damping and stiffness matrices, as well as the time-dependent vectors of force, displacement, velocity and acceleration. With the assembled elements, it utilizes the central difference method to solve the equations of motion and obtain the dynamic response of the structure.

Finally, the post-processing step generates graphs that are used to analyze the efficiency of the studied damper. It is possible to plot different graphs, such as displacement vs. time, velocity vs. time, acceleration vs. time, displacement vs. velocity, dynamic amplification factor vs. frequency ratio and maximum displacement vs. frequency ratio. Figure 2 shows the dynamic response plots screen with the "displacement vs. time" plot option selected.

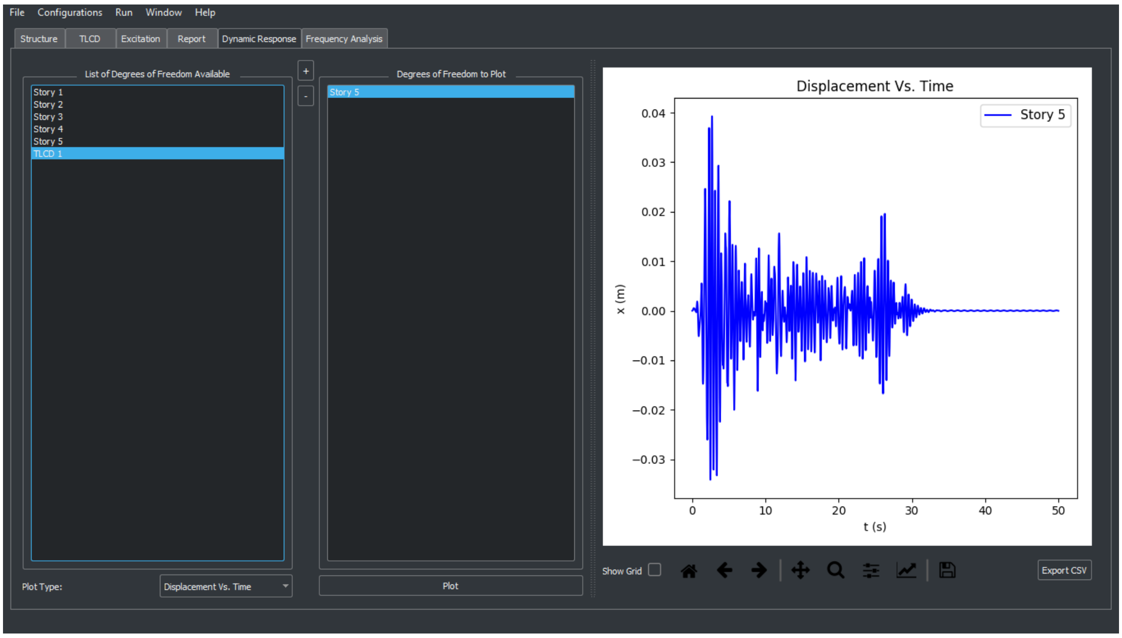

Figure 2. DynaPy's dynamic response screen

5.2 DynaPy Architecture and Methodology

DynaPy is meant to be used with its graphical user interface, but it is not tied to it. Figure 3 shows the software's flowchart when it is used with the GUI, as intended. First, using the GUI, the user inputs all the data about the structure, the external damper, the excitation and the software configurations. It is stored in an object called InputData. Then, the user has the option to run two types of analysis, a time history analysis, and a frequency analysis. By choosing the first one, the software assembles the system mass, damping and stiffness matrices, as well as the force vectors for each time step simulated. Then, the matrices and vectors are used to solve the equation of motion for each time step using one of the methods available in the DynaSolver algorithm. This algorithm outputs the dynamic response of the system in terms of displacement, velocity, and acceleration. If the user chooses the frequency analysis, instead, the software will perform a loop in which the system will be excited at the base by a sine-shaped acceleration. At each iteration, the matrices will be assembled, the equation of motion will be solved and the maximum values of displacement, velocity and acceleration will be stored. In both cases, the outputs are stored in an object called OutputData, which will handle the data for post-processing in the DynaPy GUI.

Since DynaPy was designed to be expandable and tweakable, the entire software is designed in a modular way. As a result, the functions to assemble the matrices and to solve the equations of motion, for example, are completely independent of the rest of the software, meaning that if one desires, they can code another solution method or another way to assemble the matrices in order to adapt the program to different mechanical systems.

DynaPy also has a save file system, which saves the contents of InputData to a human-readable text file that can later be used to load the data back to the program. Since the save file is human-readable, it is possible to make changes directly to the file or even to write it from scratch if the user understands the file structure. This makes it possible to completely bypass the pre-processing phase in the GUI and run DynaPy more like a script-based software.

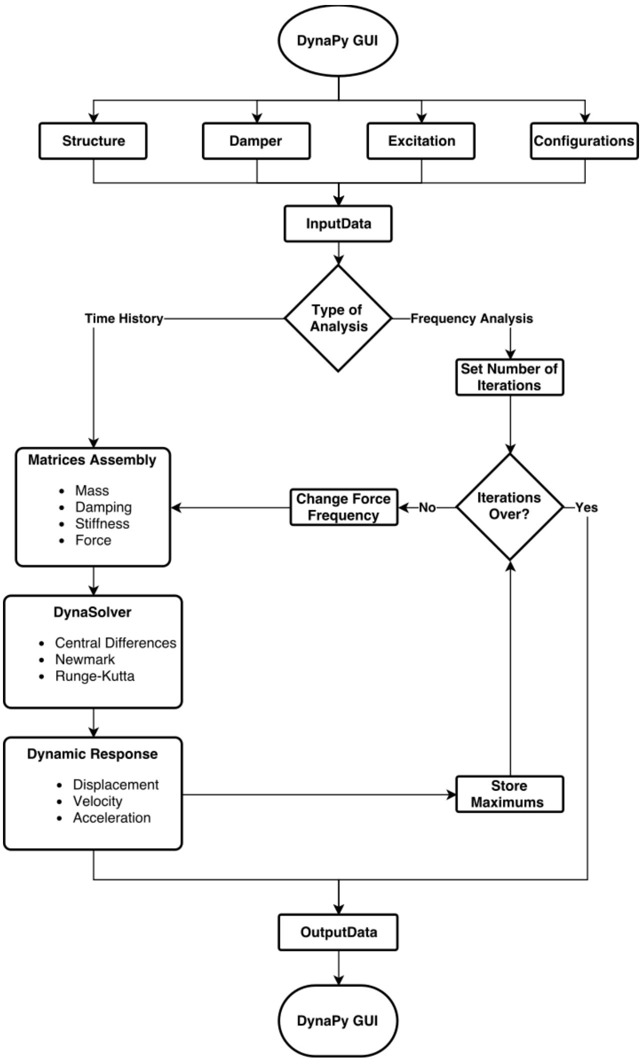

Figure 3. DynaPy's flowchart

6 Case Study

In order to visualize the effect of the TLCD on the building, a three-story building equipped with a PTLCD was modeled in DynaPy. Each story in the building was 3 m high, had 10000 kg of mass and columns made of reinforced concrete with a square cross section with 0.35 m sides. With these values, the first modal frequency of the structure is equal to 23.46 rad/s. The building damping ratio was set to 2%. The PTLCD had a diameter of 0.30 m, water height of 1 m, width of 10 m, gas height of 0.40 m, gas pressure of 9.3 atm (942.23 kPa) and its valve opening was set to 25% of the cross section area. With these values, the mass of the PTLCD is estimated to be 846.7 kg. A harmonic excitation with an amplitude of 5 m/s^2 and frequency of 23.50 rad/s, which is very close to the first modal frequency of the structure, was applied to the base. It is important to note that the addition of the PTLCD to the structure slightly changes the modal frequencies of the system. Figure 4 and Fig. 5 show the input data on the interface of the program for the structure and the PTLCD, respectively.

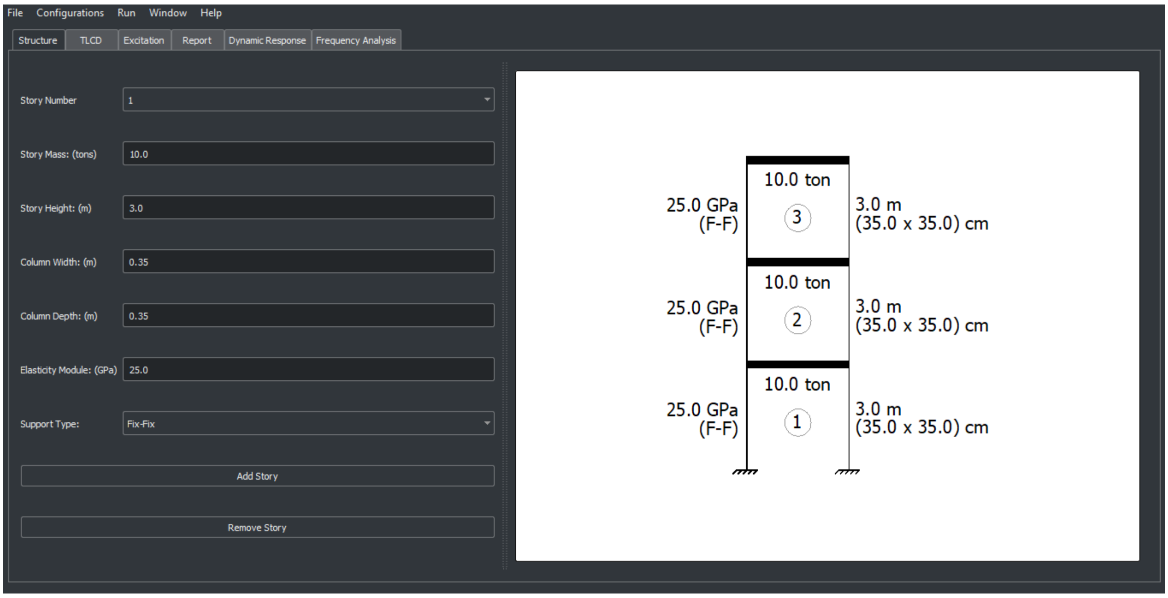

Figure 4. Structure input data

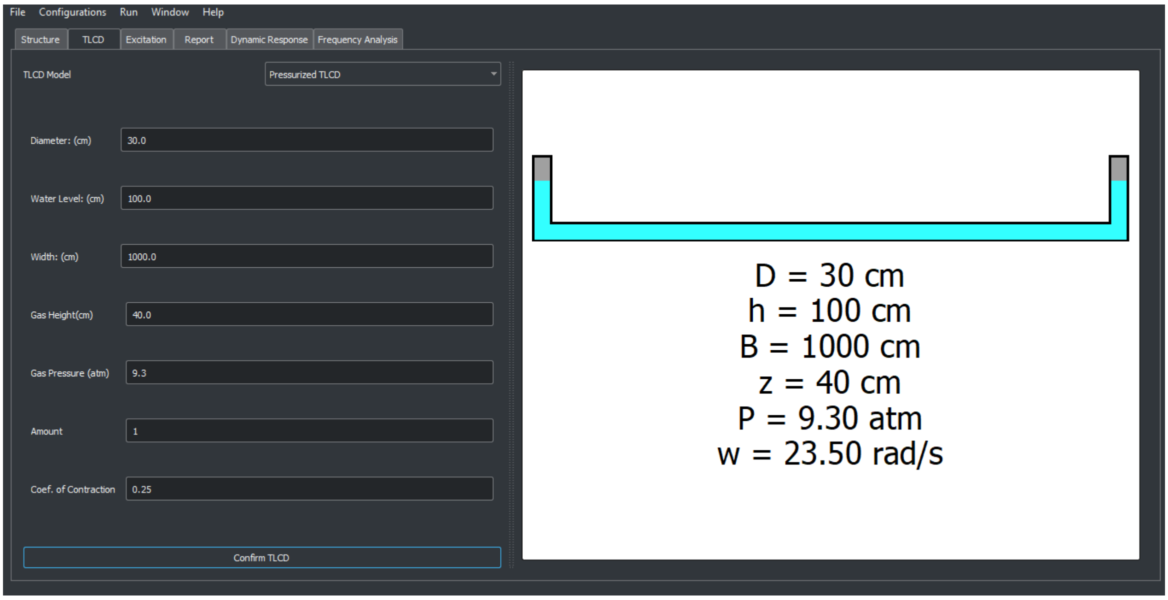

Figure 5. PTLCD input data

Figure 6 and Fig. 7 show the comparison between the dynamic response with and without the PTLCD. It was found that the use of the damping mechanism reduced the maximum displacement by about 60%, 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 2.8% of the total mass of the structure, but that is enough to provide a satisfactory damping.

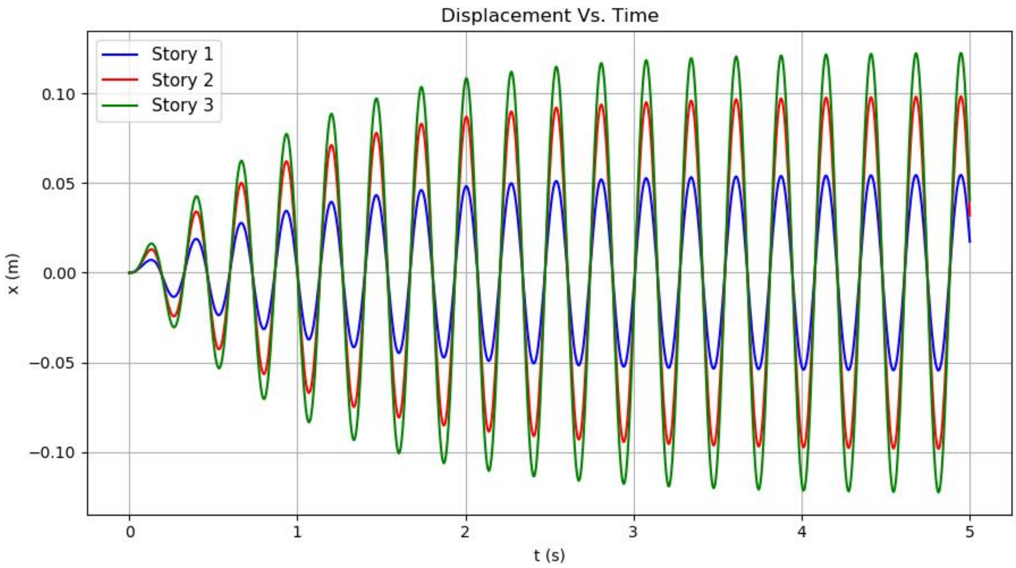

Figure 6. Response of each story of the building without PTLCD

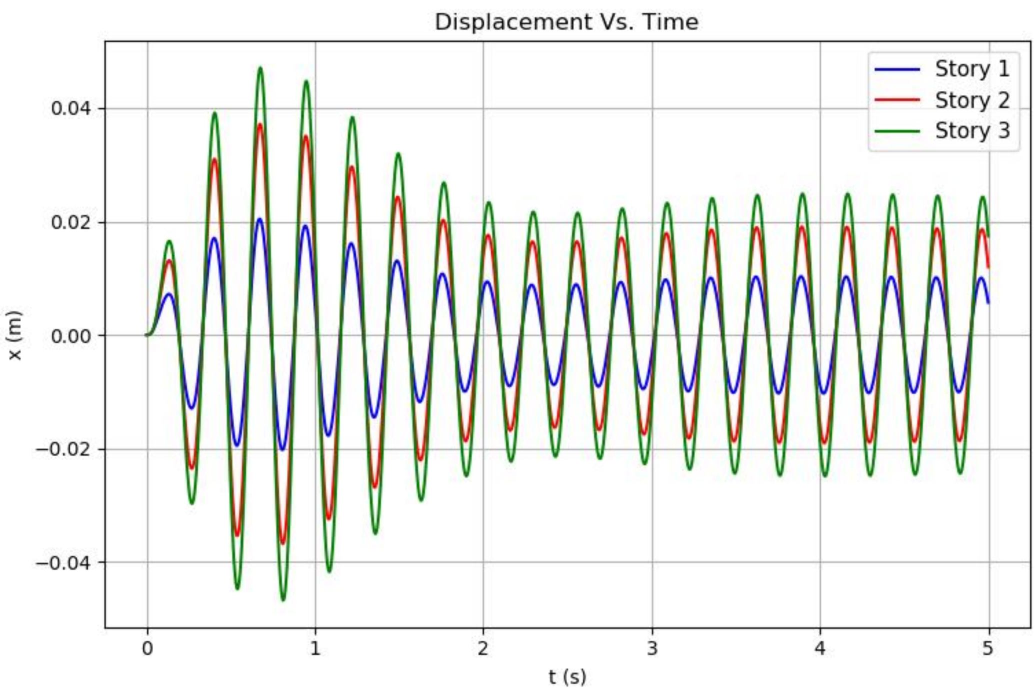

Figure 7. Response of each story of the building with PTLCD

A similar result can be found in a previous work that used DynaPy. Freitas and Pedroso [27] analyzed the use of a PTLCD on a five-story building submitted to a base harmonic excitation with a frequency equal to the natural frequency of the building. The maximum displacement was reduced by 45%, while the displacement in the steady state was reduced by about 80%. The mass of the PTLCD represented only 1.7% of the total mass of the structure.

In the same study, a more realistic simulation was done by applying the El Centro earthquake to a ten-story building equipped with a PTLCD with a mass of about 2.0% of the total mass of the structure. The use of the damping system greatly reduced the amplitude of vibration. The maximum displacement was reduced by 45% and, for most part of the analysis duration, the response with the PTLCD is significantly smaller than the one without the PTLCD.

7 Step-by-Step Mode

The new feature added to DynaPy is a run option called Step-by-Step Mode that is only available after the studied case is run and the dynamic response is generated. The following figures show the tabs of the Step-byStep Mode, which represent and summarize all the work done by DynaPy in order to run the case study presented herein. With them, the user has a full grasp of what is happening and has freedom to plot and analyse every scenario.

Figure 8 shows the Inputs Summary tab, which contains the input data entered by the user for the structure, the damper and the excitation. This tab will first appear blank, requiring the user to load the data from the case that was run by pressing the Load Results button. Additional information can be seen in the form of a pop-up window by pressing the Details button below each figure in this tab. This tab contains all the information necessary to assemble the matrices that appear in the equation of motion and is an excellent way to view all the input parameters of the system in a single screen.

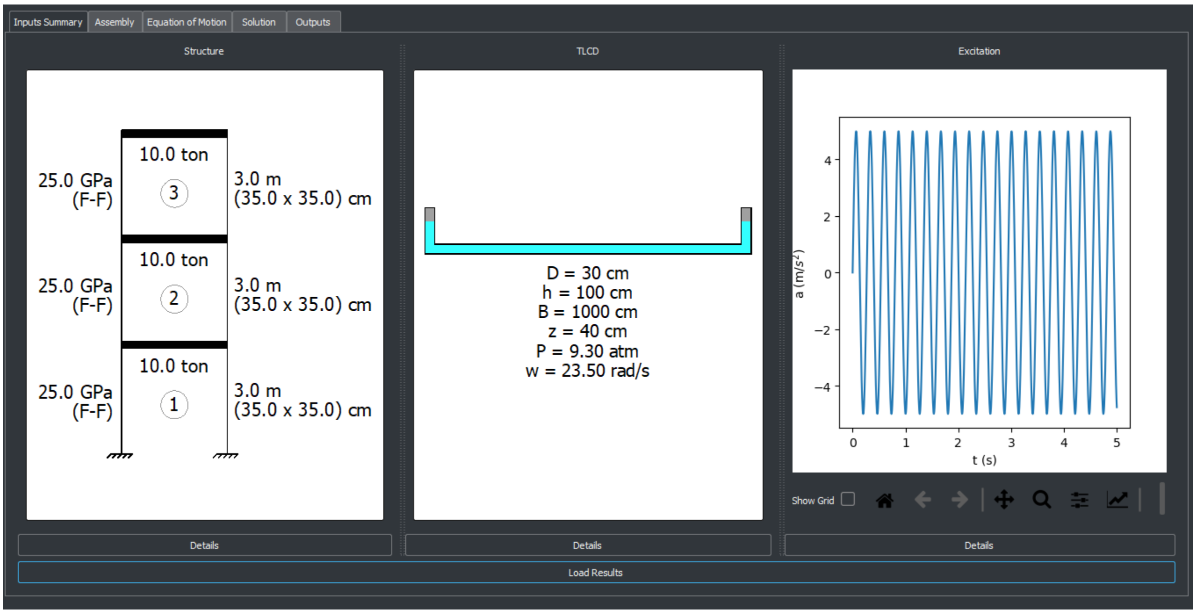

Figure 8. Inputs Summary tab

Figure 9 shows the Assembly tab, which displays the mass, damping and stiffness matrices in their symbolic or numeric values. Each one of these matrices start with null terms when the tab is first accessed. By pressing the Previous and Next buttons, the correct terms are added or removed from the matrix, respectively. Due to this, the assembly of the matrices can be visualized in an interactive way. The figure in this tab also changes accordingly when the buttons are pressed, so that the size of the matrix corresponds to the structure-TLCD system being displayed. Because of that, this tab highlights the contribution that each story and the damper have on each one of the matrices, as well as how they are coupled or not. It is also one of the most valuable tabs of the Step-by-Step Mode for teaching.

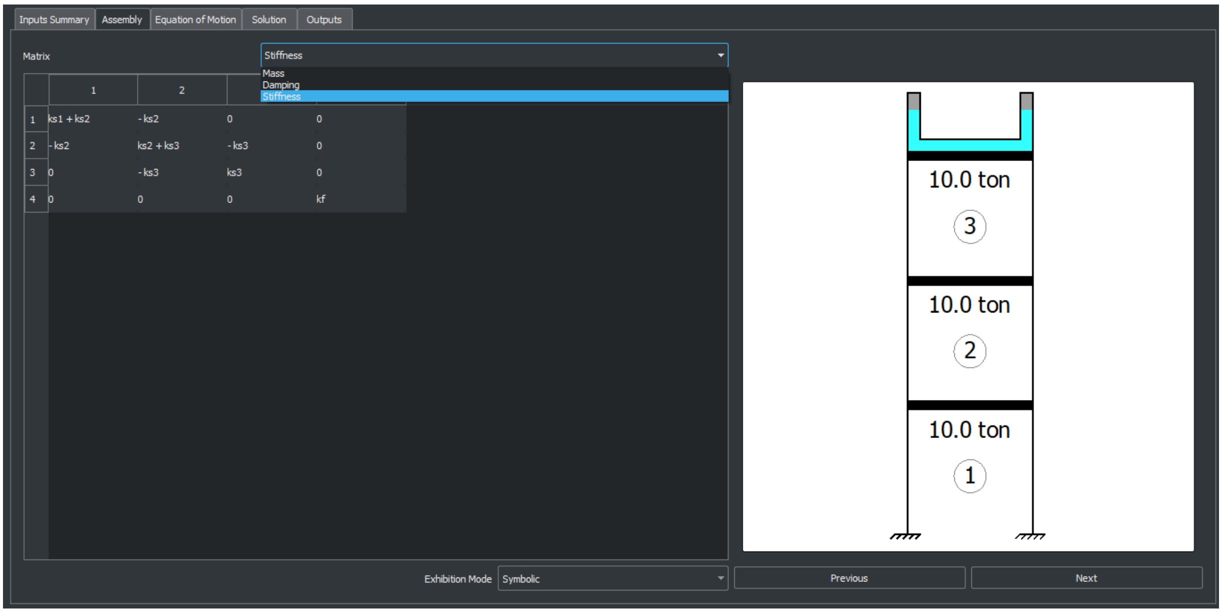

Figure 9. Assembly tab

Figure 10 shows the Equation of Motion tab, where the previously assembled matrices are used in the dynamic equation of motion. This tab contains a figure of this system of equations in its matrix form, as well as the definition of some submatrices. Below it, the user chooses a line from the system of equations to be displayed. Each equation that composes this system can be visualized separately in their symbolic or numeric form. This tab allows the user to better see all the parameters that influence the dynamic response of a given story or the damper.

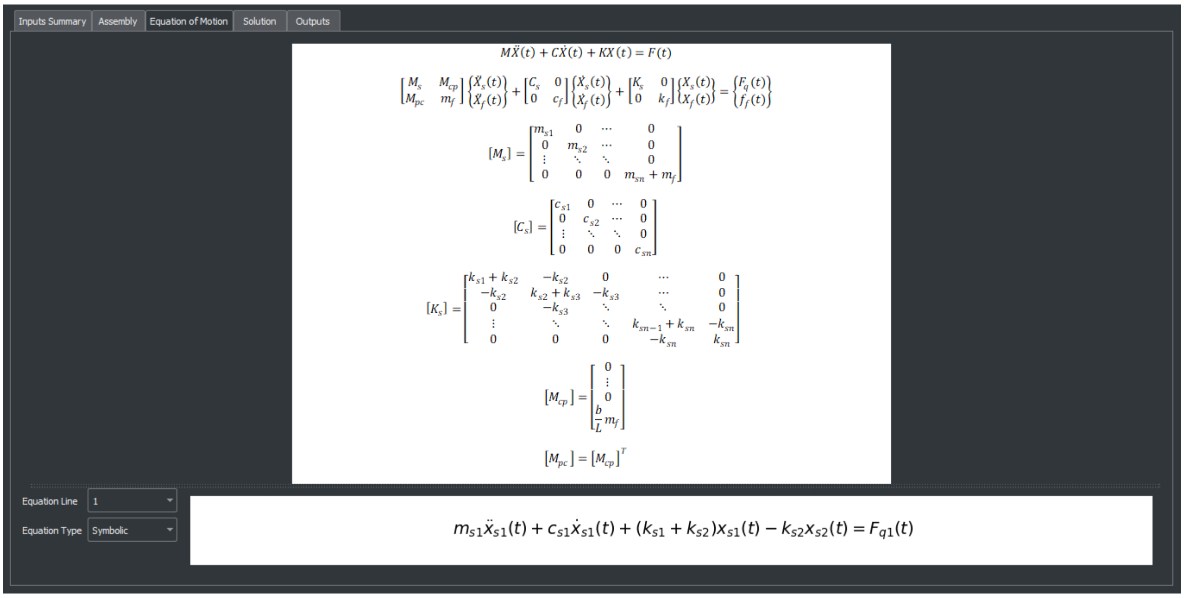

Figure 10. Equation of Motion tab

A screenshot of the Solution tab is shown in Fig. 11. This tab explains the solution steps taken by DynaPy to obtain the dynamic response of the system. This is done explaining the central difference method to the user with images containing text and equations. The Solution tab also contains additional information, such as why a nonlinearity occurs and how the modal frequencies are obtained. It is a path that connects the system parameters and its dynamic response.

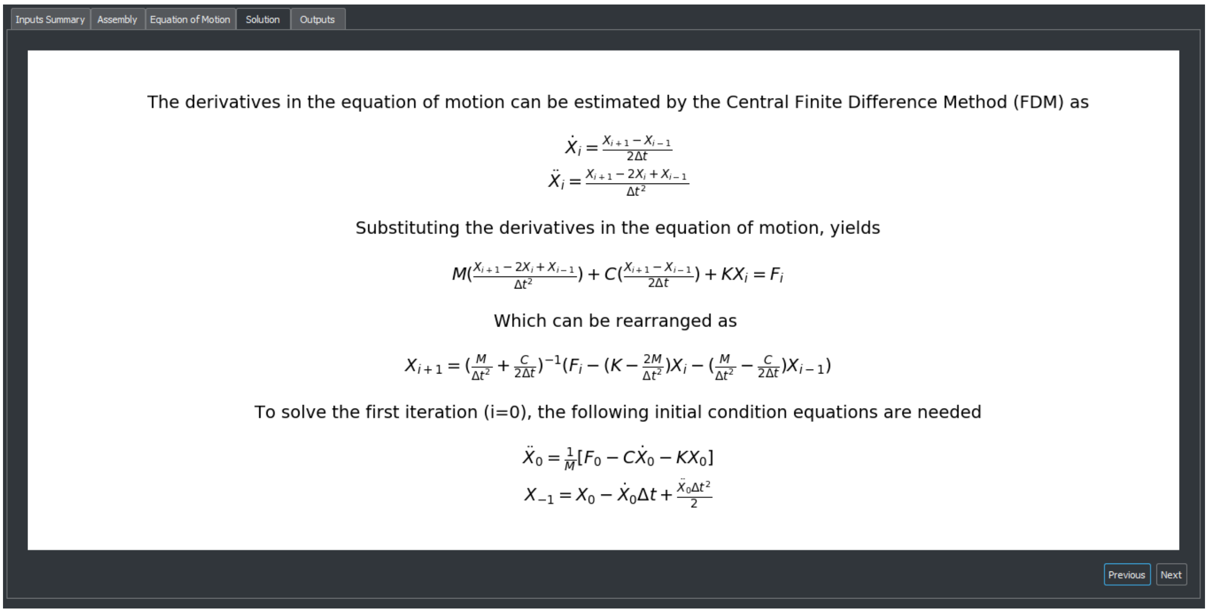

Figure 11. Explanation of the central difference method in the Solution tab

The final tab is shown in Fig. 12 and is called Outputs. It contains a canvas where it is possible to plot up to three different graphs for the response of the structure-TLCD system. To plot a graph, the user selects which degree of freedom (DOF) they want to be displayed, followed by what will be displayed on each axis. The options include the displacement x, the velocity v, the acceleration a, the force f_q and the excitation acceleration $\ddot{x}_q$. By default, the x axis is the same for all three graphs. This tab is a collection of all the output data stored by DynaPy and that can be promptly plotted by the user at will. The capability of manipulating and visualizing up to three different graphs at once makes this tab a valuable educational tool in the Step-by-Step Mode.

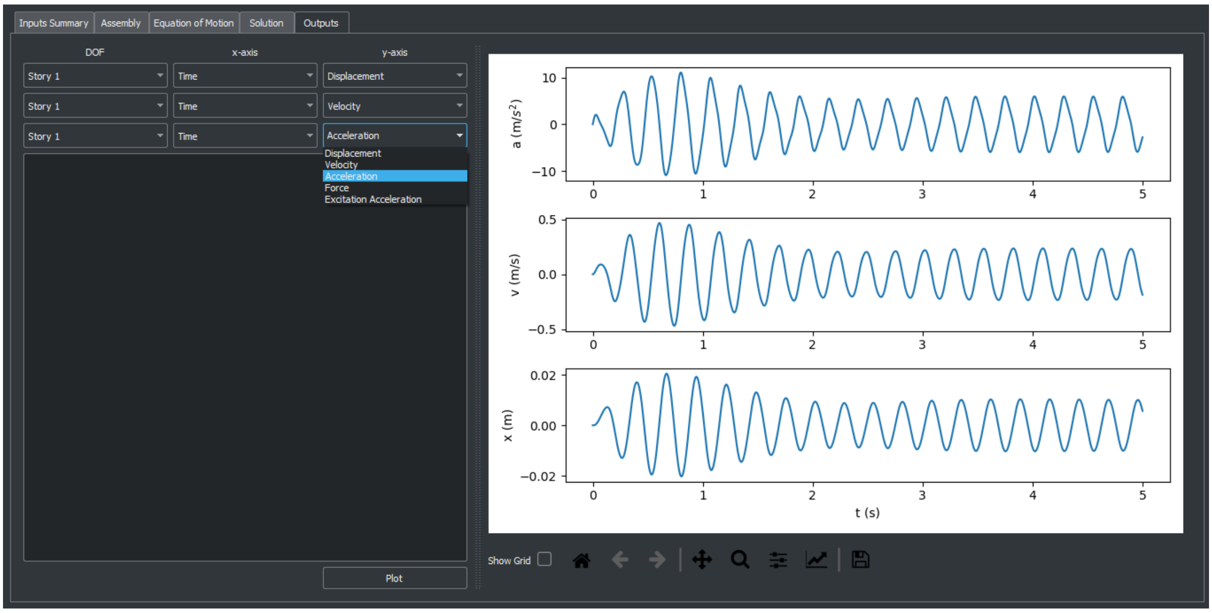

Figure 12. Outputs tab containing many plot options

8 Conclusions

Dynapy is a tool developed to assist researchers and students interested in the field of structure dynamics and vibration control. It provides a fast and interactive way to run simple simulations with 2D buildings, TLCDs and PTLCDs. Although being relatively simple, DynaPy is easy to use and provides a reliable way to test and measure the effectiveness of these damping mechanisms.

A simple run shows that the maximum response of a three-story building under a base harmonic excitation can be reduced by about 60%, while the steady state response was reduced by about 80%. For this case, even though the mass of the PTLCD represents only 2.8% of the total mass of the structure, it was enough to provide a satisfactory reduction in the response. Previous studies with DynaPy have also shown similar results. For a five-story building, also submitted to a harmonic excitation, reductions of 45% in the maximum displacement and of about 80% in the steady state were observed. A more realistic simulation, done by applying the El Centro earthquake to a ten-story building equipped with a PTLCD, showed that the use of the damping system greatly reduced the amplitude of vibration.

In this work, a new feature was added to DynaPy in the form of the Step-by-Step Mode. Containing many interactive objects on its interface, the Step-by-Step Mode guides the user through all the steps taken by the program in order to obtain the dynamic response of the studied system. Ideally, this mode should be used by professors as an interactive tool to facilitate teaching of Structural Dynamics. Not only can this tool be used to teach about the attenuation effects of TLCDs and PTLCDs on the structure vibration, but it can also be used to teach more basic topics like single degree of freedom vibrations, multiple degrees of freedom vibrations, modal analysis and numerical integration. The Assembly tab is particularly important to show the contribution of each element of the structure in the mass, damping and stiffness matrices, as well as to show how the structure-TLCD coupling is done. The Outputs tab is also very useful to show many important results in structure dynamics such as the relation between the input excitation and the resulting structural response, and the beating and resonance phenomena. With this new feature added to DynaPy, the reduction of vibrations using TLDCs and PTLCDs as well as other structural dynamics topics certainly becomes easier to understand.

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