ORIGINAL ARTICLE

Latin American Journal of Solids and Structures

www.lajss.org

A study of TLCD parameters for structural vibration mitigation

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https://doi.org/10.1590/1679-78257412

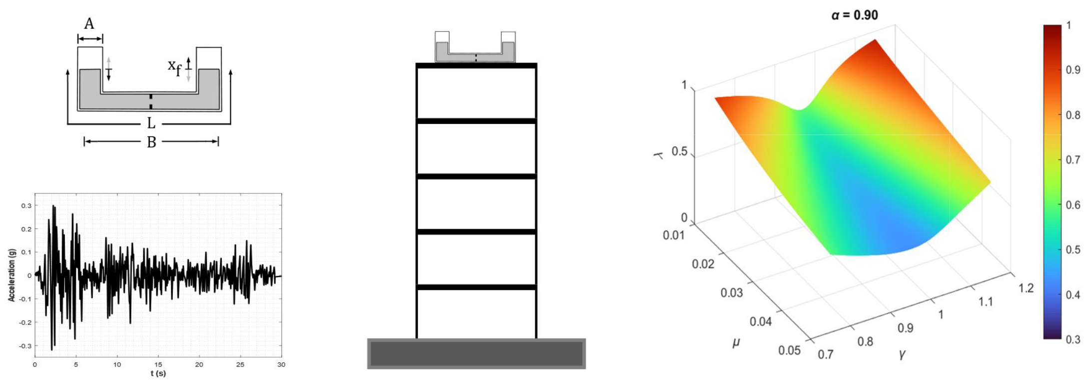
Abstract

In this article, the efficiency of the tuned liquid column damper (TLCD) in reducing structural vibration is analyzed. The analysis by numerical methods and by analytical methods is adopted in the search for the ideal parameters for the liquid column. The equivalent linear model is considered for the U-shaped liquid column equation of motion with damping resulting from an orifice. Thus, variation of TLCD parameters for different loads is investigated. Initially, for the numerical study in conjunction with the analytical formulation, a sinusoidal forcing is adopted. Subsequently, the action of an earthquake through the recorded ground accelerations is considered in the case study. Optimal TLCD parameters are presented via response map for reducing the structure's maximum permanent response to harmonic excitation and for reducing the structure's rms response to seismic excitation with wide frequency and various amplitude. The variation of the TLCD parameters presented by the response map is directly related to the force acting on the structure. However, it is verified that regardless of the acting force, there is an ideal frequency range to tune the TLCD where the greatest reductions in the primary system response are found. It appears that reducing the aspect ratio of the liquid column makes this range narrower, making the damper more sensitive to parameter variations, as well as its performance. It is also observed that the increase in the attenuator mass ratio combined with the correct tuning and damping ratios present greater reductions in structural vibration. Also, the frequency ratio is reduced with the increase of the mass ratio, while the damping rate of the liquid column increases. From the ideal liquid column parameters determined by the parametric analysis, structural response reductions of approximately 60% were achieved.

Keywords

Structural Dynamics, Vibration control, Tuned Liquid Column Damper, Parametric Analysis, Seismic Analysis

Graphical Abstract



Received: December 16, 2022. In revised form: December 28, 2022. Accepted: January 23, 2023. Available online: January 24, 2023.
https://doi.org/10.1590/1679-78257412

1 INTRODUCTION

Advances in the technology of materials used in the construction of towers, buildings and bridges, as well as projects with bold structural design, have provided more rigid and lighter structures that are highly susceptible to vibration problems. Thus, several types of shock absorbers have been studied, developed and applied (Spencer and Nagarajaiah, 2003; Saaed et al., 2013) to reduce the vibration of the main system due to dynamic loads.

The functioning of a passive device is focused on absorbing part of the energy of the structure to which it is coupled and dissipating this energy by its own mechanisms. Traditionally, the tuned liquid column damper (TLCD) consists of a U-shaped tube partially filled with water. Part of the energy absorbed from the vibrating main system is dissipated by the movement of the liquid inside the tube. The performance of this liquid column device matches the traditional mass damper (TMD) and liquid damper (TLD) (Souza, 2003; Bigdeli and Kim, 2016). However, the TLCD still offers advantages such as low cost, absence of moving mechanical parts, relatively easy installation, adaptation to existing structures and simple maintenance (Yalla and Kareem, 2000).

For the tuned liquid column damper to present good efficiency in reducing the vibrations of the primary system to which it is connected, it is necessary to pay attention to the characteristics adopted for the attenuator, such as its operating frequency, its dimensions and its damping. Usually, the damping of the movement of the liquid column occurs during the liquid's passage through a diaphragm (Balendra et al., 1995). Also, to increase the performance of the TLCD, an electro valve that varies the opening of the diaphragm according to the response of the structure and the damper can be employed (Yalla and Kareem, 2000; Souza, 2003; La and Adam, 2016). The replacement of this diaphragm by metallic balls has also been studied to dissipate the energy of the fluid (Gur et al., 2015). In terms of reducing the structure response, as well as the liquid column response, there is a gain in performance.

The dimensions adopted for the liquid column directly influence the efficiency of the absorber. (Gao et al., 1997; Balendra et al., 1999; Hochrainer and Ziegler, 2006; Altay and Klinkel, 2018) study changing the cross section of the horizontal and vertical sections of the tube. Still, so that the TLCD can act in more than one direction, Lee et al. (2011) proposes a tuned liquid column and sloshing damper (TLCSD). Also, the tuned liquid multi-column damper has been developed (Coudurier et al., 2018), presenting good responses for the vibration control of floating wind turbines, structures subjected to simultaneous dynamic loads in several directions. In addition to this, the application case of the TLCD in wind turbines has been widely studied (Balendra et al. ,1995; Colwell and Basu, 2009; Mensah and Dueñas-Osorio, 2014; Buckley et al., 2018; Hemmati et al., 2019). The liquid column damper is also of interest for reducing the response of tall buildings (Hochrainer and Ziegler, 2006; Min et al., 2005) as the case of the Comcast Center (Figure 1) building in Philadelfia, US (https://www.dhuy.com/comcast-center-tuned-liquid-column-damper).

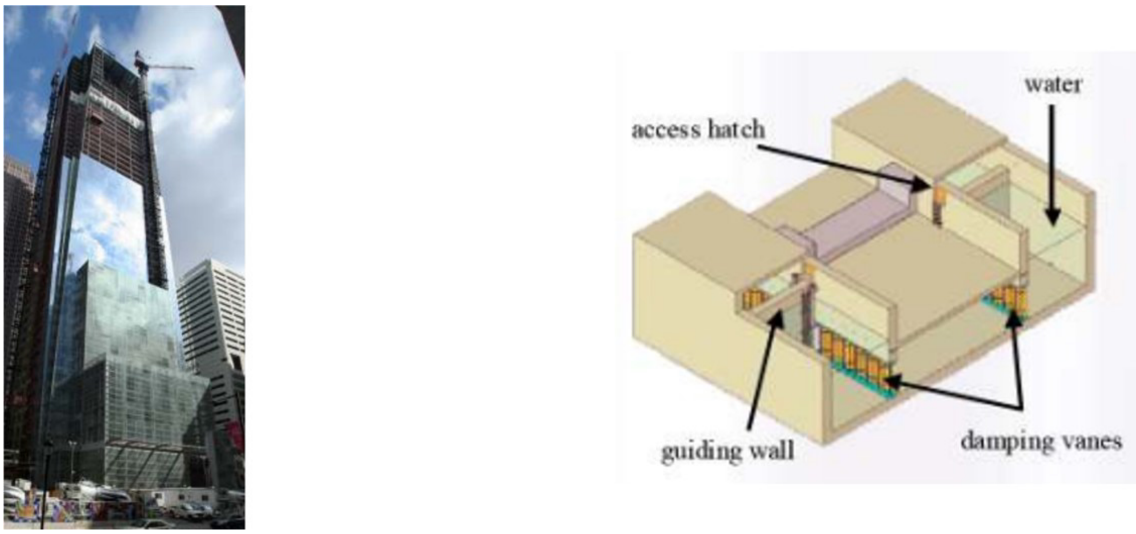


Figure 1: Application of a tuned liquid column damper (TLCD) in Comcast Center, Philadelfia, US (https://www.dhuy.com/comcast-center-tuned-liquid-column-damper). D'Huy Engineering, Inc. "Comcast Center - Tuned Liquid Column Damper". https://www.dhuy.com/. Accessed December 28th, 2022. https://www.dhuy.com/comcast-center-tuned-liquid-column-damper.

Specifically, the main dynamic load considered in these structures is due to the wind. Just like the random action of the wind, efforts have been applied to the dynamic analysis of structures with TLCD for the control of earthquake vibrations (Gosh and Basu, 2005; Chakraborty et al., 2012; Mendes et al., 2019; Espinoza et al., 2018). For a better performance of the damper, (Gosh and Basu, 2004; Sonmez et al., 2016) propose a different composition, in which the TLCD is connected to the primary structure using an adaptive spring. In addition, to having greater malleability for the functioning of the dampers, authors such as (Hochrainer and Ziegler, 2006; Shum et al., 2008; Bhattacharyya et al., 2017) have evaluated the possibility of pressurizing the vertical section of the tube, promoting additional stiffness to the attenuator and, consequently, changing the natural frequency of the TLCD. Both variations in the stiffness of the attenuator (springs and pressurized chambers) demonstrate the option to use this damper in a high frequency range, where the conventional TLCD has a performance loss.

As presented, the liquid column damper is a device that offers several configuration options, such as its geometric design, application possibilities for different types of dynamic loading and the possibility of adding complementary mechanisms to improve its performance. Thus, the TLCD is a prominent damper among many others, which justifies its study, development and application. In this article, a numerical methodology is developed to determine the optimal parameters for TLCD. The analysis of this study is conducted using DynaPy (Freitas and Pedroso, 2019), a dynamic analysis program developed by the Dynamics and Fluid Structure Group from Universidade de Brasília. The numerical results show good agreement with the analytical results. Still, a case study of a structure subject to seismic accelerations is conducted, in which the response map method is applied to define the ideal TLCD for the case. Within this article, it is possible to verify the efficiency of the liquid column damper, which, together with other aspects mentioned, proves to be a relevant device with great perspectives.

2 PROBLEM EQUATIONS

2.1 Tuned liquid column damper

The equation of motion of the U-shaped liquid column (Figure 2) is expressed as (Sakai et al.,1989)

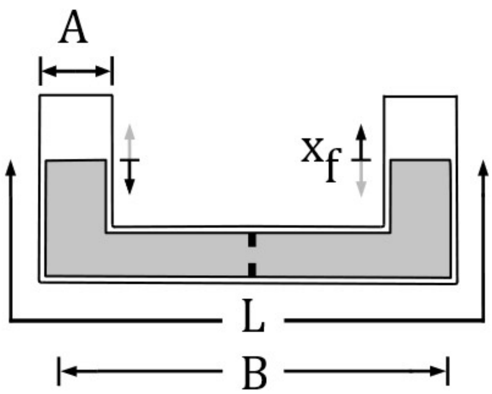


Figure 2: Configuration of the tuned liquid column damper (TLCD).

$$\rho A L \ddot{x}_f + \frac{1}{2}\rho A \xi \left|\dot{x}_f\right| \dot{x}_f + 2\rho A g x_f = 0 \quad (1)$$

ρ_f is the liquid specific mass (in this case, water), g is the gravity acceleration, A is the column cross section, B is the horizontal length of the liquid column, L is the total length of the liquid column and x_f represents the liquid column response. As can be seen from Eq. 1, the TLCD damping is nonlinear. Balendra et al., 1995; Gao et al. (1997); Yalla and Kareem (2000) and Roberts and Spanos (2003) propose to estimate an equivalent damping using statistical linearization methods and express the approximation error e between the non-linear function with the equivalent linear function c_f as

$$e = \frac{1}{2}\rho A \xi \left|\dot{x}_f\right| \dot{x}_f - c_f \dot{x}_f \quad (2)$$

where the value of the equivalent linear damping c_f can be obtained by minimizing the value of the standard deviation of the error. Balendra et al., 1995; Gao et al. (1997); Yalla and Kareem (2000) present the equivalent linear damping c_f for specific cases as harmonic excitation or random excitation. However, in this paper, whose objective is the parametric analysis of the TLCD, a generic formulation employed in Yalla and Kareem (2000) is used for the equivalent linear damping of the liquid column, expressed by

$$cf = 2\zeta_f m_f \omega_f \tag{3}$$

where ζ_f, m_f $(= \rho AL)$ and ω_f are, respectively, the damping ratio, the mass, and the natural frequency of the TLCD

2.2 TLCD coupled to the structure

The equation of motion of the structure coupled with a TLCD (Figure 3) is given by

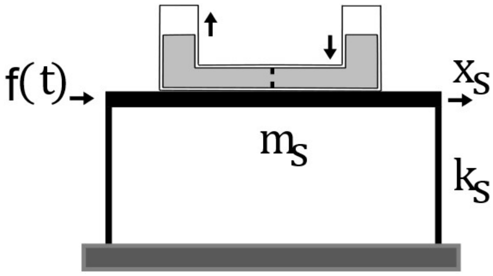


Figure 3: Structure with TLCD attached.

$$(m_s + m_f)\ddot{x}_s + c_s\dot{x}_s + k_s x_s = -\alpha m_f \ddot{x}_f + f(t) \tag{4}$$

where m_s, c_s e k_s are, respectively, the mass, the damping and the stiffness of the structure. α is the aspect ratio and represents the ratio of the horizontal length to the total length of the liquid column ($\alpha = B/L$). Finally, $f(t)$ is a force acting over the time. Thus, the response of the primary system and of the TLCD are determined by the solution of the following equation:

$$\begin{bmatrix} (m_s + m_f) & \alpha m_f \\ \alpha m_f & m_f \end{bmatrix} \begin{bmatrix} \ddot{x}_s \\ \ddot{x}_f \end{bmatrix} + \begin{bmatrix} c_s & 0 \\ 0 & c_f \end{bmatrix} \begin{bmatrix} \dot{x}_s \\ \dot{x}_f \end{bmatrix} + \begin{bmatrix} k_s & 0 \\ 0 & k_f \end{bmatrix} \begin{bmatrix} x_s \\ x_f \end{bmatrix} = \begin{bmatrix} f(t) \\ 0 \end{bmatrix} \tag{5}$$

with $k_f = 2\rho Ag$.

2.3. Parametric equations

To study the behavior of the structure with the TLCD, Eq. 4 of the system can be reduced to:

$$\begin{bmatrix} (1+\mu) & \alpha\mu \\ \alpha & 1 \end{bmatrix} \begin{bmatrix} \ddot{x}_s \\ \ddot{x}_f \end{bmatrix} + \begin{bmatrix} 2\zeta_s\omega_s & 0 \\ 0 & 2\zeta_f\omega_f \end{bmatrix} \begin{bmatrix} \dot{x}_s \\ \dot{x}_f \end{bmatrix} + \begin{bmatrix} \omega_s^2 & 0 \\ 0 & \omega_f^2 \end{bmatrix} \begin{bmatrix} x_s \\ x_f \end{bmatrix} = \begin{bmatrix} f(t)/m_s \\ 0 \end{bmatrix} \tag{6}$$

where $\mu = m_f/m_s$ represents the mass ratio, ζ_s represents the structure damping ratio and ω_s represents the natural frequency of the structure. Adopting $\gamma = \omega_f/\omega_s$ as the frequency ratio or tuning ratio, one has:

$$\begin{bmatrix} (1+\mu) & \alpha\mu \\ \alpha & 1 \end{bmatrix} \begin{bmatrix} \ddot{x}_s \\ \ddot{x}_f \end{bmatrix} + \begin{bmatrix} 2\zeta_s\omega_s & 0 \\ 0 & 2\zeta_f\gamma\omega_s \end{bmatrix} \begin{bmatrix} \dot{x}_s \\ \dot{x}_f \end{bmatrix} + \begin{bmatrix} \omega_s^2 & 0 \\ 0 & (\gamma\omega_s)^2 \end{bmatrix} \begin{bmatrix} x_s \\ x_f \end{bmatrix} = \begin{bmatrix} f(t)/m_s \\ 0 \end{bmatrix} \tag{7}$$

3 NUMERICAL SOLUTION SCHEME

The solution of the equation of motion is obtained by direct integration of the differential equations through the average linear acceleration method, i.e., Newmark method with γ=0.50 and β=0.25. The step size is 0.001 second. In this work, the results presented were obtained using a MATLAB computational routine and the software DynaPy, originally coded by Freitas and Pedroso (2019).

DynaPy is a modelling and simulation software of structure dynamics 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 original version, this software supported shear building structures, TLCDs, PTLCDs, harmonic excitations and generic excitations. Implementations were added by Ghedini et al. (2019) and further development of new routines and approaches to new issues related to the theme continue. The two most important and fundamental packages are called Numpy (Walt et al., 2011) and Matplotlib (Hunter, 2007). 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, it is possible to perform numerical analyses and do the post-processing with ease. The program is composed of three main parts - pre-processing, processing and post-processing. DynaPy is meant to be used with its graphical user interface (GUI), but it is not tied to it. Figure 4 shows the software's flowchart when it is used with the GUI, as intended.

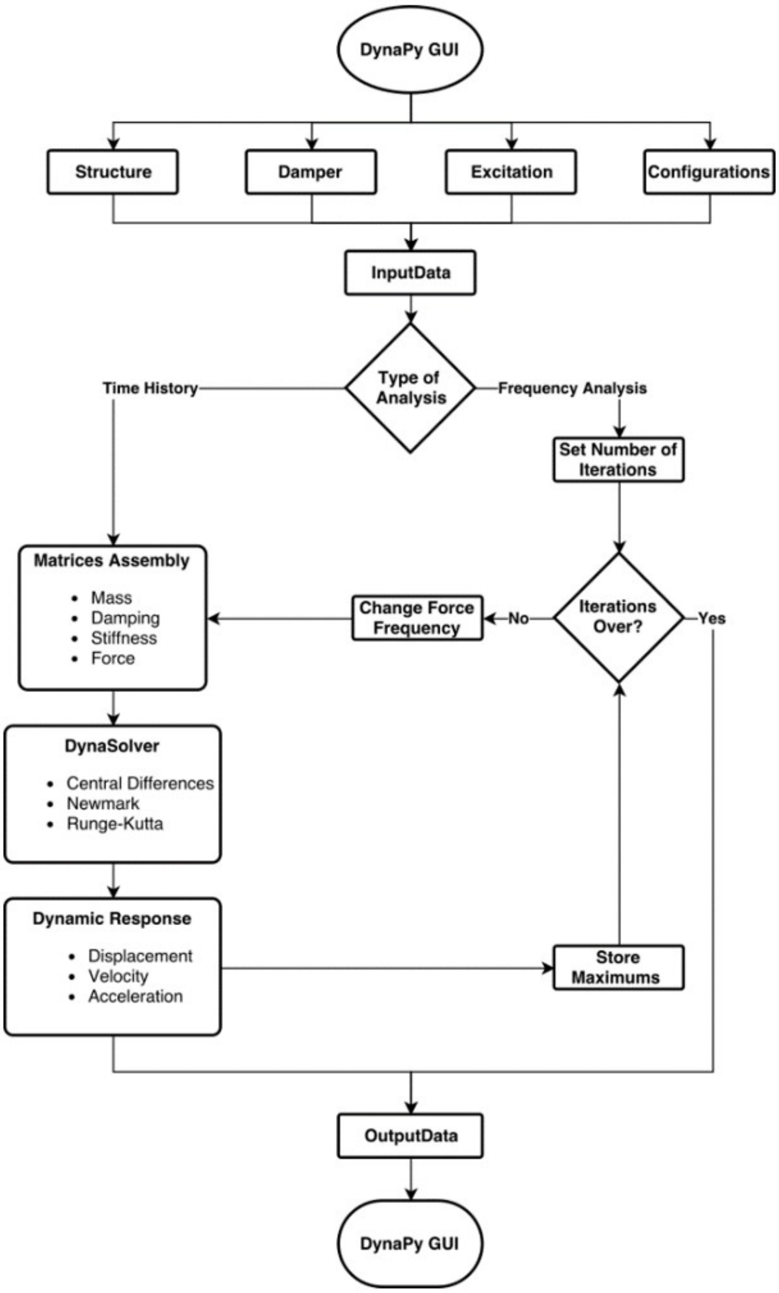


Figure 4: DynaPy's flowchart.

3.1 Analytical and numerical solution in the time domain

To validate the numerical solutions obtained from the computational routines, a damped SDOF system subjected to a harmonic excitation was analyzed. The analytical solution for forced harmonic vibrations with viscous damping are available in the literature in many forms, such as

$$x(t) = e^{-\zeta\omega_n t}(A\sin\omega_d t + B\cos\omega_d t) + \frac{f_0/k}{\sqrt{(1-\beta^2)^2+(2\zeta\beta)^2}}\, sin(\omega t - \theta) \tag{8}$$

in which A and B are constants evaluated from the initial conditions of displacement and velocity of the system, $\beta = \omega/\omega_n$ is the frequency ratio and represents the ratio of the excitation frequency to the natural frequency of the system, f_0/k is the equivalent static deflection that would result from applying a force of magnitude f_0 to the system and θ is the phase angle of the steady-state solution, given by

$$\theta = \tan^{-1}\left(\frac{2\zeta\beta}{1-\beta^2}\right) \tag{9}$$

The SDOF system analyzed has $\omega = 68.8530$ rad/s, $\zeta = 0.01$, $\omega_d = 68.8496$ rad/s, $\Omega = 20$ rad/s, $r = 0.2905$, $\psi = 0.0063$ radian, and f_0/k=0.0211 m. The initial conditions for displacement and velocity are $x(0) = \dot{x}(0) = 0$. For those conditions, the evaluated constants are A = -6.6904·10^{-3} m and B = 1.4616·10^{-4} m. Figure 5 shows the comparison between the analytical and numerical solutions.

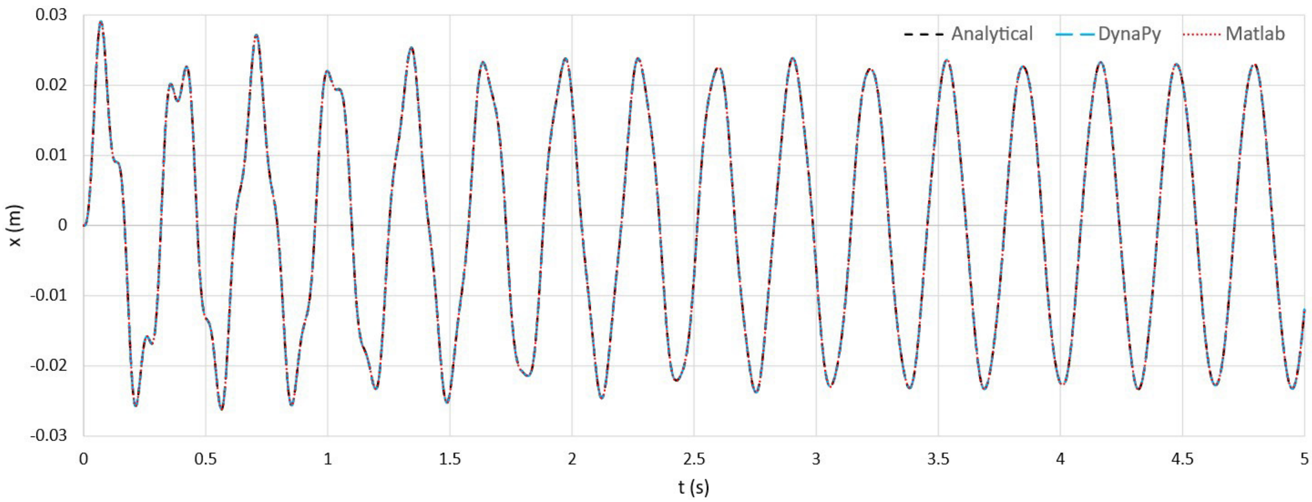


Figure 5: Comparison between analytical and numerical solutions.

As can be seen by the superposition of the solutions, the numerical results show good agreement with the analytical results.

3.2. Frequency domain solution through a harmonic excitation

In a single degree of freedom (SDOF) system, the natural frequency is determined in a straightforward manner and many formulations for several problems are available in the literature. For a multi-degree of freedom (MDOF) system, the natural frequencies are obtained from an eigenvalue problem. In the case of a coupled structure-TLCD system, they are determined from

$$\begin{bmatrix} (1+\mu) & \alpha\mu \\ \alpha & 1 \end{bmatrix} \begin{bmatrix} \ddot{x}_s \\ \ddot{x}_f \end{bmatrix} + \begin{bmatrix} \omega_s^2 & 0 \\ 0 & (\gamma\omega_s)^2 \end{bmatrix} \begin{bmatrix} x_s \\ x_f \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \tag{10}$$

which nontrivial solution is an eigenvalue problem and can be obtained by

$$det\left(\begin{bmatrix} \omega_s^2 & 0 \\ 0 & (\gamma\omega_s)^2 \end{bmatrix} - \Omega^2 \begin{bmatrix} (1+\mu) & \alpha\mu \\ \alpha & 1 \end{bmatrix}\right) = 0 \tag{11}$$

Expanding the determinant yields

$$(1+\mu-\alpha^2\mu)\Omega^2 - [\omega_s^2 + \gamma\omega_s^2(1+\mu)]\Omega + \gamma^2\omega_s^4 = 0 \tag{12}$$

from which the following natural frequencies of a coupled structure-TLCD system are evaluated

$$\Omega_{1,2} = \sqrt{\{\omega_s^2 + (\gamma\omega_s)^2(1+\mu) \pm \Lambda\}/\{2(1+\mu-\alpha^2\mu)\}} \quad (13)$$

where

$$\Lambda = \sqrt{[\omega_s{}^2 - \gamma^2\omega_s{}^2(1+\mu)]^2 + 4\alpha^2\mu\gamma^2\omega_s{}^4} \quad (14)$$

Thus, the natural frequencies of the structure with the liquid column damper can be determined analytically.

To implement another validation test, a frequency sweep was conducted for an undamped coupled structure-TLCD system. The coupled system has the following parameters: $\omega_s = 68.853$ rad/s, $\zeta_s = 0$, $\alpha = 0.95$, $\mu = 0.03$, $\gamma = 0.95$, $\zeta_f = 0$. The analytical frequencies obtained for this system are $\Omega_1 = 61.6689$ rad/s and $\Omega_2 = 72.9238$ rad/s. Using DynaPy, a frequency plot against amplitude consisting of 301 points ranging from 55 to 80 rad/s was done. Figure 6 shows the maximum displacement recorded for each excitation frequency.

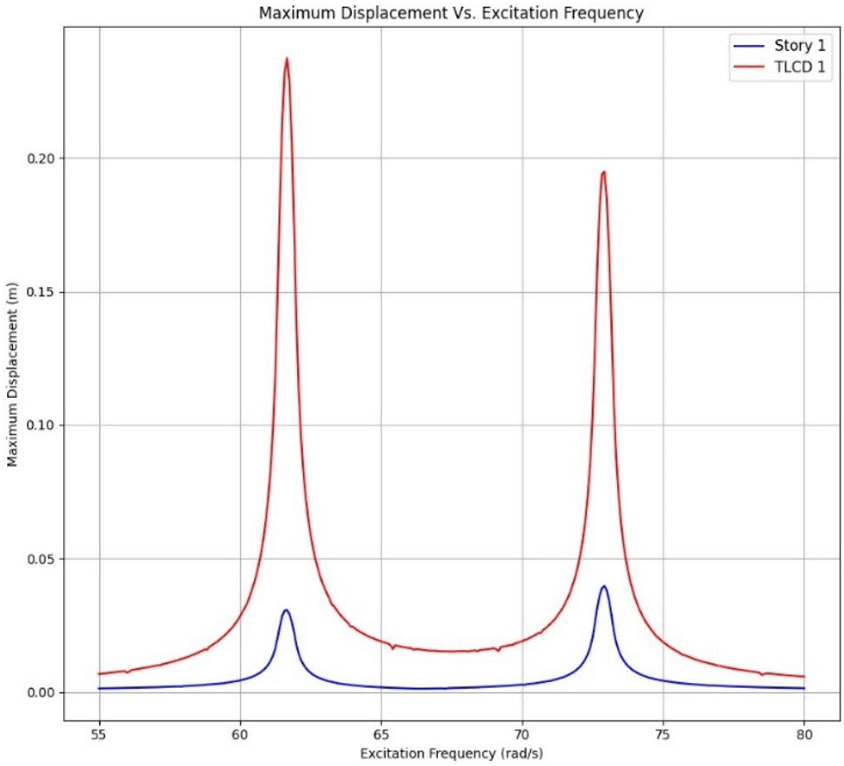


Figure 6: Frequency analysis in DynaPy.

Using the analytical natural frequencies as a starting point, two separate sweeps were performed in the 61-62 rad/s range and in the 72.5-73.5 rad/s range, consisting of 101 points each. The natural frequencies obtained this way were $\Omega_1 = 61.68$ rad/s and $\Omega_2 = 72.94$ rad/s, with respective errors of 0.0181% and 0.0222% when compared to the analytical frequencies. Once again, the numerical results obtained using DynaPy represent a valid approximation to the analytical solution.

4 PARAMETRIC ANALYSES

In order to evaluate how the parameters presented in section 2.3 influence the behavior of a structure with a coupled TLCD, a series of analyses were conducted in the time domain through the solution of Eq. 6 using the Newmark method, from which the maximum displacements of the structure in its steady state of vibration were obtained.

Initially, an uncoupled structure with a fundamental frequency of $\omega_s = 68.853$ rad/s was adopted as reference. Then, a variation of the parameters of aspect ratio α, mass ratio μ, tuning ratio γ and damping ratio of the TLCD ζ_f was performed. This variation produced the surfaces and graphics presented in the following sections.

For all cases, the force acting on the system was a harmonic excitation with unity amplitude and frequency equal to that of the uncoupled structure. The maximum displacements of the coupled structure in each of the simulations were taken from the response after about forty-three system oscillation cycles. This was done to obtain values corresponding to the steady-state and to avoid isolated peaks that eventually appear in the transient state. The total analysis time was 10 seconds, in which the excitation force remained acting on the system.

4.1 Mass ratio (μ) and tuning ratio (γ)

To evaluate the influence of the μ and γ parameters, four possible values were initially defined for the parameter α (0.60, 0.70, 0.80 and 0.90). From these values of α, surfaces obtained through the variation of μ (0.01 to 0.05), γ (0.84 to 1.16) and ζ_f (0.03 to 0.12) were generated, shown in Figure 7 in isometric view and in Figure 8 as a colormap. The vertical axis represents the response ratio λ, which is the ratio of the maximum steady-state displacement of the structure coupled with the TLCD to the maximum displacement of the uncoupled structure, considering the ζ_f that guaranteed the best performance of the damper.

Both Figure 7 and Figure 8 demonstrate that greater values of α return smaller values of λ, that is, the TLCD acts more effectively in attenuating structure vibrations. The use of a value of α equal to 0.60 (Figure 7.a) returned a value of 0.0628 for λ, while α equal to 0.90 (Figure 7.d) allowed a value of λ equal to 0.0296. In addition to the reduction of the minimum surface value, there was a general decrease in the values of the response ratio, including for tuning ratios far from the unit value. This is noticed by the smoothing of the surface slopes toward its lowest point.

Also, it can be verified the presence of a region with considerably smaller values for the response ratio (λ) when the tuning ratio (γ) is close to unity, indicating that the relationship between the structure and TLCD frequencies is a parameter of extreme importance in the attenuator design.

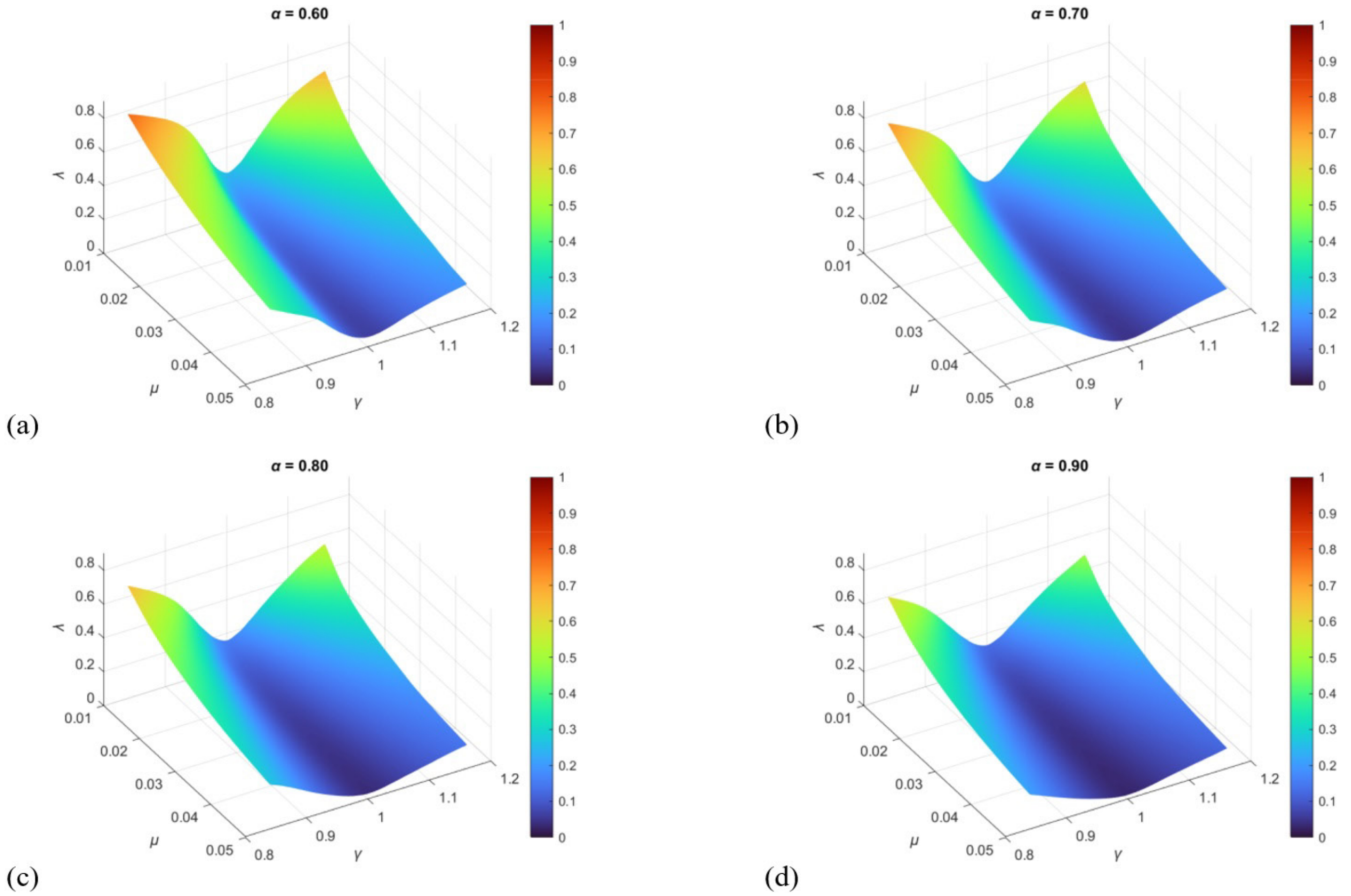


Figure 7 Surfaces relating the response ratio (λ) to the parameters of mass ratio (μ) and tuning ratio (γ), considering different values of aspect ratio: (a) α = 0.60 (b) α = 0.70 (c) α = 0.80 e (d) α = 0.90.

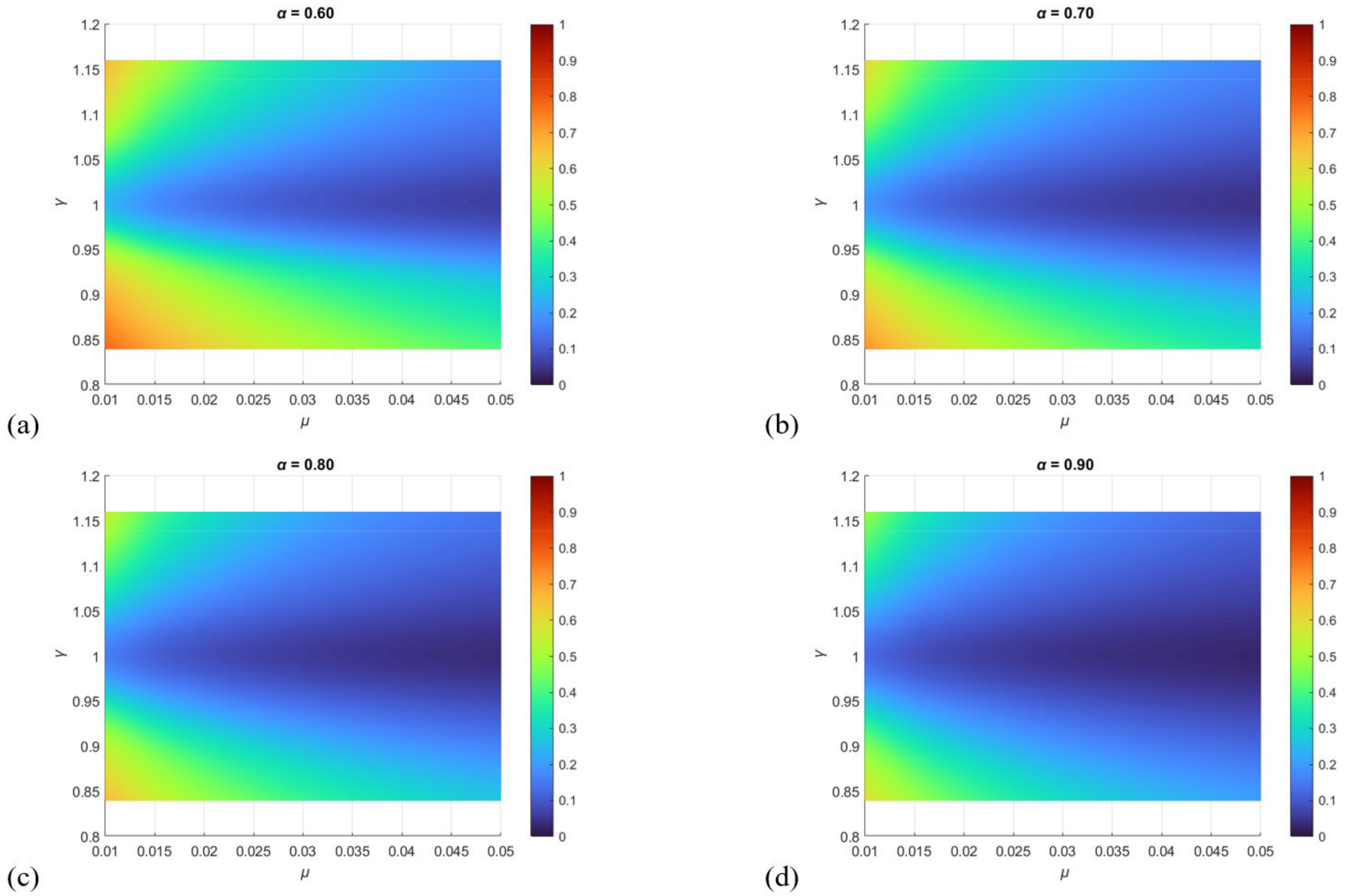


Figure 8 Colormap relating the response ratio (λ) to the mass ratio (μ) and the tuning ratio (γ), considering different values of aspect ratio (α): (a) α = 0.60 (b) α = 0.70 (c) α = 0.80 e (d) α = 0.90.

Also, it can be verified the presence of a region with considerably smaller values for the response ratio (λ) when the tuning ratio (γ) is close to unity, indicating that the relationship between the structure and TLCD frequencies is a parameter of extreme importance in the attenuator design. Figures 7 and 8 allow the visualization of a smooth decreasing slope of the surface along the axis corresponding to the mass ratio parameter (μ) as this ratio is increased. This is due to the mass coupling between the structure and the TLCD and the reduction mechanism of the structure responses due to the inertial effect of the horizontal displacement of the fluid in the attenuator.

4.2 Damping ratio (ζ_f)

The results of the response ratio (λ) presented in the previous section, obtained from the variation of the parameters α, μ, γ and ζ_f, are related to the maximum displacements of the structure coupled with the TLCD, considering the ζ_f that guaranteed the best performance of the attenuator. Thus, for each combination of the other parameters a more adequate damping ratio was calculated for the TLCD. This was done within the range determined for its variation, which was from 0.03 to 0.12. Figure 9 and Figure 10 present, respectively, the surface and its respective colormap in which the vertical axis corresponds to the parameter ζ_f. It is possible to verify that there is a wide range in which the ideal TLCD damping ratio is a minimum of the predefined interval (0.03). This range lies around the unity tuning ratio. These values change significantly as γ moves away from unity.

It is noticed that the mass ratio (μ) exerts little influence on the ideal damping ratio when the TLCD and structure are tuned, which corresponds to most cases in practice. Furthermore, an increase of the aspect ratio (α) promotes an enlargement of the range corresponding to the minimum value of ζ_f, as is easily verified by comparing Figure 10a and Figure 10d.

Therefore, for this studied case, in which a harmonic excitation force acts on the coupled system with a frequency equal to that of the uncoupled structure, small values of fluid damping ratio (ζ_f) already allow an optimal attenuation of the maximum displacements of the structure when the TLCD is properly tuned.

In this case, the reduction of vibrations is due to inertial forces arising from the fluid displacement in the horizontal section of the attenuator. Thus, the reduction little depends on the dissipation of energy by the movement of fluid.

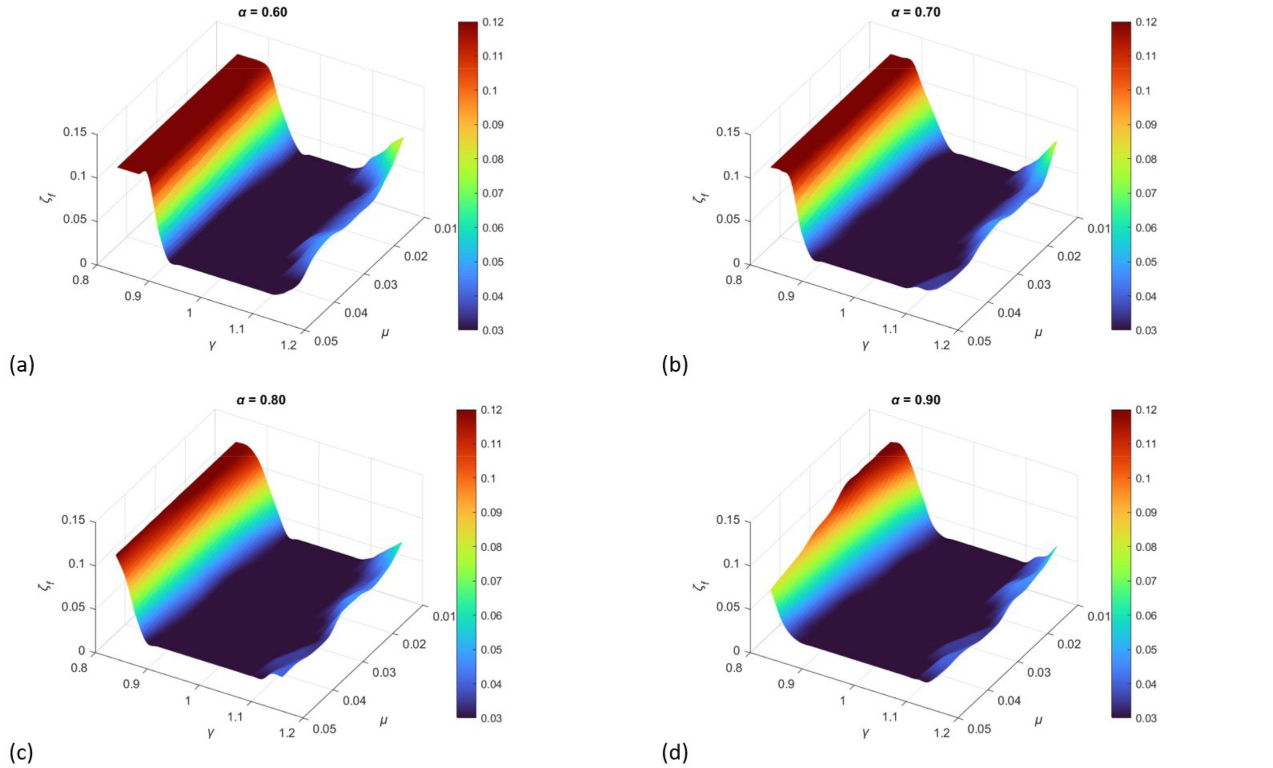


Figure 9 Surfaces relating the TLCD damping ratio (ζ_f) to the mass ratio (μ) and tuning ratio (γ) parameters, considering different values of aspect ratio (α): (a) α = 0.60 (b) α = 0.70 (c) α = 0.80 e (d) α = 0.90.

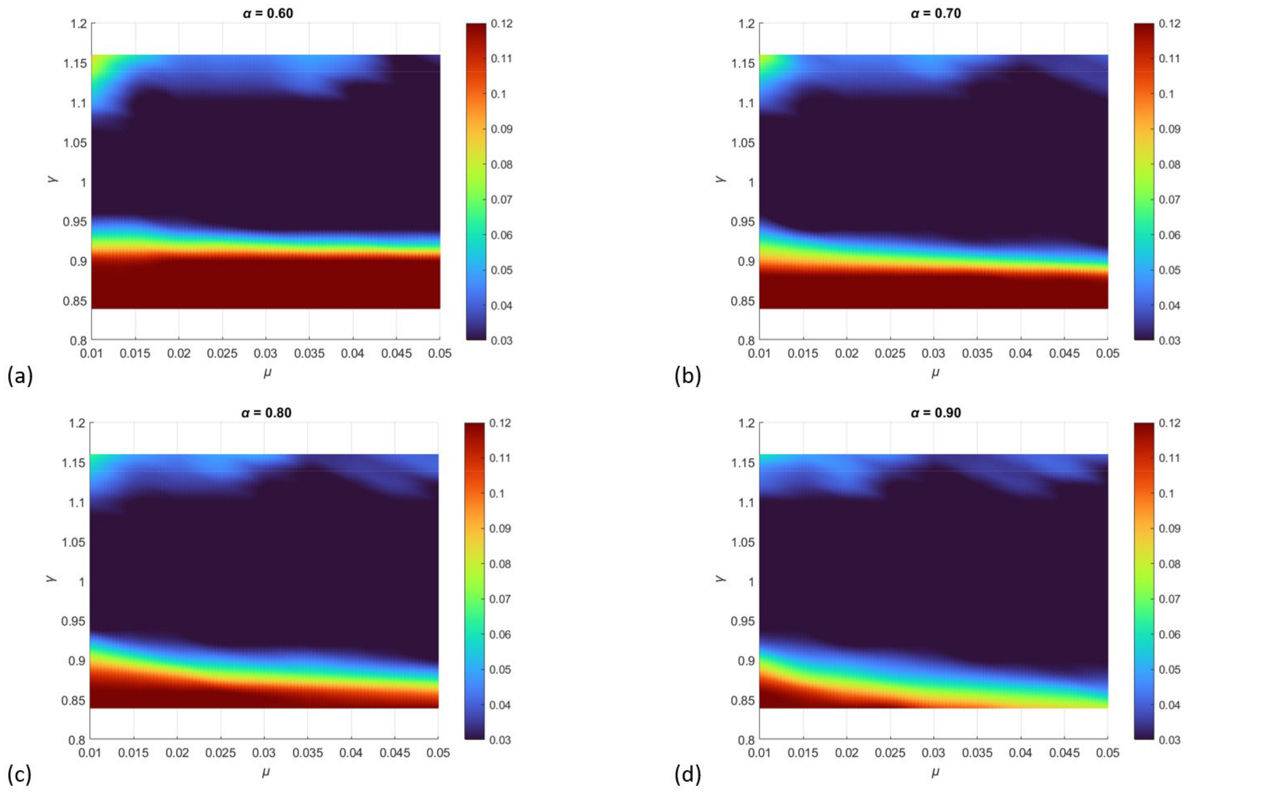


Figure 10 Colormap relating the response ratio (ζ_f) to the mass ratio (μ) and the tuning ratio (γ), considering different values of aspect ratio (α): (a) α = 0.60 (b) α = 0.70 (c) α = 0.80 e (d) α = 0.90.

5 CASE STUDY

The results obtained from the analyses in the previous section were for an SDOF structure coupled with a TLCD. Despite being a simple model, the relations obtained can be used for the control of an MDOF structure's dominant vibration mode. To visualize the effect that the TLCD has in controlling an MDOF structure, DynaPy will be used in a case study (Figure 11). The example is a five-story building subjected to the horizontal north-south El Centro ground motion record available in La and Adam (2016).

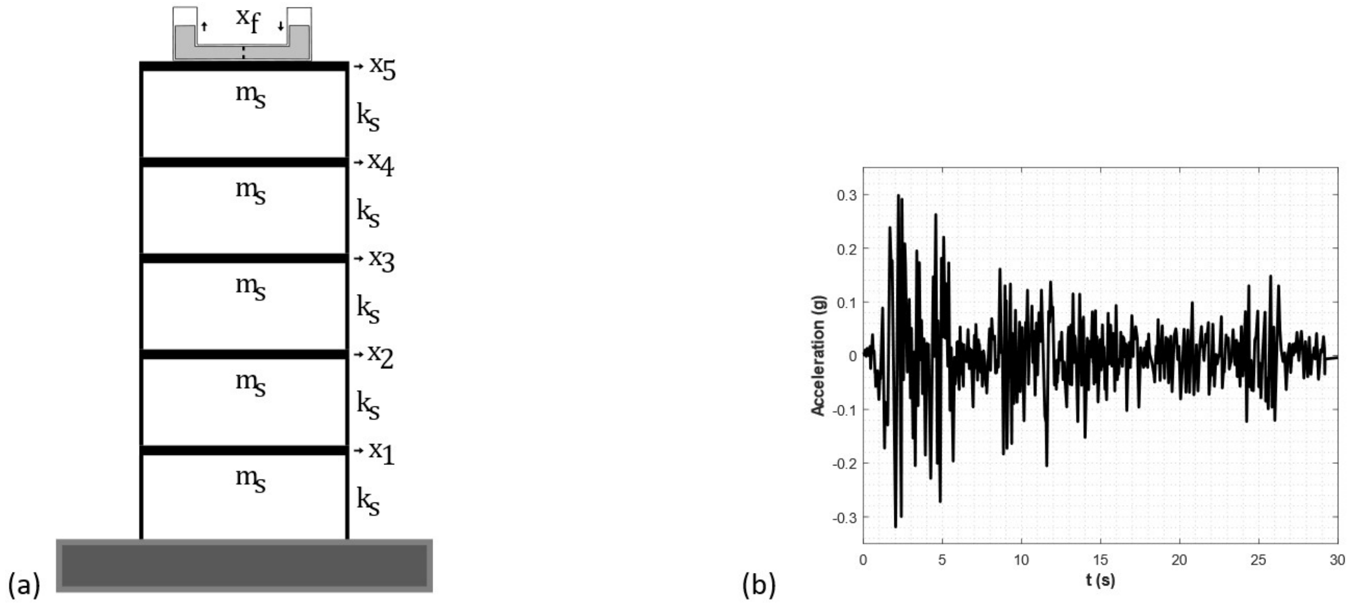


Figure 11 (a) Five-story shear building with TLCD attached to the fifth story and (b) time history of ground acceleration for the El Centro earthquake

The building was equipped with a TLCD and modeled in DynaPy. The lumped mass m_s at each floor is 45.3576 ton, the lateral stiffness k_s of each story is 5523.5034 kN/m and the structure damping ratio considered is zero. For the given values of k_S and m_S, the natural frequencies ω_n (rad/s) are 3.141, 9.168, 14.453, 18.567, 21.176.

To determine the ideal TLCD to be attached to the structure subjected to the random action of the El Centro earthquake, a parametric study of the liquid column is conducted using the response map of the last story of the structure (x_5). According to the previous study, the values (0.60, 0.70, 0.80 and 0.90) are considered for the aspect ratio α, while the values considered for the mass ratio μ, tuning ratio γ and damping ratio ζ_f are in the range (0.01 to 0.05), (0.75 to 1.15) and (0.00 to 0.15), respectively.

Given that the earthquake signal is random, the rms response is adopted for the structure response due to the seismic excitation. Thus, the vertical axis represents the rms response ratio (λ), defined by the ratio between the rms displacement of the top story of the structure coupled with the TLCD and the rms displacement of the top story of the uncoupled structure.

Figure 12 and Figure 13 present the results in isometric view and as a colormap, respectively. Higher mass ratios represent a greater reduction in displacements. Also, the higher the TLCD aspect ratio, the greater the attenuator efficiency. The tuning frequency is more relevant for attenuators with lower B/L ratios, given that there is a significant performance loss with smaller reductions in the structure displacement outside of the central region. The results of the response ratio λ presented in the previous section, obtained from the variation of the parameters α, μ, γ and ζ_f, are related to the maximum displacements of the structure coupled to the TLCD considering the ζ_f that guaranteed the best performance of the attenuator.

Figure 14 and Figure 15 present the damping ratio values ζ_f of the liquid column, in which they are associated with the minimum values determined for the top story rms displacement of the structure coupled with the TLCD. Unlike the previous case, it is observed from the variation of parameters α, μ, γ, that there is a reduced range for the ideal damping ratio of the TLCD. Once again, however, the range for its ideal value is close to a unity tuning ratio.In this case of the structure subjected to an earthquake, the aspect ratio, the mass ratio and the tuning ratio demonstrate a greater relationship with the ideal TLCD damping ratio.

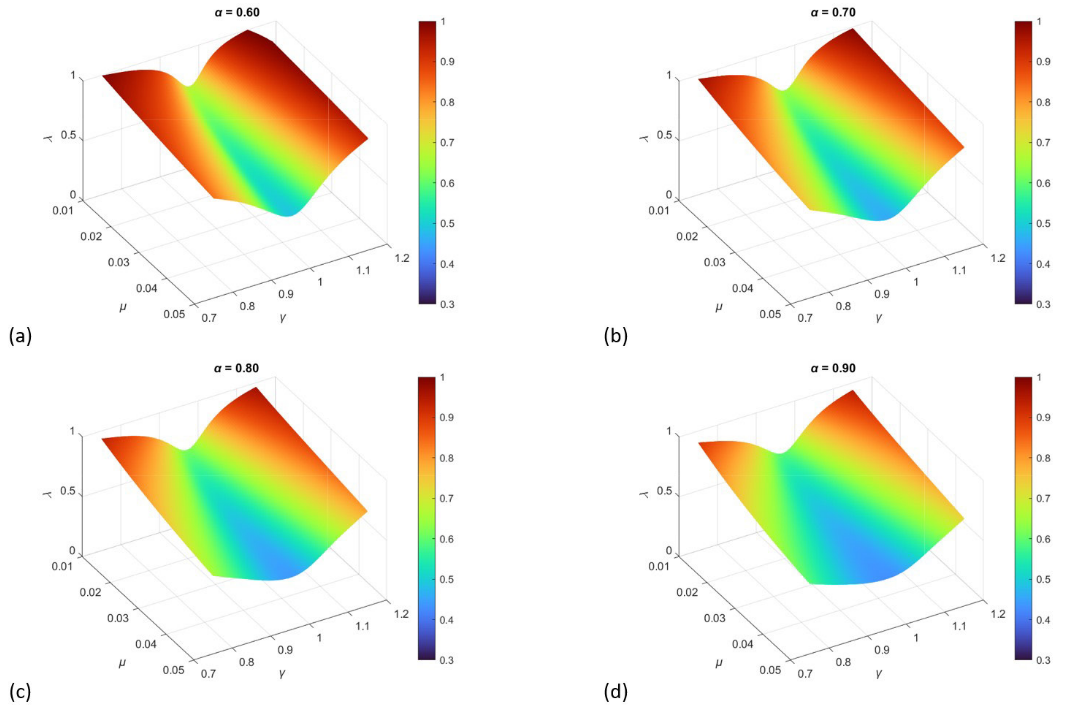


Figure 12 Surfaces relating the structure displacement response ratio (λ) for the El Centro earthquake to the parameters of mass ratio (μ) and tuning ratio (γ), considering different values of aspect ratio (α): (a) α = 0.60 (b) α = 0.70 (c) α = 0.80 e (d) α = 0.90.

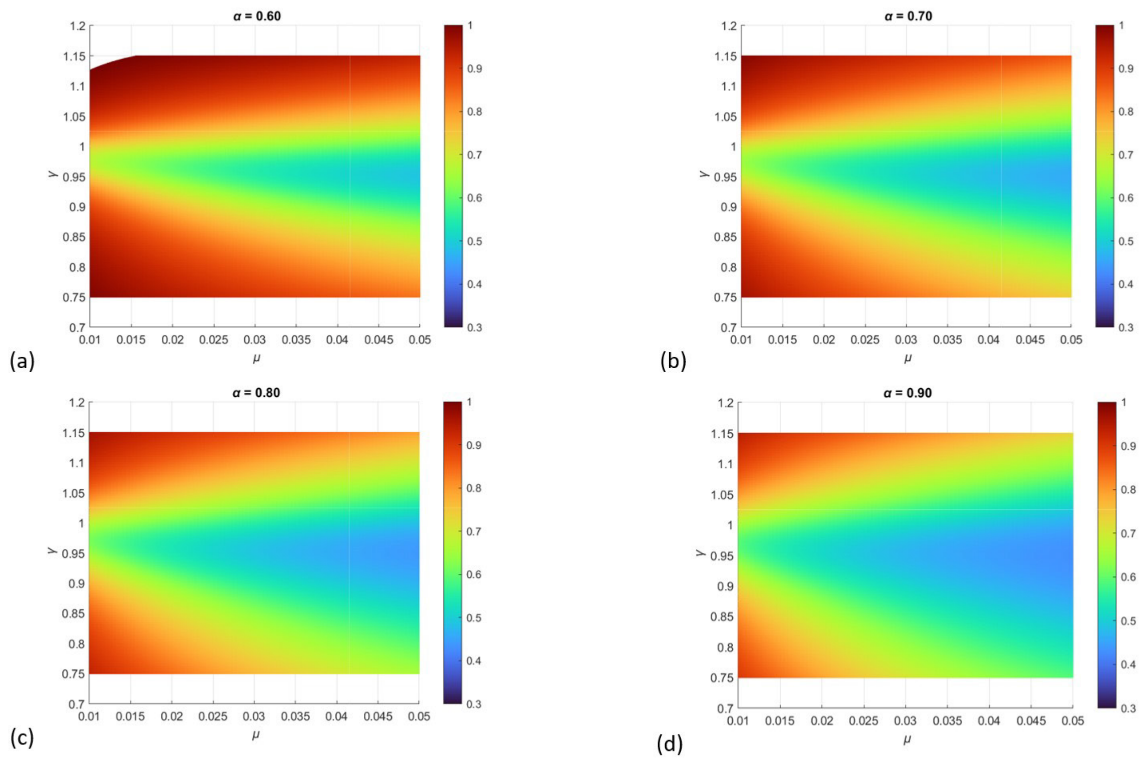


Figure 13 Colormap relating the structure response ratio (λ) for the El Centro earthquake to the parameters of mass ratio (μ) and tuning ratio (γ), considering different values of aspect ratio (α): (a) α = 0.60 (b) α = 0.70 (c) α = 0.80 e (d) α = 0.90.

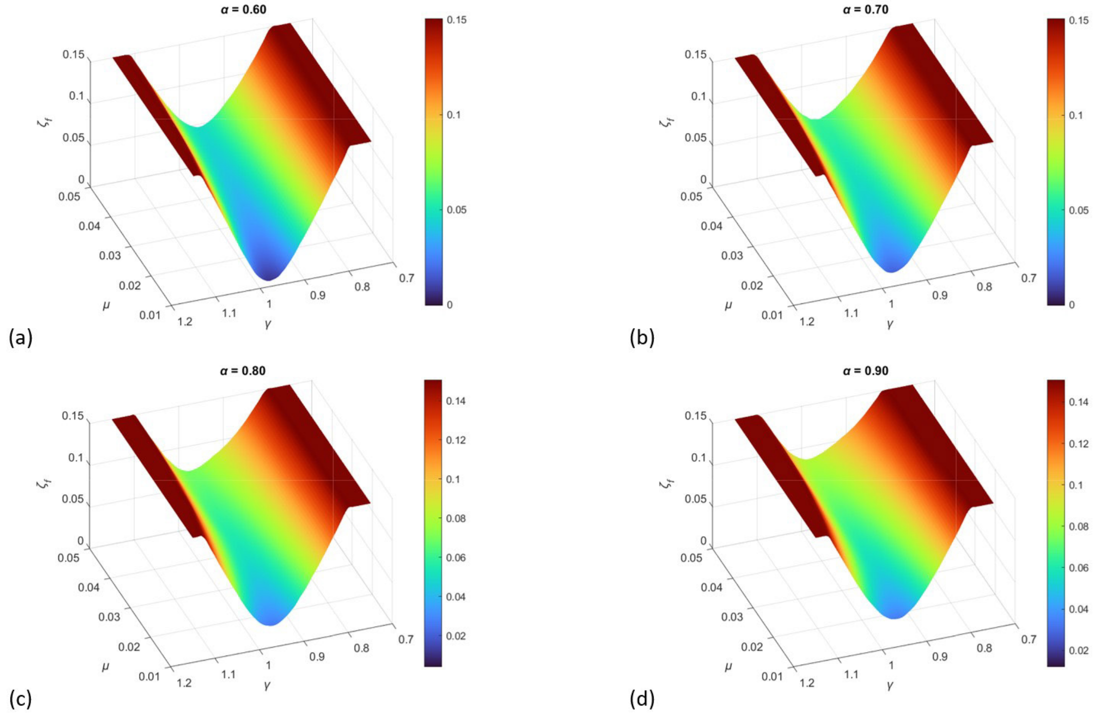


Figure 14 Surfaces relating the TLCD damping ratio (ζ_f) to the mass ratio (μ) and tuning ratio (γ) parameters, considering different values of aspect ratio (α): (a) α = 0.60 (b) α = 0.70 (c) α = 0.80 e (d) α = 0.90.

Increasing the attenuator mass requires a higher damping ratio, while increasing the aspect ratio (α) smoothes the surface behavior for different frequencies. And again, for a lower aspect ratio, the surface presents a narrow valley for the damping values. Thus, it is demonstrated that for the case of a force with different frequency amplitudes, such as an earthquake, the variation of the parameters of the liquid column is significant for its behavior and performance.

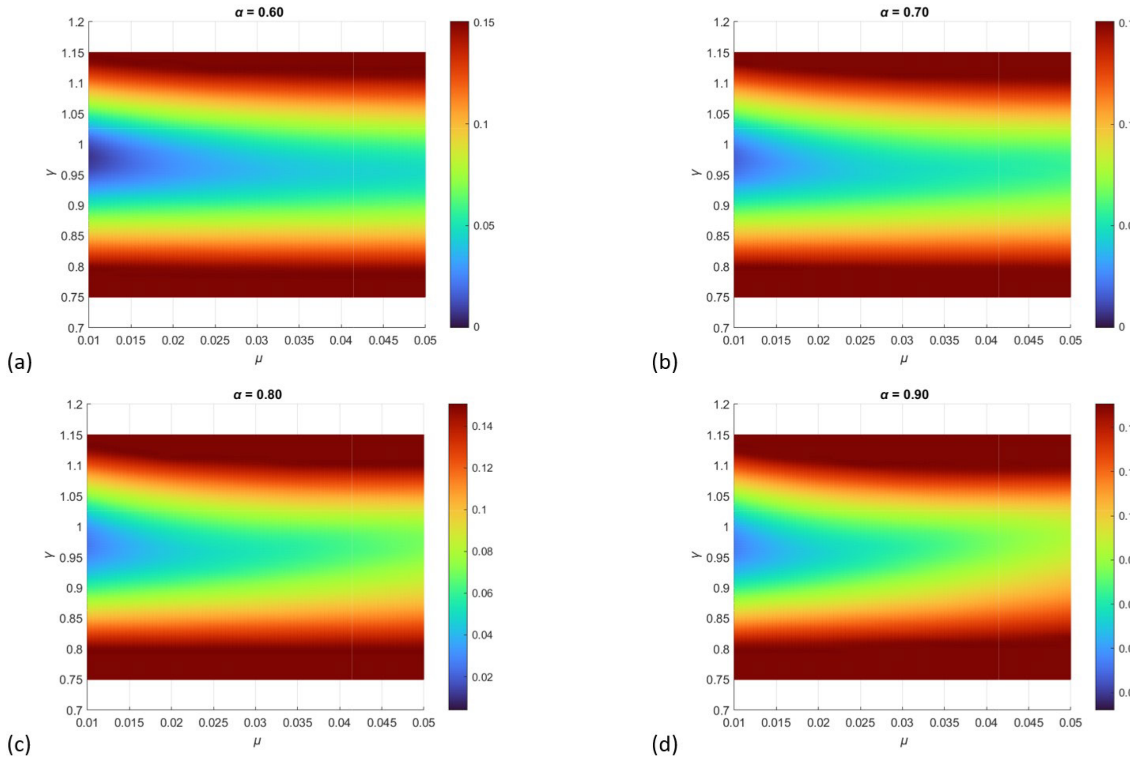


Figure 15 Colormap relating the TLCD damping ratio (ζ_f) to the mass ratio (μ) and tuning ratio (γ) parameters, considering different values of aspect ratio (α): (a) α = 0.60 (b) α = 0.70 (c) α = 0.80 e (d) α = 0.90.

As shown, the parameters adopted for the liquid column damper influence its performance. Figure 16 presents the time response of the top of the structure (x_5) with an ideal TLCD obtained from the response map and dimensioned with the parameters shown in Table 1. Increasing the mass ratio of the TLCD provides greater reductions in the rms displacement of the top of the structure. For μ equal to 1% and 5%, the response reduction is approximately 40% and 58%, respectively.

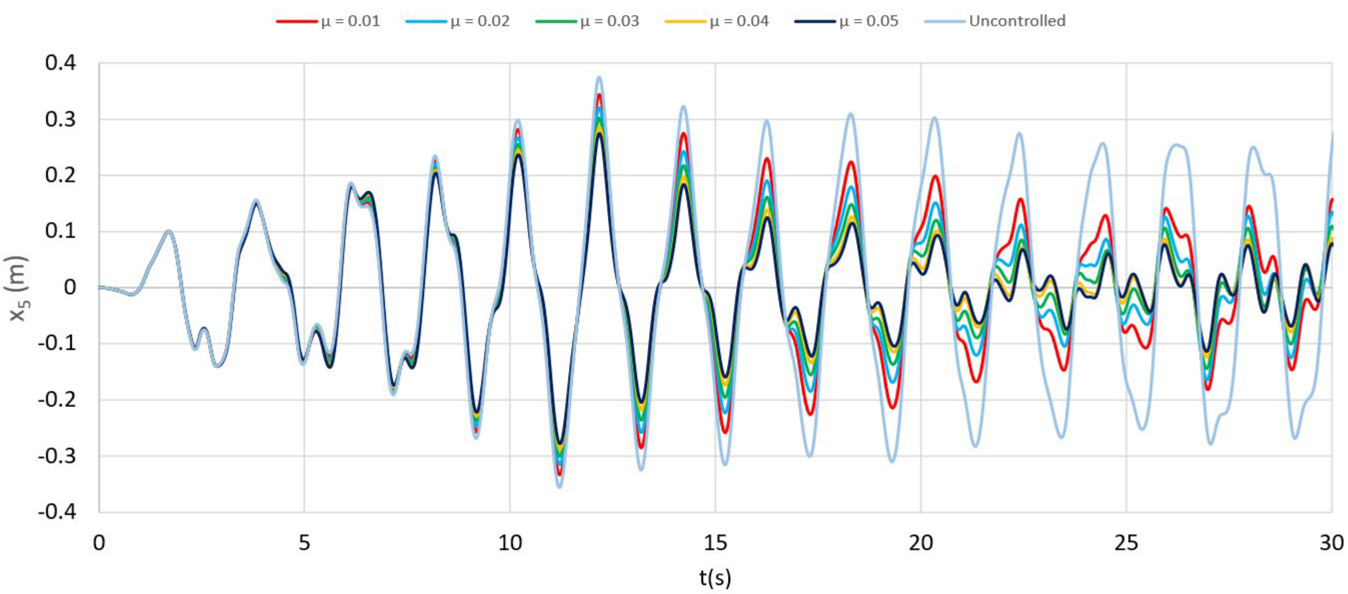


Figure 16 Time response of the top of the structure (x_5) with the mass ratio variation of the ideal TLCD designed from the response map.

Table 1 Mass ratio variation of the ideal TLCD designed from the response map.

α	μ	γ	ζ_f	λ
0.90	0.01	0.9681	0.0339	0.5928
0.90	0.02	0.9560	0.0521	0.5135
0.90	0.03	0.9520	0.0645	0.4713
0.90	0.04	0.9520	0.0765	0.4463
0.90	0.05	0.9480	0.0906	0.4293

It is also observed that changing the aspect ratio causes a significant change in the damping ratio of the liquid column (Table 2), while the tuning frequency is slightly altered. The ideal TLCD determined from the parametric study and dimensioned with the parameters shown in Table 2 for the variation of α has the time response of the top of the structure (x_5) shown in Figure 17. The aspect ratio has influence on the response, but it is small when compared to the mass ratio. This is a relevant factor for structures with limited space to receive the TLCD.

Table 2 Aspect ratio variation for the TLCD with a fixed mass ratio of 5% and designed from the response map.

α	μ	γ	ζ_f	λ
0.60	0.05	0.9520	0.0469	0.4881
0.70	0.05	0.9480	0.0593	0.4585
0.80	0.05	0.9480	0.0735	0.4402
0.90	0.05	0.9480	0.0906	0.4293

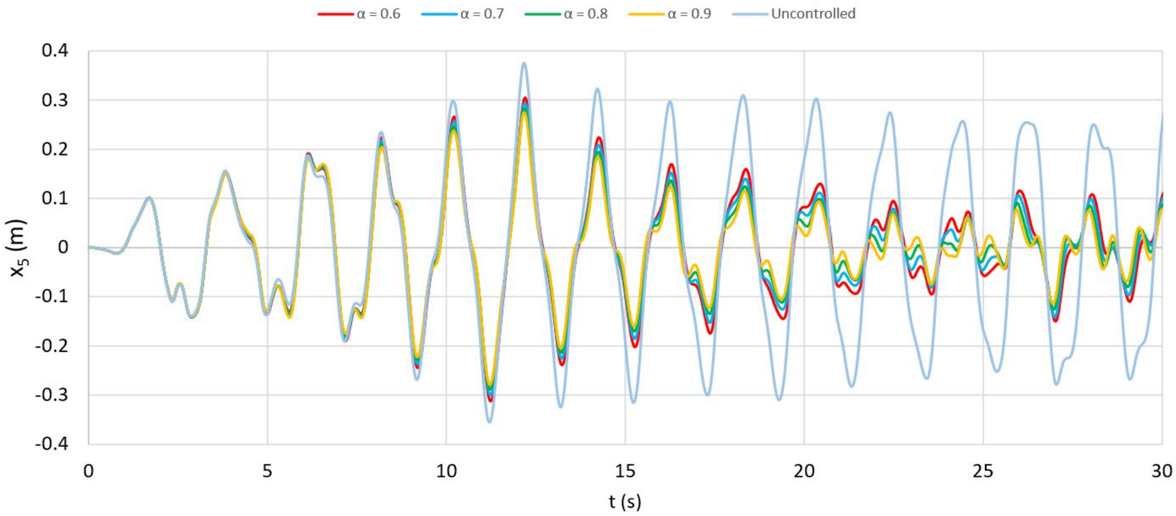


Figure 17. Time response of the top of the structure (x_5) with the aspect ratio variation for the TLCD with a fixed mass ratio of 5% and designed from the response map.

Furthermore, the definition of the TLCD damping ratio ζ_f directly influences the mitigation of structural vibrations. As shown in Table 3 and Figure 18, it is strongly related to the damper damping and tuning ratio. The highest values adopted for the damping ratio do not guarantee the damper best performance and, consequently, the greatest reductions in structure response. As the liquid column tuning approaches, the ideal value for the case (α and μ equal to 0.9 and 1%) the damping ratio is reduced. Thus, the choice of the TLCD damping rate must be made after defining the liquid column damper operating frequency.

Table 3 Response mitigation with TLCD tuning and damping ratio variation for a fixed aspect ratio of 0.90 and mass ratio of 1%.

α	μ	γ	ζ_f	λ
0.90	0.01	1.0000	0.0423	0.6528
0.90	0.01	0.9843	0.0361	0.6099
0.90	0.01	0.9681	0.0339	0.5928
0.90	0.01	0.9439	0.0383	0.6222
0.90	0.01	0.9197	0.0502	0.6813

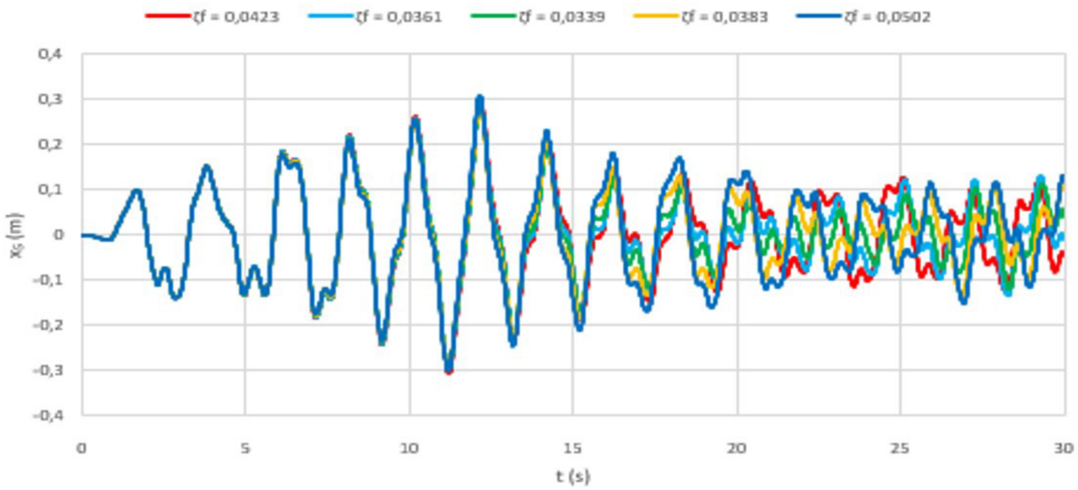


Figure 18. Time response of the top of the structure (x_5) with the different cases of TLCD damping ratio as presented in Table 3.

6 CONCLUSIONS

The effectiveness of a TLCD in reducing structural vibration has been demonstrated for different types of force. A numerical analysis methodology was presented to determine the parameters of the liquid column damper by means of a structure response map. As shown by the response map, it appears that the TLCD tuning range, represented by the tuning ratio, has a great influence on the damper's performance. However, it is interesting to note that even if the TLCD is not perfectly tuned it is still possible to obtain satisfactory performance from the damper. This is an important factor, since real structures throughout their service life may present changes in their fundamental frequency generated by deterioration. Increasing the mass ratio, followed by decreasing the tuning frequency and then by increasing the liquid column damping ratio are the steps that generate greater reductions in structural displacement. However, the structure naturally imposes a limit on the configuration of the TLCD. Thus, it is important to emphasize that the reduction of the aspect ratio makes the TLCD more sensitive to parameter variations. Therefore, the value of the methodology applied in this article for the parametric analysis of the liquid column damper and its design is reinforced.

Acknowledgments

The first author would like to thank for Brazilian Council for Scientific and Technological Development (CNPq) for Doctoral scholarship support (GD doctoral category – process number 141968/2020-6).

Author's Contributions: Conceptualization, M Mendes and L Pedroso; Formal analysis, M Mendes, L Ghedini, and R Batista; Investigation, M Mendes, L Ghedini, and R Batista; Methodology, M Mendes and L Pedroso; Software, M Mendes, L Ghedini, and R Batista; Supervision, M Mendes and L Pedroso; Validation, M Mendes and L Ghedini; Visualization, M Mendes, L Ghedini and R Batista; Writing – original draft, M Mendes, L Ghedini and R Batista.

Editor: Marcílio Alves

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