A Parametric Study of Intervening Factors in Vibration Mitigation in Wind Towers Controlled by TLCDs

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Abstract. Wind turbine support towers are tall and slender structures, because of this, they have low natural vibration frequencies, which make them susceptible to vibrations due to wind, earthquakes, and/or other dynamic actions. These vibrations can cause sensory discomfort and structural damage, causing collapse by amplification of structural responses or the failure of some structural components due to fatigue. Therefore, it is interesting to implement vibration control devices to attenuate the vibrations. This work analyzes Tuned Liquid Column Dampers (TLCDs) as a passive structural control. The mathematical formulations of the wind tower motion equations are presented for structural systems with a single, and with several degrees of freedom, under bending effects, and for the incompressible fluid column (TLCD). Initially, the tower and TLCD systems are studied separately, and later in a coupled manner, within a wide range of parameter values, an aspect that allows the construction of response maps representing the ratio of attenuated and non-attenuated structural response. A simplified way of optimizing parameters of a TLCD model in the time and frequency domain under harmonic excitation is proposed to improve the performance of TLCDs, as well as simulations on wind towers with many degrees of freedom, dimensions, and real conditions.

Keywords: Tunned Liquid Column Dampers, Vibration Control, Wind Action, Wind Turbine, Structural Dynamics.

1 Introduction

Global warming and its consequences for climate change and energy demands with the increase in population, and the search for new sources of renewable and sustainable energy, which minimally impact the environment, make wind energy an important alternative to be considered in current times. Thus, wind turbines appear to be privileged energy sources in these scenarios. However, these structures are subject to various dynamic loads such as wind, earthquakes, rotor and blade movements, etc., which induce undesirable structure vibrations. Several technically available devices could be used to mitigate these effects. However, the tuned liquid column damper (TLCD) has a series of advantages that make it competitive considering other alternatives available for it. This device is characterized by a column of incompressible liquid filling the volume of a U-tube, located at the top of the tower when wanting to attenuate the 1st mode (dominant mode for this type of structure). When the tower with the wind turbine equipment is dynamically excited, the liquid column oscillates out of phase with the structure, attenuating the dynamic response. Vibration attenuation occurs due to the inertial forces of the horizontal movement of the fluid and its energy dissipation internally in the device (Pedroso [1]).

The application of TLCDs in offshore wind turbine structures under the actions of waves and winds was the subject of study by Colwell and Basu [2]. Buckley et al. [3] and Colwell & Basu [2] found that TLCD performs satisfactorily even if it is not perfectly tuned to the structure. The use of TLCDs and/or reservoirs with free surfaces (sloshing) in tall buildings to control vibrations was also studied by Morais et al. [4] and Conceição et al. [5], showing the efficiency of these devices.

Studies on the effect of the opening ratio of the central diaphragm on TLCD damping demonstrate the relevance of this parameter in the device's efficiency (Wu [6]). Oscillatory flow in a column of incompressible liquid with pressure losses in ducts with diaphragms and perforated plates was investigated by Pedroso and Gibert [7] in research applied to nuclear reactors, but which have similarities to the case of TLCDs. The pioneering studies of Sakai et al. [8] also used TLCD in buildings.

Behbahani et al. [9] used baffles in the TLCD as an alternative to diaphragms, which allowed increasing the efficiency of the device. The possibility of pressurizing the fluid columns was also evaluated, which provides greater rigidity to the damper, enabling its application in structures with higher natural frequencies (Pedroso [10], Shum et al. [11]). TLCDs with different cross sections have the advantage of facilitating the tuning of the device with the structure, since their natural frequency is a function of the relationship between these sections, and not just the total length of the liquid column (Pedroso [1], Gao et al. [12]).

TLCDs equipped with embossments inside them as energy dissipation mechanisms demonstrated that they are an interesting alternative to the attenuator version without a central diaphragm (Park et al. [13]). Variations of the TLCD have been proposed, such as the tuned liquid column and sloshing damper (TLCSD), which allows attenuation through sloshing (Lee et al. [14]), and the tuned liquid multi-column damper (TLMCD), with application in databases floating offshore wind turbines (Coudurier et al. [15]). Espinoza et al. [16] conducted studies to optimize the frequency and pressure loss coefficient of TLCD in structures with non-linear behavior. Mendes et al. [17] present a parametric optimization of a (TLCD) to control the structural vibration of an offshore wind turbine under random action of wind and ocean waves.

The present work aims to analyze, by analytical and numerical simulations, the dynamic behavior of wind turbine support towers and evaluate the effect of using TLCDs as control devices through a wide variation of the parameters involved. A simplified model with a single degree of freedom to represent the structure and the incompressible fluid column (TLCD) is considered, resulting in a system with two degrees of freedom to represent the Structure-TLCD coupled system. Figure 1 illustrates the modeling of the systems and the representation of the problem.

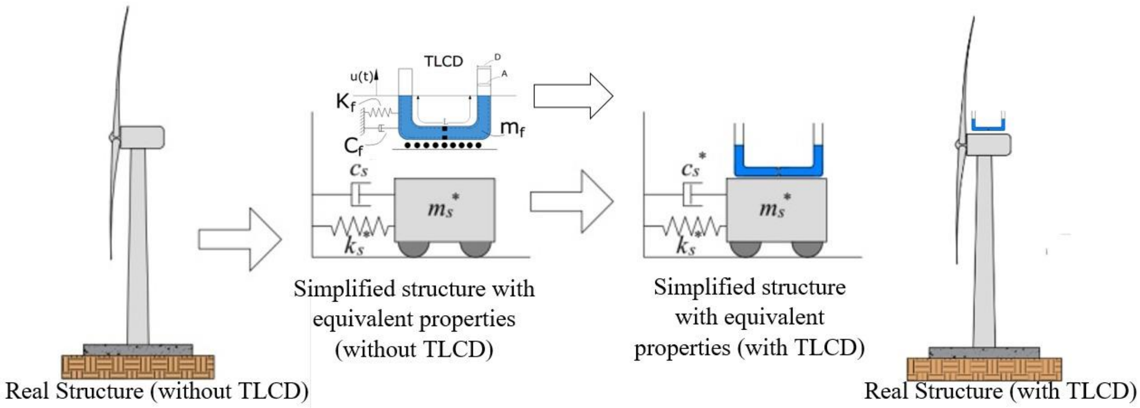


Figure 1. Simplified uncoupled and coupled Structure-TLCD Systems. Adapted from Batista e Pedroso [18].

2 Formulation of the equations of motion of uncoupled and coupled structure-TLCD systems

2.1 Uncoupled Systems with Single Degree of Freedom (SDoF)

Considering the simplification that can initially represent the structure (tower + wind turbine), characterized by the dominant response of the 1st mode, or an equivalent generalized system, and the fluid column (TLCD), as simple uncoupled/independent systems with one single degree of freedom (SDoF) (Fig. 2(a) and 2(b)), where the fluid is considered viscous and incompressible; The equations that describe the movement of these two systems have similarities and can be presented in a manner analogous to the traditional forms provided in Structure Dynamics (Pedroso [1]).

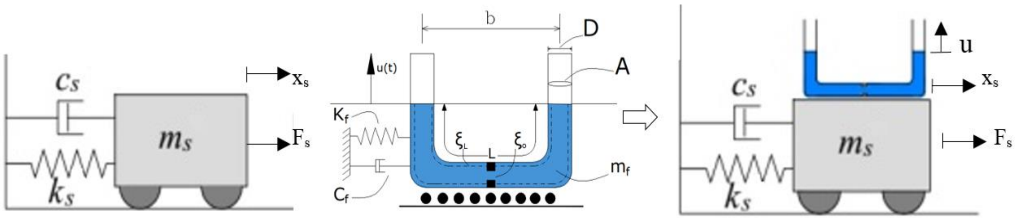


Figure 2. Representation for uncoupled and coupled systems: (a) Structure, (b) TLCD, and (c) Coupled system. Adapted from de Batista e Pedroso [18].

i) Motion equation of the structure: Initially considering the structure as a SDoF (Fig. 2a): the dynamic equilibrium equation that governs the movement is given by:

$$m_s\ddot{x} + c_s\dot{x} + k_s x = F_s(t) \tag{1}$$

where m_s is the mass of the structural system, which can contain the mass of tower + wind turbine; c_s is the damping constant; k_s is the stiffness associated with the elastic force, and $F_s(t)$ is the external load applied to the structure as a function of time (t); x(t), $\dot{x}$ (t) e $\ddot{x}(t)$ are, respectively, the displacement, velocity and acceleration of the system as a function of time t; and $\omega_s = \sqrt{(k_s/m_s)}$ is its natural vibration frequency.

ii) Motion equation of the Tuned Liquid Column Damper (TLCD): The TLCD (Fig. 2b) is also characterized as a SDoF, in which the movement of the entire column of incompressible fluid moves in block. The complete formulation for the oscillatory movement of the fluid column that characterizes TLCD can be found in the extensive exposition on the subject in Pedroso [1,19]. The equation that describes the movement of the TLCD is given by:

$$m_f\ddot{u} + c_f\dot{u} + k_f u = F_f(t) \tag{2}$$

where the total mass of fluid in the TLCD is $m_f = \rho_f AL$, where ρ_f is the density of the fluid. The restoring force, or stiffness of the fluid column, is obtained by taking into account the fluid difference between the ends of the TLCD, $k_f = 2\rho_f Ag\mathrm{L}$; $\omega_f = \sqrt{(2\mathrm{g}/\mathrm{L})}$ is the natural frequency of the fluid column, and $F_f(t)$ is the force acting on the TLCD.

Assuming that the TLCD is excited by a force $F_f(t)$, induced by the horizontal acceleration from a harmonic oscillation of the structure, whose displacement is of the form:

$$x(t) = x_0 \sin(\omega_s t), \tag{3}$$

The motion equation (2) results:

$$\ddot{u} + 2\omega_f\zeta_f\dot{u} + \omega_f^2 u = \alpha x_0^2 \sin(\omega_s t), \tag{4}$$

where ω_f, ζ_f and α are, respectively, the vibration frequency, the equivalent damping rate (pressure losses due to pipeline roughness, or localized losses), and the ratio between the horizontal mass ($m_{fh} = \rho_f Ab$) and the total mass of the TLCD ($\alpha = b/L$).

Considering that stationary part of the solution of Eq. (4) is also a harmonic oscillatory movement of the type $u(t) = u_0 \sin(\omega_s t - \theta)$; by some algebraic manipulations it is possible to express the maximum movement of the fluid column (u_0), concerning the amplitude of the structure movement (x_0), given by equation (5), where (ψ) represents the amplification ratio of the displacement of the fluid column in relation to the structure.

$$\psi = \frac{u_0}{x_0} = \frac{\alpha\beta'^2}{\sqrt{[1-\beta'^2\,]^2 + \left[2\zeta_f\beta'\right]^2}} \tag{5}$$

where β' is the ratio between the structure frequency (ω_s) and the TLCD frequency (ω_f).

2.2 Structure-TLCD coupling system with 2 Degrees of Freedom (2DoF)

The equation of motion for the structure-TLCD coupled system excited by an external force applied to the structure is given by several authors (Pedroso [1], Batista and Pedroso [18], Mendes et al. [19]):

$$\begin{bmatrix} m_s + m_f & \alpha m_f \\ \alpha m_f & m_f \end{bmatrix} \begin{bmatrix} \ddot{x} \\ \ddot{u} \end{bmatrix} + \begin{bmatrix} c_s & 0 \\ 0 & c_f \end{bmatrix} \begin{bmatrix} \dot{x} \\ \dot{u} \end{bmatrix} + \begin{bmatrix} k_s & 0 \\ 0 & k_f \end{bmatrix} \begin{bmatrix} x \\ u \end{bmatrix} = \begin{bmatrix} F_s(t) \\ F_f(t) \end{bmatrix} \tag{6}$$

It is verified that the motion equations of structure and TLCD are coupled by the mass. Dividing the first equation by the mass of the structure and the second by the mass of the fluid and considering that only the structure is excited directly by an external force ($F_f(t) = 0$), we have:

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

The most representative dimensionless parameters of the dimensionless coupled system are defined: mass ratio (μ), aspect ratio (α), and tuning ratio (γ); in addition to those already defined: damping rate (ζ) and vibration frequency (ω). All are represented in equation (8).

$$\mu = \frac{m_f}{m_s};\ \alpha = \frac{b}{L};\ \gamma = \frac{\omega_f}{\omega_s};\ c_s = 2m_s\zeta_s\omega_s;\ c_f = 2m_f\omega_f\zeta_f;\ \omega_s^2 = \frac{k_s}{m_s};\ \omega_f^2 = \frac{k_f}{m_f} \tag{8}$$

3 Analysis of Results

3.1 Maximum displacement of the TLCD concerning the maximum displacement of the structure

Figures 3.a and 3.b present the relationships (ψ) between the maximum TLCD displacement (u_0) concerning the maximum structure displacement (x_0) for different values of TLCD equivalent damping ratio (ζ_f), frequency ratio (β') and aspect ratio (α). The displacement of the fluid column is important because it can represent a limiting factor for using the device as an attenuator.

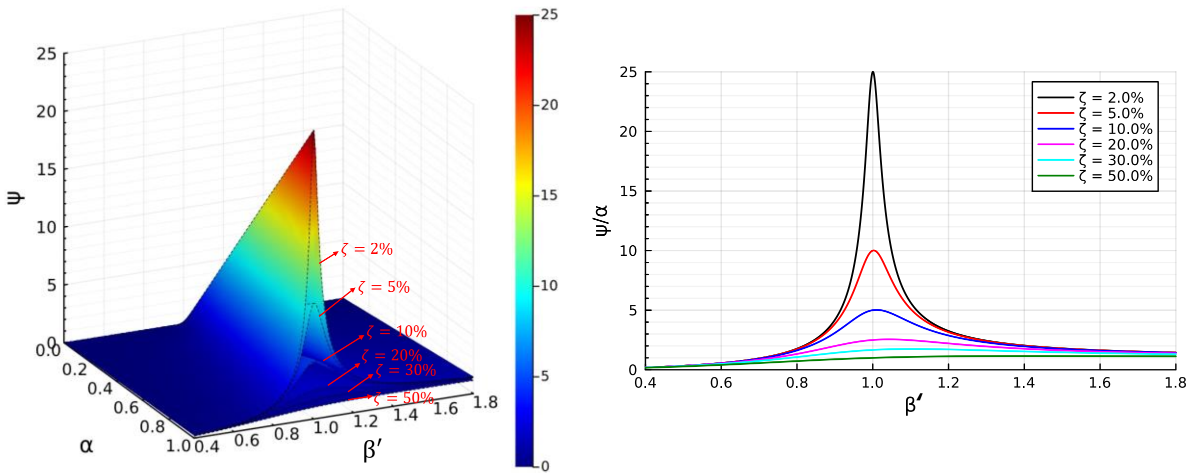


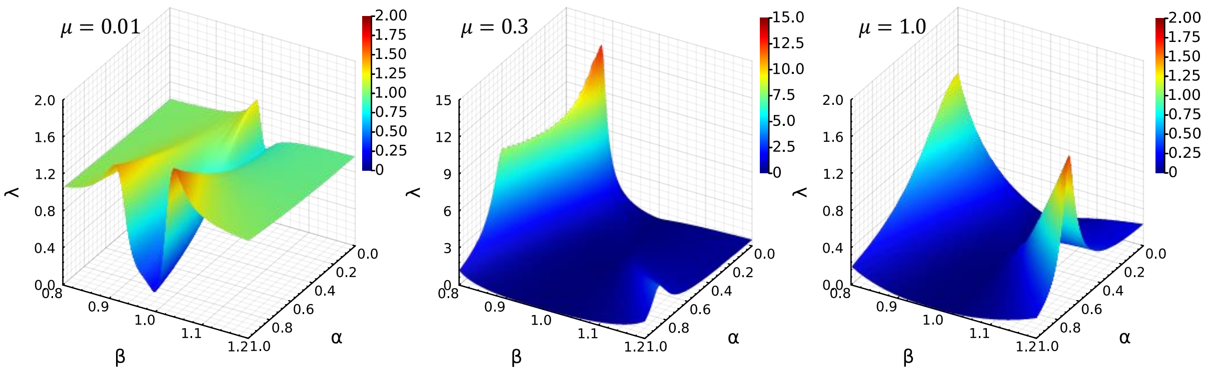
Figure 3. Ratio between the maximum displacement of the TLCD and the maximum structure displacement.

It is verified that the ratio between the displacements varies linearly concerning the α parameter, higher values correspond to greater responses, this is because higher values of α correspond to greater excitation forces for the TLCD since they are proportional to its mass horizontal. Concerning the β' parameter, it can be seen that when β' tends to zero ($\omega_f \gg \omega_s$), ψ also tends to zero, indicating that the TLCD fluid column presents negligible displacement, when β' approaches unity ($\omega_f \cong \omega_s$), ψ presents the highest values mainly for lower damping ratios, and when β' moves away from unity ($\omega_f \ll \omega_s$), ψ tends to a constant value, becoming independent of β' and the TLCD damping rate ζ_f, being variable only concerning the α parameter. Finally, concerning the ζ_f parameter, it appears that lower values of ζ_f correspond to higher values of ψ. Therefore, if it is necessary to tune the TLCD frequency close to the structure frequency ($\beta' \cong 1$), to adjust the amplitude of the TLCD fluid displacement, limiting it to the available design conditions, it is advisable to try to increase the TLCD damping.

3.2 Vibration attenuation

To analyze the effectiveness of the TLCD as a vibration attenuator, the responses generated for the isolated structure and coupled to the TLCD being excited by a harmonic force with a defined amplitude are evaluated. The influence of the TLCD on the original structure is evaluated by the attenuation λ parameter, defined by the ratio between the root mean square value (RMS) of the structure's displacements, in the stationary regime, with and without the TLCD installed: $\lambda = RMS_{(structure+TLCD)}/RMS_{(structure)}$.

Considering damping rates equal to 1% and 3% for the structure (ζ_s) and for the TLCD (ζ_f), respectively, and a frequency ratio (γ) equal to 95%, for mass ratios (μ) equal to at 1%, 30%, and 100%, the response surfaces for $\lambda(\beta, \alpha)$ are shown in Figure 4.

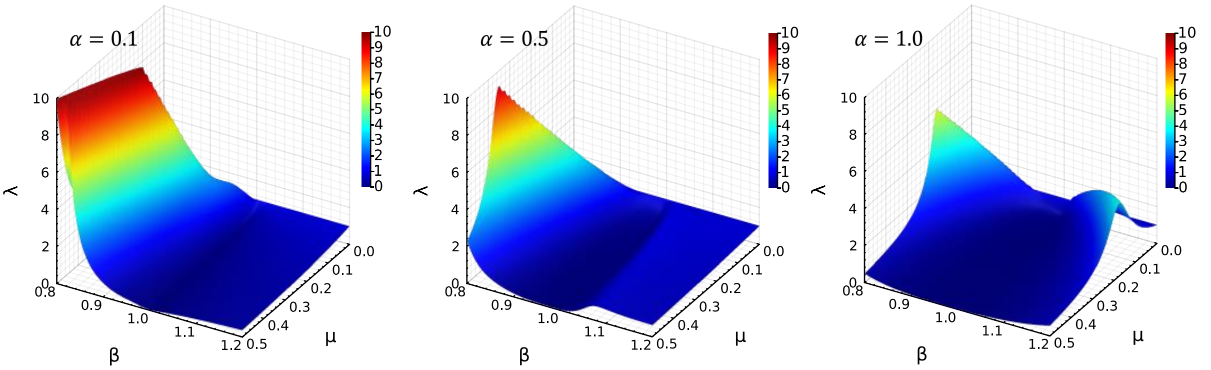


(a) **(b)** **(c)**

Figure 4. $\lambda(\beta, \alpha)$ for different values of μ: (a) μ = 0.01, (b) μ = 0.3 and, (c) μ = 1.0

It is verified that as the mass parameter (μ) increases, the predominant frequency of the coupled system reduces so that the largest response amplitudes occur for values of β increasingly smaller than unity. In other words, in a TLCD design, its frequency should be calibrated below the frequency of the isolated structure (γ <1.0), anticipating a reduction in the resonant frequency of the coupled system. The presence of two resonant frequencies in the coupled system is also verified, the first referring to the structure (β < 1.0) and the second referring to the TLCD (β > 1.0). For small values of α, the difference between frequencies is almost imperceptible because almost the entire mass of the TLCD would be in its vertical section ($b \ll L$), whereas it becomes clearer for larger values of α. It can also be seen that higher values of α present greater attenuation even for small values of the mass α parameter , as long as the excitation frequency (β) is carefully evaluated. Finally, despite higher values of μ can provide greater attenuation, mainly for small values of α, an increase in μ can generate the opposite effect expected, amplifying the responses if the γ parameter is not carefully calibrated.

Considering the same values previously adopted for ζ_s, ζ_f, and γ, for aspect rates (α) equal to 0.1, 0.5, and 1.0, the response surfaces for $\lambda(\beta, \alpha)$ are show in Figure 5.



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

Figure 5. $\lambda(\beta, \alpha)$ for different values of α: (a) α = 0.1, (b) α = 0.5, (c) α = 1.0

It is confirmed that for small values of α and larger values of μ, the TLCD can amplify the response instead of attenuating it, and even though the attenuation is relatively small compared to the adoption of larger values of α. Therefore, it is advisable to adopt higher values of α, which also allows obtaining greater attenuations for a greater range of β, even using a lower mass ratio, as shown in Figure 5.c.

Considering ζ_s = 1%, α = 0.7 and μ = 0.1, the response surfaces for $\lambda(\beta,\gamma)$ are show in Figure 6 for TLCD damping rates (ζ_f) equal to 1%, 10% and 50%. Once again, the importance of calibrating the γ parameter concerning the β parameter is verified, so that the TLCD works as an attenuator. Initially, it appears that for all damping rate values considered, the TLCD reduces vibrations to β = 1.0, however, this reduction may be related to the change in the natural vibration frequency in the coupled system, which indirectly decreases the frequency resonant. For lower damping rates, vibration reduction is guaranteed as long as $\gamma < \beta$. For γ slightly greater than β, vibration amplification may occur; this safety interval is greater for lower damping rates, however, response amplifications are significantly greater outside this interval.

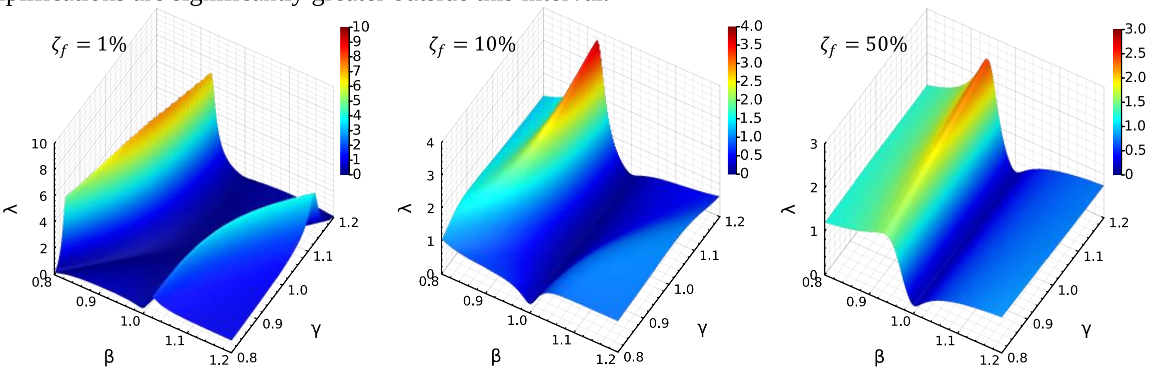


Figure 6. $\lambda(\beta,\gamma)$ for different values of ζ_f: (a) ζ_f = 1%, (b) ζ_f = 10%, (c) ζ_f = 50%

To demonstrate the effectiveness of the results presented, the structure of a wind turbine is considered, whose properties indicated in the work of Batista and Pedroso [18] are natural vibration frequency equal to 0.3342 Hz, and generalized mass equal to 408.71 tons. The structure is excited by a harmonic force with an intensity of 50 kN with a frequency equal to the frequency of the structure. Adopting the values of α = 0.7, μ = 0.1, γ = 0.95, and ζ_f = 3%, for the dimensionless parameters of the TLCD, we have the displacements presented in Figure 7. The RMS of the responses without and with the TLCD are equal to 0.976m and 0.054m, respectively, representing an attenuation ratio λ = 0.0551, that is, a reduction of 94.49% of the displacement RMS.

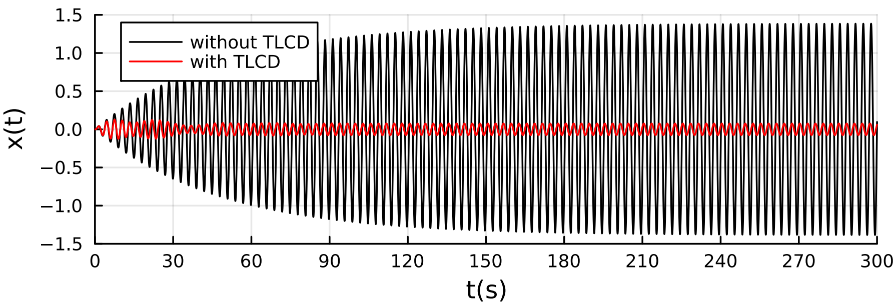


Figure 7. Example of TLCD effects

4 Conclusions

The study of devices for attenuating vibrations in wind turbine structures is of great relevance today, given the global interest in the migration of energy generation to renewable sources, such as wind. The expressions developed that adopted a simplified formulation allow relatively simple preliminary analyses of these structures, providing satisfactory results when it is desired to control the first mode of vibration of the towers, which is the dominant one in real situations.

The graphical interpretation of results allowed a wide variation of wind turbine structure parameters without and with coupled TLCDs, validating the implemented methods and providing relevant information about the damper performance by reducing displacements in the structure. For the simulations, carried out with the application of harmonic excitation forces, it was found that the increase in the TLCDs mass allows a better reduction of the structure's displacements during resonant excitation. Despite this, as it increases the system's total weight, adding more mass must be done with caution.

The effect of the TLCD diaphragm opening ratio (increase in localized pressure loss reflected by high damping values (ζ_f) in the fluid column) was also verified, indicating that slightly lower values for this parameter can promote better performance within the tracks analyzed in this work. However, its reduction must be evaluated carefully, as high damping values (ζ_f) (high losses due to small holes) excessively restrict the fluid oscillation, compromising the device's functioning.

Finally, in addition to verifying the usefulness of response maps for the dynamic analysis of wind turbine structures with TLCDs, the efficiency of these devices in attenuating displacements (vibrations) in these structures was once again demonstrated.

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