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ON A LIQUID TUNED DAMPER AND NONLINEAR MASS TUNED DAMPER PASSIVE APPLICATION IN A BUILDING TO REDUCE HIGH VIBRATIONS

Wagner Barth Lenz
UTFPR – Federal University of Technology – Paraná, Monteiro Lobato Avenue, 84016-210, Ponta Grossa – SP, Brazil
wagner_barth@hotmail.com

Ângelo Marcelo Tusset
UTFPR – Federal University of Technology – Paraná, Monteiro Lobato Avenue, 84016-210, Ponta Grossa – SP, Brazil
tusset@utfpr.edu.br

Rodrigo Tumolin Rocha
UTFPR – Federal University of Technology – Paraná, Monteiro Lobato Avenue, 84016-210, Ponta Grossa – SP, Brazil
digao.rocha@gmail.com

Frederic Conrad Janzen
UTFPR – Federal University of Technology – Paraná, Monteiro Lobato Avenue, 84016-210, Ponta Grossa – SP, Brazil
fcjanzen@utfpr.edu.br

José Manoel Balthazar
ITA - Aeronautics Technological Institute, Marechal Eduardo Gomes Square, 12228-900, São José dos Campos – SP, Brazil
jmbaltha@gmail.com

Abstract. *Building and constructions sites all over the world have been subject to vibration. These vibrations are induced most commonly by wind and ground excitation, for example, trains, roads and earthquakes are the main cause of the ground vibration. The combination of them can cause fatigue in the material of a structure. To reduce the oscillation on buildings, passive and active control methods are used to prevent fail and excessive displacements. In this paper, the analyses are focused on a building with five floors with the alternative of a passive strategy, such as NTMD (nonlinear tuned mass damper) and TLD (tuned liquid damper). Both methods have nonlinear behaviours and reduce the vibration energy in the building changing the building dynamics. In addition, the energy pumping effect was analyzed to investigate the amount of energy stored and dissipated between the elements.*

Keywords: *nonlinear tuned mass damper, tuned liquid damper, energy pumping, passive control strategy*

1. INTRODUCTION

Recently, one of the most explored passive controller is the nonlinear energy-sink (NES) (Vakakis, *et al.*, 2008; Gendelman, *et al.*, 2001), which is basically a nonlinear tuned mass damper (NTMD). Due to undesired vibrations in some kind of structures, strategies of different dampers were studied. Such studies showed that this kind of device may be used as an energy pumping or dissipative device as its configurations is a spring-mass-damper system. When a structure is subjected to an environment excitation, for example, seismic oscillations or wind which may damage a building, the NMTD is coupled to reduce high amplitudes of vibration of such building, reducing damage risk (Abe, 1996).

In addition, the study of energy harvesting from ambient vibration has increased substantially in the past few decades. The most promising and studied is the energy harvesting from kinect energy provided by external excitation in structures, however, many structures to be explored by a transducer has low amplitude of vibration. With the NMTD, it is possible to pump energy into the system, improving the energy harvesting (Rocha, *et al.*, 2016).

The NES device is not only considered as a linear device, it may be considered as a nonlinear device as in the works of (Rocha, *et al.*, 2016; Alexander and Schilder, 2009; Rüdinger, 2007). These kinds of device have demonstrated a very good performance from energy pumping and dissipation of energy into a system due to its spring-mass-damper configuration.

Other passive control strategy is the tuned liquid damper (TLD) device, which is a water reservoir that uses the dynamic effect of sloshing energy of the water to suppress the dynamic response of the system when it is subjected to an excitation (Fujino, *et al.,* 1992; Mondal, *et al.,* 2014). The TLD systems can be very effective when coupled to structures excited by wind or seismic oscillations, as NES, and are highly effective in suppress high amplitudes of vibration of such structures, which may be damaged (Banerji, *et al.*, 2000; Sun, *et al.,* 1992; Fujino, *et al.*, 1993; Das and Choudhury, 2017). This kind of damper is extremely easy to its application and works on the principle of energy dissipation through liquid sloshing and wave breaking on a free surface.

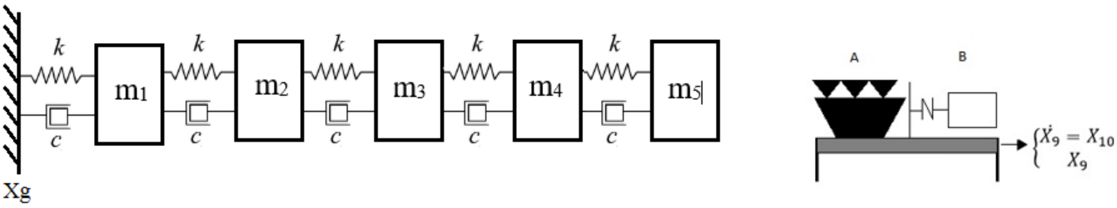
Therefore, this work aims to control the vibration of a five floors building using the NTMD and TLD strategies, without any use of active control. As both techniques aim to reduce oscillations due to resonance, they can be tuned to change natural frequencies of the building, i.e., makes possible more flexibility and capacity to control any type of vibration.

2. PHYSICAL AND MATHEMATICAL MODEL

The complete model of this work consists in a five floors building with a TLD and NTMD coupled on the last floor. The five floors building, illustrated in Fig. 1a, is based on the work of (Yu, *et al.*, 1999), which consists in a five-degrees-of-freedom mass-spring-damp system. Each floor is represented by a mass m_i, where i is the number of the floor. The division between the floors are represented by a stiffness k and a structural damping c, except the first floor due to the attachment with the ground.

At the bottom of the building is considered a base displacement x_g, which represents a seismic motion of harmonic kind, applied in the system in the interval of time $5 \leq t \leq 10$ [s].

The suppression devices, i.e., the nonlinear tuned mass damper and the tuned liquid damper are coupled at the top of the build, as depicted in Fig. 1b where A represents the TLD and B represents the NTMD. The TLD has two stages of dissipation that are strong and weak wave. The design includes the direction of excitation and shape to improve the application of the device (Banerji, *et al.*, 2000). The NTMD is set with the same natural frequency of the last floors of the building, consequently, it will begin to oscillate in the opposite phase decreasing the original vibration of the structure, which may be very high.



(a) (b)

Figure 1. (a) Physical model of the five floors building; (b) "A" is the tuned liquid damper (TLD) and "B" is the nonlinear tuned mass damper (NTMD)

Next, the mathematical modelling of the five floors building with base excitation and passive control strategy coupling is developed.

2.1 Mathematical modelling

The spring force for each floor is given by Eq. (1).

$$F_{si} = k_i \Delta x = k_i \left(x_{i-1} - x_i \right) \tag{1}$$

The damping force for each floor is given by Eq. (2).

$$F_{di} = c_i \Delta \dot{x} = k_i \left(\dot{x}_{i-1} - \dot{x}_i \right) \tag{2}$$

The base-excitation of the system is given by a harmonic motion of the ground, where displacement and speed are denoted, respectively, by Eq. (3).

$$x_g = A\sin(2\pi ft)$$
$$\dot{x}_g = A2\pi f\cos(2\pi ft) \tag{3}$$

The ground is excited in the interval of time 5 ≤ t ≤ 10 [s]. If there is no excitation, then

$$x_g = \dot{x}_g = 0 \tag{4}$$

Considering the Newton's law as the modelling method to this system and considering Eqs. (1), (2) and (3). The equations of motion of the system are given by Eq. (5)

$$\begin{aligned} m_1\ddot{x}_1 &= -F_{s1} - F_{d1} + F_{s2} + F_{d2} \\ m_2\ddot{x}_2 &= -F_{s2} - F_{d2} + F_{s3} + F_{d3} \\ m_3\ddot{x}_3 &= -F_{s3} - F_{d3} + F_{s4} + F_{d4} \\ m_4\ddot{x}_4 &= -F_{s4} - F_{d4} + F_{s5} + F_{d5} \\ m_5\ddot{x}_5 &= -F_{s5} - F_{d5} + F_{TLD} + F_{NTMD} \end{aligned} \tag{5}$$

where F_{TLD} is the force of the TLD and F_{NTMD} is the force of the NTMD, when coupled to the structure. It is highlighted that they are not coupled at the same time.

The force of the TLD is given by the stiffness and damping, denoted by Eq. (6).

$$F_{TLD} = K_{TLD}\Delta x + C_{TLD}\Delta\dot{x} \tag{6}$$

where K_{TLD} is the stiffness of the TLD, C_{TLD} is the damping coefficient of the TLD.

The stiffness directly depends on the mass of the fluid in the reservoir and the natural frequency of the fluid, whose fluid is water. Then, the stiffness is given by Eq. (7).

$$K_{LTD} = k_w m_w (2\pi f_w)^2 \tag{7}$$

where m_w is the mass of water, f_w is the natural frequency of the water.

Depending on the amplitude of water vibration in the reservoir of the TLD, the stiffness (elastic response of the water) of water k_w will depend on the condition of amplitude given by Eq. (8).

$$k_w = \begin{cases} 1.075\Lambda^{0.007} & if \quad \Lambda \le 0.03 \\ 2.52\Lambda^{0.25} & if \quad \Lambda > 0.03 \end{cases} \tag{8}$$

where the amplitude in wave form of water vibration is given by Eq. (9).

$$\Lambda = \frac{Amplitude\ of\ \ vibration}{h_0} \tag{9}$$

The natural frequency of the water depends on the quadratic filled area in a rectangular reservoir, as illustrated in Fig. 2, and the equations that represents the natural frequency can be represented by Eq. (10).

$$f_w = \frac{1}{2\pi}\sqrt{\frac{\pi g}{L}\tanh\left(\frac{\pi h_0}{L}\right)} \tag{10}$$

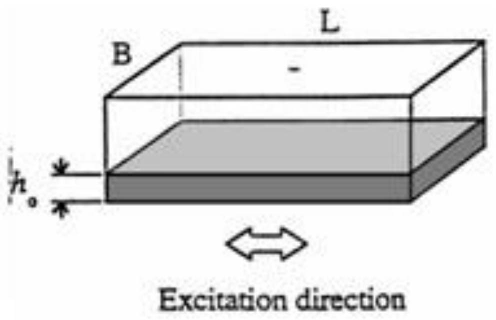


Figure 2. TLD reservoir representation

The damping of the water, i.e., damping generate by water, is given by Eq. (11).

$$C_{TLD} = \frac{\Lambda^{0.35}}{2} m_w \sqrt{\frac{K_{TLD}}{m_w}} \tag{11}$$

whose damping depends on the amplitude of vibration in wave form Λ, mass of water m_w and the stiffness K_{TLD}.

The force of the NTMD device is given by a nonlinear spring-mass system, whose nonlinearity is provided by a cubic spring, as denoted by Eq. (12).

$$F = k_{nl} x^3 \tag{12}$$

Therefore, the equations of motion of the system are considered in state-space notation, given by Eq. (13).

$$\begin{aligned}
\dot{x}_1 &= \dot{x}_2 \\
\dot{x}_2 &= \frac{1}{m_1}\left(-F_{s1} - F_{d1} + F_{s2} + F_{d2}\right) \\
\dot{x}_3 &= \dot{x}_4 \\
\dot{x}_4 &= \frac{1}{m_2}\left(-F_{s2} - F_{d2} + F_{s3} + F_{d3}\right) \\
\dot{x}_5 &= \dot{x}_6 \\
\dot{x}_6 &= \frac{1}{m_3}\left(-F_{s3} - F_{d3} + F_{s4} + F_{d4}\right) \\
\dot{x}_7 &= \dot{x}_8 \\
\dot{x}_8 &= \frac{1}{m_4}\left(-F_{s4} - F_{d4} + F_{s5} + F_{d5}\right) \\
\dot{x}_9 &= \dot{x}_{10} \\
\dot{x}_{10} &= \frac{1}{m_5}\left(-F_{s5} - F_{d5} + F_{LTD} + F_{NMTD}\right)
\end{aligned} \tag{13}$$

Therefore, the next section will show some numerical analysis of the system.

3. NUMERICAL SIMULATIONS AND DISCUSSIONS

The numerical simulations were carried out using the 4th order Runge-Kutta method. The parameters are described in Tab. 1.

Table 1. Parameters of the five floors building system

Parameter	Value	Means
$m_{1,5}$	98.3kg	Mass of each floor
$k_{2,5}$	6.84×10^5N/m	Stiffness of second to five floor
k_1	5.16×10^5N/m	Stiffness of first floor
$c_{2,5}$	50N/ms	Damping of second to five floor
c_1	125N/ms	Damping of first floor
L	0.0605m	Length of water reservoir
h_0	0.05m	Depth of water reservoir
ρ_w	1000kg/m^3	Water density
V	1.83018×10^{-4}m^3	Volume of water reservoir

The relation to define the mass of water is given by Eq. (14), which depends on the volume of the reservoir, density of water and *N*, which is the percentage of water related to the volume of the reservoir.

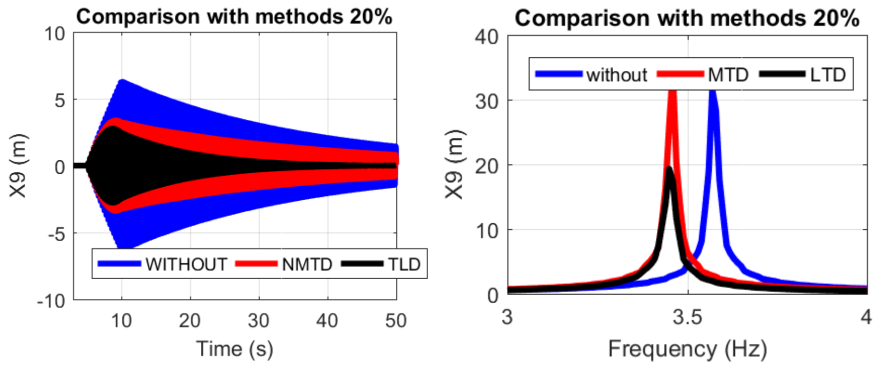
$$m_w = \frac{NV}{\rho_w} \tag{14}$$

The numerical results are shown in three stages, which are the building without the passive controllers, and then adding these controllers related to the last floor motion.

Figures 3a and 3c shows the time histories of displacement and velocity, respectively, of the last floor. The displacement and velocity without any passive controller, when the system is excited at the base, are very higher, (> 6m of amplitude and almost 150m/s of velocity). The values of displacement and velocity show that the movement of the five floor at their highest peaks, it may be a problem for a building due to structural damage. Afterwards, the NTMD is coupled in the last floor with a mass of 20% of the reservoir. With this passive method, the high peaks of amplitude and velocity were suppressed. In addition, when the TLD is considered with 20% of the reservoir mass, the amplitude and velocity are suppressed almost instantaneously. Such amplitudes of motion possibilities safe vibration of the structure when subjected to seismic harmonic base excitation.

Figures 3b and 3d reflects the use of passive controllers at the natural frequency of the building. The natural frequencies of the last floor changes and led the system out of resonance, decreasing the amplitude of vibration of the last floor of the building.

Here, the TLD showed to be more effective to suppress the effect of resonance than the NTMD, however, both of them were able to damp the system.



(a) (b)

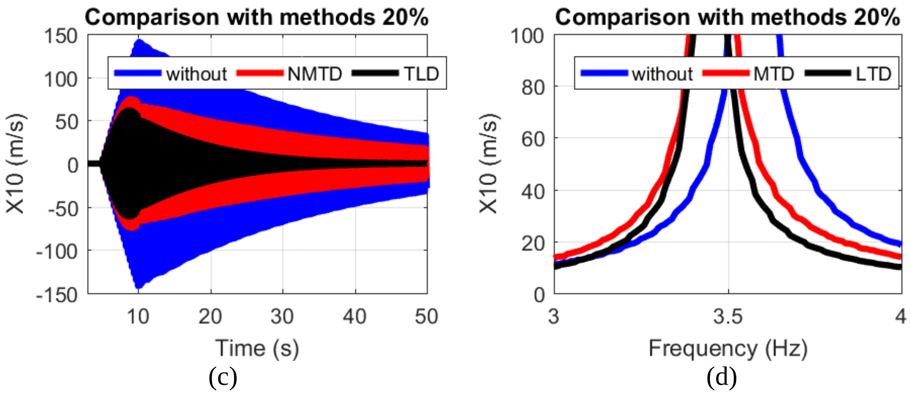


Figure 3. Time history of (a) displacement and (c) velocity of the last floor without control (in blue), with NTMD control (in red) and with TLD (in black); Frequency analysis related to (b) displacement and (d) velocity of the last floor without control (in blue), with NTMD control (in red) and with TLD (in black)

A deep study of the TLD device is considered and showed in Figs 4. Three different quantities of water were considered in order to compare with the last floor motion without control, which are the time histories of Fig. 4a, displacement and Fig. 4c, velocity of the last floor, and frequency analysis related to Fig. 4b, displacement and Fig. 4d, velocity the last floor without control (in blue), with 20% of TLD (in red), 40% of TLD (in black) and 60% of TLD (in magenta. With the increase of water percentage, the natural frequency of the structure changed and the high amplitudes of vibration were suppressed.

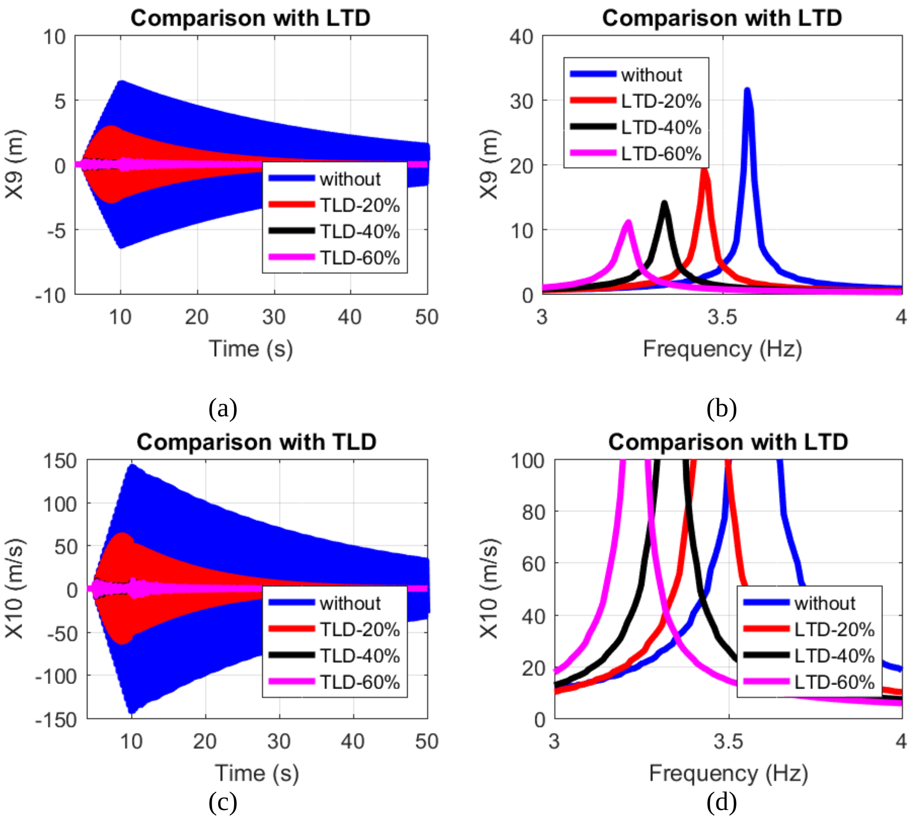


Figure 4. Time history of (a) displacement and (c) velocity of the last floor without control (in blue), with 20% of TLD (in red), 40% of TLD (in black) and 60% of TLD (in magenta); Frequency analysis related to (b) displacement and (d) velocity the last floor without control (in blue), with 20% of TLD (in red), 40% of TLD (in black) and 60% of TLD (in magenta

4. CONCLUSIONS

This work presented a dynamical study of a five floors building considering a passive control strategy to suppress high amplitudes of vibration due to seismic base excitation. The passive control strategies considered to suppression were the Tuned Liquid Damper (TLD) and the Nonlinear Tuned Mass Damper (NTMD).

As shown in Fig. 3b and 3d the displacement of the TLD compared with the NTMD has a higher damping capability, and in Fig. 3a and 3c it has a lower speed than the nonlinear damping. In this case, improving the comfort and safety because of the lower speeds.

In Fig. 4a and 4c, 40% and 60% overlap each other, it is suggested that 40% has the same of dissipation energy for impact of 60% and Figs. 4b and 4d shows that they have different damping capability and different frequencies for continuous application such as wind and road excitation.

Both controllers were effective in control the high amplitudes of displacement of the last floor due to the seismic base excitation. In these results, the TLD was the most effective way to reduce fastly the high vibrations, neutralizing any possibility of damage/fracture.

5. ACKNOWLEDGEMENTS

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