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A Bidirectional Tuned Liquid Column Damper for Reducing the Seismic Response of Buildings

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Abstract

In this article a new bidirectional tuned liquid column damper (BTLCD) is proposed for controlling the seismic response of structures. The device acts as two independent and orthogonal tuned liquid column dampers (TLCDs), but due to its configuration it requires less liquid than two equivalent independent TLCDs. The equations of motion of the system formed by the BTLCD and the primary structure to be controlled, are obtained by means of Lagrangian dynamics explicity considering the non symetrical action of the damping forces. First, the primary structure was assumed to have two degrees of freedom (DOFs). Assuming that the system is excited by a base acceleration that can be considered to be a white noise random process, the optimum design parameters of the device were obtained to minimize the response of the primary structure. The optimum design parameters are presented as expressions covering a wide range of possible configurations for the device in a controlled structure. The use of a BTLCD to control the seismic response of several DOF structures was also studied, showing that if the structural response occurs mainly in two perpendicular modes, then the optimum design parameters for two DOF structures can be used. Finally, experimental analysis of the BTLCD for controlling the seismic response of 3-story structure scale model are developed in order to verify the effectiveness and accuracy of the equations and design procedures proposed herein.

Keywords: Bidirectional, Tuned liquid column damper, vibration control, optimal control, passive dampers, vibrations

1. Introduction

More than 50% of the world's population lives in cities. The continuous growth of urban areas, together with the development of modern construction techniques, have resulted in an increasing number of tall buildings. These types of structures are characterised by its flexibility, with long vibration periods and low intrinsic damping. Consequently, when subjected to dynamic loads such as earthquakes, tall buildings develop oscillations that may persist long after the events themselves have ceased. The vibration levels of such structures may exceed the serviceability criteria, causing discomfort to occupants. In some cases the vibration may even be greater than agreed safe levels, causing possible damage to nonstructural or structural components. Several devices have been proposed to reduce the structural response of tall buildings. Among these, passive energy dissipation devices have been widely accepted and used in several structures [1]. These type of devices absorbs part of the energy supplied to the structure by external actions, such as winds or earthquakes, thereby reducing its response. Although there are many kinds of passive dampers, tuned liquid dampers (TLD) stand out due to its advantages, such as their low cost of manufacture and maintenance. There is also practically no weight penalty to the building if the water is used for other purposes such as to prevent the spread of fire, or for drinking.

One key type of TLD is the tuned liquid column damper (TLCD). First proposed by Sakai et al. [2], in essence this device consists of a U-shaped liquid tank. When the device is subject to an external perturbation causing a displacement of the free Surface of the liquid, gravity acts as a restoring force, allowing it to oscillate. A restriction is positioned in the centre of the horizontal section of the device, which together with the friction, and the sudden change in flow direction between the horizontal and vertical sections, produces an energy dissipation mechanism that dampens the oscillation of the liquid. Several investigations have been carried out to the determine the optimum design parameters of TLCDs. Gao et al. [3] studied TLCD optimisation for sinusoidal type excitations by numerical means. Kareem and Yalla [21] determined the optimum design parameters for one-DOF primary structures subjected to random-type actions. More recently Shum et al. [4] proposed optimal tuning parameters for base-excited damped structures. Considering the nonclassical nature of the damping forces, Wu and Hsieh studied the dynamic characteristics of the TLCD, and showed the existence of two coupled natural frequencies between the primary structure and the device [5]. Wu et al. proposed a design guide for TLCDs and primary structures subject to random wind loading [6]. Ghosh and Basu [7, 8] studied an alternative TLCD configuration to control short period and nonlinear structures, connecting the device via a spring to the primary structure to be controlled. Another option for controlling short-period oscillations is the use of pressurized air columns as shown by Shum et al. [9]. The use of multiple TLCDs for seismic applications has also been studied, showing that the use of such configurations does not necessarily imply an improvement in structural control compared with a single TLCD. However, their use increases robustness with respect to errors in estimating the dynamic parameters of the controlled structure [10, 11]. Multiple TLCDs have also been studied for the reduction of coupled lateral and torsional vibrations in long span bridges [12, 9].

Although the use of TLCDs can be an efficient way of reducing the response of buildings, one major disadvantage is their inability to act in two perpendicular directions. This can be very useful for controlling the structural response of buildings for two perpendicular modes with high participation factors, as in the case of several tall buildings. The vibrational control of such structures using TLCDs has been the subject of research by various investigators. One of the first attempts to use a bidirectional TLCD was made by P.A. Hitchcock in 1997. The device can be regarded as several TLCDs that share a common horizontal mass of water [13]. In 2010, Lee et al. Proposed the use of a bidirectional tuned and sloshing damper, which acts as a TLCD in one direction and as a sloshing damper in the perpendicular direction [14].

In this paper a new bidirectional tuned liquid column damper is proposed. The device acts like a TLCD in two orthogonal directions; thanks to its configuration, the mass of liquid required is reduced compared with two independent TLCDs. The first objective of this study was to derive the equations of motion of the system formed by the BTLCD and the primary structure to be controlled, when both are subject to a base acceleration. The formulation of the equations of motion, by means of Lagrangian dynamics, explicitly considers the non-classical damping inherent in the system. The optimal parameters are derived assuming that the base acceleration can be expressed as a white noise random process. Although several previous investigations have dealt with the determination of the optimal parameters, in this study the non symmetrical action of the damping forces, as shown by Wu and Hsieh [5], are explicity considered in the derivation of the optimal tuning parameters of the BTLCD. Based on this characterisation, the optimum parameters minimising the mean square displacement of the controlled structure are found for both directions. The optimal design parameters of the device are presented as functions of the mass ratio, μ, the shape factor of the device, ζ, the ratio of the cross-sections of the vertical and horizontal parts of the device, υ, and the critical damping ratio for the primary structure, ξ_p. Finally, an optimal design procedure for BTLCD in several degrees of freedom structures is proposed.

2. BTLCD description

The device proposed is shown in Fig.1, and can be regarded as four single TLCDs combined in one unit. The configuration of the BTLCD, which in plan view has the shape of an annular rectangle, can be adjusted to two different frequencies of oscillation by modifying the total length of the liquid conduits. A restriction or orifice located in the mid-point of the horizontal tanks is used to control the damping of the oscillation of the liquid inside the device. For the purpose of describing the motion of the liquid mass inside the BTLCD, two degrees of freedom are selected: displacement of the liquid in the containers parallel to the X direction, u_{dx}, and displacement of the liquid in the containers parallel to the Y direction, u_{dy}.

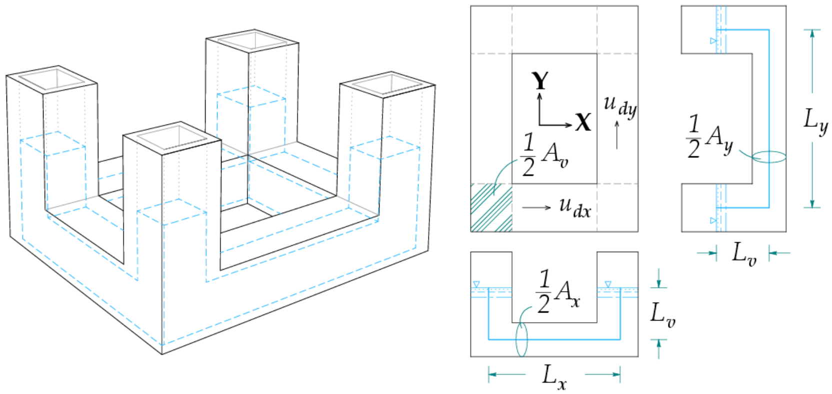

Fig. 1 – Schematic view of the BTLCD and its main geometrical properties.

The proposed BTLCD also requires less liquid compared with other configurations. In using two single and perpendicular TLCDs, it can be seen that when the oscillation is in one of the principal directions, the liquid in the TLCD oriented perpendicular to this direction performs no useful function, and it becomes a penalty mass. In the BTLCD, it is only the liquid inside the horizontal conduits between the vertical columns that has no use under this condition. The use of TLCDs in a crossed configuration also requires a greater amount of liquid than the proposed BTLCD. This is due to the fact that the BTLCD, understood as four single TLCDs, shares the vertical columns, there being no requirement for individual vertical columns for each of the four TLCDs.

3. BTLCD and the controlled structure equations of motion

The system under investigation is shown in Fig.2 and can be separated into two substructures. One of them is the BTLCD and the other is the two-DOF primary structure. As indicated in Section 2, the motion of the liquid inside the BTLCD is defined by u_{dx} and u_{dy}, which measure the displacement of the liquid relative to the mass of the primary structure in the X and Y directions, respectively. The motion of the primary structure is described using the degrees of freedom x and y, which measure the relative motion between its mass and the ground in the X and Y directions, respectively. If the entire system is now subject to a base acceleration defined by $\ddot{u}_{sx}$ and $\ddot{u}_{sy}$, then the equations of motion of the system can be derived using the Lagrange equations, [15].

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_i}\right) - \frac{\partial T}{\partial q_i} + \frac{\partial V}{\partial q_i} = Q_i \qquad i = 1 \dots n \tag{1}$$

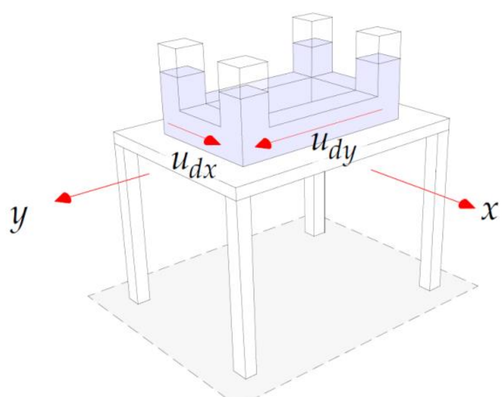

Fig. 2 – A two degrees of freedom primary structure with a bidirectional tuned liquid column damper.

where T and V correspond to the total kinetic energy and the total potential energy of the system, q_i is the i-th generalised coordinate, $Q_i$is the generalised non conservative force associated with q_i, n is the total number of degrees of freedom of the system, four in this case, and t is the time.

Assuming that the fluid is incompressible and the transverse velocity profile of the liquid is constant, implying that the fluid flux is turbulent, the kinetic energy and the potential energy for the entire system can be readily obtained. The equations of motion of the system can now be obtained by substituting the corresponding terms into the Lagrangian equations. By doing so we obtain:

$$\left.\begin{array}{r} M_T\ddot{x} + C_x\dot{x} + K_x x = -M_T\ddot{u}_{sx} + c_{dx}\dot{u}_{dx} - m_{hx}\ddot{u}_{dx} \\ M_T\ddot{y} + C_y\dot{y} + K_y y = -M_T\ddot{u}_{sy} + c_{dy}\dot{u}_{dy} - m_{hy}\ddot{u}_{dy} \\ m_{ex}\ddot{u}_{dx} + \upsilon_x c_{dx}\dot{u}_{dx} + k_{dx}u_{dx} = -m_{hx}\upsilon_x(\ddot{u}_{sx} + \ddot{x}) \\ m_{ey}\ddot{u}_{dy} + \upsilon_y c_{dy}\dot{u}_{dy} + k_{dy}u_{dy} = -m_{hy}\upsilon_y(\ddot{u}_{sy} + \ddot{y}) \end{array}\right\} \tag{2}$$

where the coefficients c_{dx} and c_{dy} are the linear equivalent damping forces of the device [6], $M_T = m_p + m_f + m_u$ is the total mass of the system; $m_{hx} = A_x L_x \rho_f$ and $m_{hy} = A_y L_y \rho_f$ are the liquid mass inside the horizontal conduits parallel to the X and Y directions, respectively; $\upsilon_x = A_v/A_x$ and $\upsilon_y = A_v/A_y$ are the quotients between the areas of the vertical columns and the the horizontal conduits in the X and Y directions, respectively; m_{ex} and m_{ey} are the effective liquid masses in the X and Y directions, and are defined by: $m_{ex} = A_x L_{ex}\rho_f$ and $m_{ey} = A_y L_{ey}\rho_f$ where $L_{ex} = \upsilon_x L_x + 2L_v$ and $L_{ey} = \upsilon_y L_y + 2L_v$ are the effective lengths in the X and Y directions; and finally $k_{dx} = 2A_x\rho_f g$ and $k_{dy} = 2A_y\rho_f g$ are the equivalent stiffnesses of the device.

In order to obtain more general results from the equations of motion, the system of Eqs. (2) can be rewritten using nondimensional parameters, resulting in the following system of equations:

$$\left.\begin{array}{r} \alpha_x\ddot{x} + 2\alpha_x\omega_{px}\xi_{px}\dot{x} + \alpha_x\omega_{px}^2 x = -\alpha_z\ddot{u}_{sx} + 2\omega_{dx}\xi_{dx}\mu_x\dot{u}_{dx} - \alpha_x^2\ddot{u}_{dx} \\ \alpha_y\ddot{y} + 2\alpha_y\omega_{py}\xi_{py}\dot{y} + \alpha_y\omega_{py}^2 y = -\alpha_y\ddot{u}_{sy} + 2\omega_{dy}\xi_{dy}\mu_y\dot{u}_{dy} - \alpha_y^2\ddot{u}_{dy} \\ \ddot{u}_{dx} + 2\upsilon_x\omega_{dx}\xi_{dx}\dot{u}_{dx} + \omega_{dx}^2 u_{dx} = -\alpha_x\upsilon_x(\ddot{u}_{sx} + \ddot{x}) \\ \ddot{u}_{dy} + 2\upsilon_y\omega_{dy}\xi_{dy}\dot{u}_{dy} + \omega_{dy}^2 u_{dy} = -\alpha_y\upsilon_y(\ddot{u}_{sy} + \ddot{y}) \end{array}\right\} \tag{3}$$

In the system of Eqs. (3), the parameters $\omega_{dx} = \sqrt{2g/L_{ex}}$ and $\omega_{dy} = \sqrt{2g/L_{ey}}$ are the natural frequencies of oscillation of the device; $\omega_{px} = \sqrt{K_x/M_T}$ and $\omega_{py} = \sqrt{K_y/M_T}$ are the frequencies of oscillation of a structure with the same stiffness as the primary structure, but with a mass equal to the total mass of the system; $\xi_{dx} = c_{dx}/2m_{ex}\omega_{dx}$ and $\xi_{dy} = c_{dy}/2m_{ey}\omega_{dy}$ are the critical damping ratios of the device; $\xi_{px} = C_x/2M_T\omega_{px}$ and $\xi_{py} = C_y/2M_T\omega_{py}$ are the critical damping ratios of the structure with the same stiffness as the primary structure, but with a mass equal to the total mass of the system. The parameters $\alpha_x = L_x/L_{ex}$ and $\alpha_y = L_y/L_{ey}$ can be related to the terms: $\zeta_x = L_x/(L_x + 2L_v)$ and $\zeta_y = L_y/(L_y + 2L_y)$ which essentially define the shape factors of the device. It is clear that when $\upsilon_x = \upsilon_y = 1$,then $\alpha_x = \zeta_x$ and $\alpha_y = \zeta_y$.

3.1 Equivalent damping for random base acceleration

The nonlinear equations of motion derived in the previous section can be replaced by equivalent linear ones with known solutions. The difference, or error, between the linear equivalent representation and the actual nonlinear one can be written as: $\varepsilon = c_d\dot{u}_d - C_{NL}(u_d,\dot{u}_d)\dot{u}_d$ (directional subscripts will be omitted for clarity), where $C_{NL}(u_d,\dot{u}_d)$ represent in general terms the nonlinear damping force. In this case, the expression of $C_{NL}(u_d,\dot{u}_d)$ is a function of the flow resistance. Assuming the flow is turbulent [16], and minimising the mean square value of the error, $E\{\varepsilon^2\}$, it can be shown that: [17, 18]

$$c_d = \sqrt{\frac{2}{\pi}}\rho_f A\upsilon^2\eta\sigma_{\dot{u}_d} \tag{4}$$

Where is assumed that the probability density function of the nonlinear damping force is Gaussian [17, 6, 18]. The Eq. (4) can be rewritten as:

$$\eta = \sqrt{2\pi}\frac{m_e\omega_d\xi_d}{A\upsilon^2\rho_f\sigma_{\dot{u}_d}} \tag{5}$$

From the Eq. (5), the flow resistance coefficient can be obtained as a function of the frequency of oscillation, ω_d, and the critical damping ratio of the device, ξ_d.

4. BTLCD Optimum design parameters for random white noise base acceleration

4.1 Undamped primary structure

Assuming that the base acceleration is represented by a Gaussian white noise process with constant power spectral density $\ddot{u}_{so}$, response of the primary structure can be expressed as [19]: $E\{x^2\} = \ddot{u}_{so}\int_{-\infty}^{\infty}|H_x(\omega)|^2 d\omega$, where $H_x(\omega)$ is the transfer function between the base acceleration and the displacement of the primary structure in the X direction, using integral tables [19] the the mean square displacement can be written as

$$E\{x^2\} = \frac{\pi\ddot{u}_{so}}{\omega_p^3}\cdot\frac{\left(\frac{B_0^2}{A_0}\right)(A_2A_3 - A_1A_4) - A_3(B_1^2 + 2B_0B_2) + A_1B_2^2}{A_1(A_2A_3 - A_1A_4) - A_0A_3^2} \tag{6}$$

The terms A and B are detailed:

$$\begin{array}{llll} A_0 = f^2 & A_2 = -\left(1 + f^2 + 4\xi_p\xi_d f\right) & A_4 = 1 - \mu\alpha\upsilon & B_1 = -2f\xi_d\upsilon(1+\mu) \\ A_1 = 2f\left(f\xi_p + \upsilon\xi_d\right) & A_3 = -2\left(\xi_p + \xi_d f\upsilon(1+\mu)\right) & B_0 = -f^2 & B_2 = 1 - \mu\alpha\upsilon \end{array} \tag{7}$$

where $f = \omega_d/\omega_p$ is the frequency ratio. Returning to Eq. (6), the mean square of the displacement of the primary structure can be obtained as a function of μ, ξ_p, α, υ, ξ_d and$f$. The value of ξ_p is mainly given by the problem itself, and can be related to μ and α. The parameters μ, α and υ can be determined by the designer at an early stage. It can also be shown that the optimal value of υ is 1 [6], and as the value of ζ ($\zeta = \alpha$ when $\upsilon = 1$) approaches to 1, the reduction in the response of the primary structure increases [6, 20]. This implies that a device with equal cross-sections ($A_v = A_x = A_y$) and with the largest possible horizontal dimensión is always preferable. Of course, it is not always possible to obtain these conditions, but they nevertheless represent a desirable design. For instance, architectonic restrictions may not allow large plan dimensions of the device, forcing the reduction of the shape factor ζ. The values of f and ξ_d that minimize $E\{x^2\}$, given by the Eq. (6) can be expressed as indicated in Eq. (8) and Eq. (9):

$$f|_{OPT} = \sqrt{\frac{2\mu\alpha\upsilon\left[\mu\left(1 - \alpha\upsilon(2+\mu)\right) + 1 - \frac{3}{2}\alpha\upsilon\right] + 2\alpha\upsilon - \mu}{(1+\mu)\left[2\mu\alpha\upsilon\left(\mu + \frac{3}{2}\right) + 2\alpha\upsilon - \mu\right]}} \tag{8}$$

$$\xi_d|_{OPT} = \frac{\alpha}{2}\sqrt{\frac{\mu\left[4\mu^2\alpha\upsilon(\alpha\upsilon(\mu+2) - 1) + 6\mu\alpha\upsilon\left(\frac{5}{6}\alpha\upsilon - 1\right) + \mu - 4\alpha\upsilon\right]}{\left[2\mu\alpha\upsilon\left(\mu + \frac{3}{2}\right) + 2\alpha\upsilon - \mu\right]\left[2\mu^2\alpha\upsilon(\alpha\upsilon(\mu+2) - 1) + 2\mu\alpha\upsilon\left(\frac{3}{2}\alpha\upsilon - 1\right) - 2\alpha\upsilon + \mu\right]}} \tag{9}$$

4.1 Damped primary structure

Unlike the previous case, obtaining closed expressions for the optimum design parameters f and ξ_d is far too complex, and a numerical optimisation procedure must be used instead. Here we use the normalised mean square of the displacement of the primary structure as the parameter to be minimized, i.e.: $\bar{E}\{x^2\} = E\{x^2\}/E^*\{x^2\}$, where $E^*\{x^2\}$ is the mean square of the displacement of the structure, with the same stiffness and damping as the structure to be controlled, but with a mass equal to the total mass of the system. In order to provide design expressions that cover most practical cases, the numerical optimisation was performed considering the following range of values: $0.001 \leq \mu \leq 0.15$; $0.4 \leq \alpha \leq 0.95$; $0.005 \leq \xi_p \leq 0.1$ and $\upsilon = 1$.

In the Fig.5 the results of the numerical optimisation procedure are shown. The following numerical expression for the optimum frequency ratio, $f|_{OPT}$, as function of μ, α, and ξ_p for $\upsilon = 1$ is proposed.

$$f|_{OPT} = f|_{OPT}(\xi_p = 0) + \sqrt{1 - 2\xi_p^2} - 1 + \Delta f \tag{10}$$

where the first term of the right-hand side of Eq. (10) is the optimum frequency ratio for the undamped primary structure, Eq. (8), and Δf is the difference between these terms and the optimal frequency ratio obtained by the numerical optimisation procedure. Using curve fitting, Δf can be adjusted as a power function of μ, as shown in Eq. (11). This equation used in combination with the Eq. (10), gives a close approximation to the optimal frequency ratio found by numerical optimisation procedure.

$$\Delta f = (1.2\alpha + 1.285)\xi_p \mu^{\lfloor (2.346 - 0.793\alpha)\xi_p^2 + (0.67\alpha - 1.492)\xi_p + 0.466 \rfloor} \tag{11}$$

The values of the optimum critical damping ratio of the device can also be adjusted using curve fitting. In this case the optimal damping ratio can be written as:

$$\xi_d|_{OPT} = \xi_d|_{OPT}(\xi_p = 0) - \Delta\xi_d \tag{12}$$

where $\Delta\xi_d$ is the difference between the optimum damping values for undamped primary structure, Eq. (9), and those obtained by the numerical optimisation procedure for the damped primary structure. The difference $\Delta\xi_d$, is again adjusted as a power function in μ, for $\upsilon = 1$, as follows:

$$\Delta\xi_d = (0.557 - 0.235\alpha)\xi_p \mu^{\lfloor (8.955\alpha - 31.243)\xi_p^2 + (1.738 - 0.782\alpha)\xi_p + 0.953 - 0.169\alpha \rfloor} \tag{13}$$

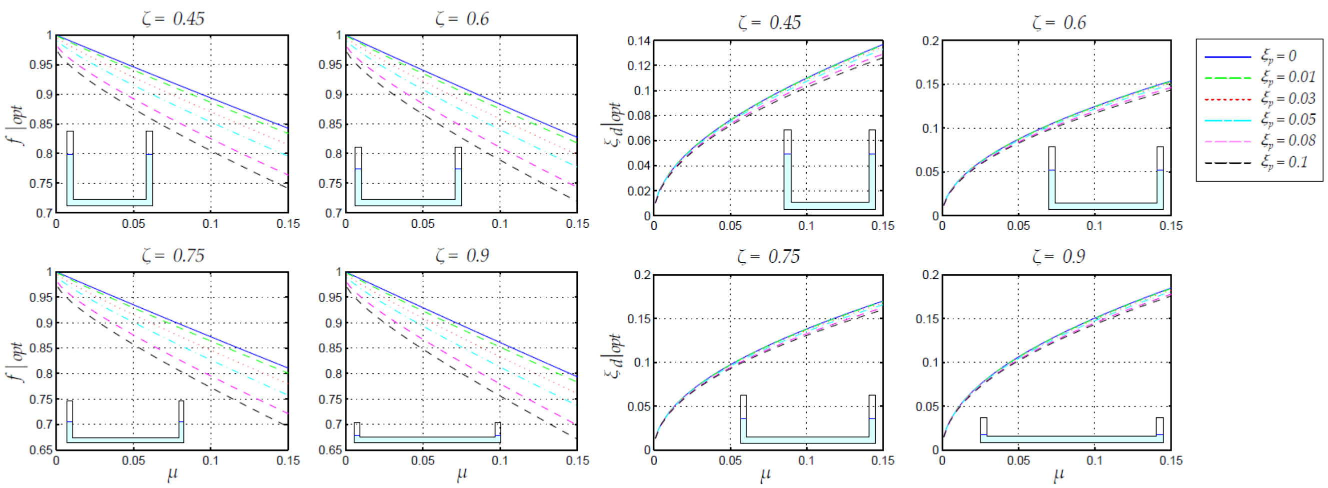

Fig. 5 – Optimum frequency and critical damping ratios values for $\upsilon = 1$

5. BTLCD for several degrees of freedom structures

Considering a several degrees of freedom structure with BTLCD, the equations of motion can be found by means of the Lagrange equations for the system, which can be written in vector notation as [15]:

$$\frac{d}{dt}\left\{\frac{\partial T}{\partial \dot{U}}\right\} - \left\{\frac{\partial T}{\partial U}\right\} + \left\{\frac{\partial V}{\partial U}\right\} = \{Q\} \tag{14}$$

In this case we have a total of $2N + 2$ equations of motion, N being the total number of levels of the primary structure. Once the kinetic energy and potential energy are found, the equations of motion of the entire system can be written as:

$$\begin{bmatrix} [\bar{M}_p] & [M_{pd}] \\ [M_{pd}]^T & \begin{bmatrix} m_{ex}/v_x & 0 \\ 0 & m_{ey}/v_y \end{bmatrix} \end{bmatrix} \begin{Bmatrix} \{\ddot{U}_p\} \\ \ddot{u}_{dx} \\ \ddot{u}_{dy} \end{Bmatrix} + \begin{bmatrix} [C_p] & [C_{pd}] \\ [0] & \begin{bmatrix} c_{dx} & 0 \\ 0 & c_{dy} \end{bmatrix} \end{bmatrix} \begin{Bmatrix} \{\dot{U}_p\} \\ \dot{u}_{dx} \\ \dot{u}_{dy} \end{Bmatrix} + \begin{bmatrix} [K_p] & [0] \\ [0] & \begin{bmatrix} k_{dx}/v_x & 0 \\ 0 & k_{dy}/v_y \end{bmatrix} \end{bmatrix} \begin{Bmatrix} \{U_p\} \\ u_{dx} \\ u_{dy} \end{Bmatrix} = -\begin{bmatrix} [\bar{M}_p] & [M_{pd}] \\ [M_{pd}]^T & \begin{bmatrix} m_{ex} & 0 \\ 0 & m_{ey} \end{bmatrix} \end{bmatrix} \begin{Bmatrix} [r] \\ [0] \end{Bmatrix} \{\ddot{u}_s\} \tag{15}$$

where

$$[L]^T = \begin{bmatrix} 0 & \dots & 1 & \dots & 0 & 0 & & \dots & & 0 \\ 0 & & \dots & & 0 & 0 & \dots & 1 & \dots & 0 \\ 1 & & i & & & & & i+N & & 2N \end{bmatrix} \tag{16}$$

and

$$[\bar{M}_p] = [M_p] + [L] \begin{bmatrix} m_f + m_u & 0 \\ 0 & m_f + m_u \end{bmatrix} [L]^T;\ [M_{pd}] = [L] \begin{bmatrix} m_{hx} & 0 \\ 0 & m_{hy} \end{bmatrix};\ \ [C_{pd}] = [L] \begin{bmatrix} c_{dx} & 0 \\ 0 & c_{dy} \end{bmatrix} \tag{17}$$

where $\{U_p\}$ are the degrees of freedom of the primary structure, $[r]$ is the influence matrix of $\{U_p\}$, and $\{u_s\} = \langle u_{sx}, u_{sy} \rangle^T$ is the vector of the external displacements. It should be noted that the $(1, i)$ and $(2, N+i)$ components of the influence matrix should be equal to 1, $[M_p]$, $[C_p]$ and $[K_p]$ are the mass damping and stifness matrix of the primary structure.

Examining the system of Eqs. (15), it remains clear that the damping matrix is non symetrical. The last two equations of the system of Eqs. (15), which describe the motion of the liquid inside the device, remain as:

$$\left.\begin{aligned} m_{ex}\ddot{u}_{dx} + v_x c_{dx}\dot{u}_{dx} + k_{dx}u_{dx} &= -m_{hx}v_x(\ddot{u}_{sx} + \ddot{u}_i) \\ m_{ey}\ddot{u}_{dy} + v_y c_{dy}\dot{u}_{dy} + k_{dy}u_{dy} &= -m_{hy}v_y(\ddot{u}_{sy} + \ddot{u}_{i+N}) \end{aligned}\right\} \tag{18}$$

The first $2N$ equations of the system of Eqs. (15) can be rewritten in terms of modal coordinates, $\{U_p\} = [\Phi]\{q\}$, after premultiplying these equations by $[\Phi]^T$. Assuming classic damping matrix of the primary structure, we can write the j-th equation of Eqs. (15) as follows:

$$m_j\ddot{q}_j + c_j\dot{q}_j + k_jq_j = -\sum_{k=1}^{2N} \phi_{k,j}M_k\ddot{u}_s - \phi_{i,j}\left[(m_f + m_u)(\ddot{u}_i + \ddot{u}_s) - c_{dx}\dot{u}_{dx} + m_{hx}u_{dx}\right] - \phi_{i+N,j}\left[(m_f + m_u)(\ddot{u}_{i+N} + \ddot{u}_s) - c_{dy}\dot{u}_{dy} + m_{hy}u_{dy}\right] \tag{19}$$

If we need to control vibrational modes along two orthogonal directions simultaneously, and these modes are widely representative of the structural response, we can express the displacements of the i-th level of the primary structure as: $u_i \approx \phi_{i,r}q_r$; $u_{i+N} \approx \phi_{i+N,s}q_s$, where r and s are the controlled modes in two perpendicular directions. Using the foregoing approximations, the Eq. (19) can be reduced to the following two equations of motion for the coordinates u_i and u_{i+N}:

$$\left.\begin{aligned} (\tilde{m}_r + m_f + m_u)\ddot{u}_i + \tilde{c}_r\dot{u}_i + k_ru_i &= -(\Gamma_r\tilde{m}_r + m_f + m_u)\ddot{u}_s + c_{dx}\dot{u}_{dx} - m_{hx}\ddot{u}_{dx} \\ (\tilde{m}_s + m_f + m_u)\ddot{u}_{i+N} + \tilde{c}_s\dot{u}_{i+N} + k_su_{i+N} &= -(\Gamma_s\tilde{m}_s + m_f + m_u)\ddot{u}_s + c_{dy}\dot{u}_{dy} - m_{hy}\ddot{u}_{dy} \end{aligned}\right\} \tag{20}$$

where $\tilde{m}_r = m_r/\phi_{i,r}^2$, $\tilde{c}_r = c_r/\phi_{i,r}^2$ and $\tilde{k}_r = k_r/\phi_{i,r}^2$, the definitions of terms $\tilde{m}_s$, $\tilde{c}_s$ and $\tilde{k}_s$ are analogous but in this case use $i+N$ instead of i. A closer look at the latter definitions shows that the optimal location of the device should at the position with the largest modal component. This reduces the mass of the equivalent structure, $\tilde{m}_r$, to its minimum possible value, thereby yielding the largest posible mass ratio between the device and the equivalent structure. If we examine the system of Eqs. (20) and the Eqs. (18), and compare them with the system of Eqs. (2), it remains clear that they differ only in the terms Γ_r and Γ_s.

6. BTLCD design example

A BTLCD will be designed to control the response of the first two perpendicular modes shapes of a 3 story scale model shown in Figure 9, with a total mass 270[kg]. The periods of oscillation, damping ratios and mode shapes were identified empirically using the Eigensystem Realization Algorithm (ERA) by means of pullback and hit test. The periods of oscillation of the two first translational modes are 1.52[seg] and 1.10[seg] for X and Y direction, respectively. Since the modal displacement is greater in the roof, that is the optimal location of the device. The equivalents properties of the single degree of freedom structures are: effective mass in X direction: $\tilde{m}_1 = \frac{1[kg]}{0.087^2} = 131.5[kg]$, effective stiffness in X direction: $\tilde{k}_1 = (1[kg] \cdot (2\pi/1.52[seg])^2)/0.087^2 = 22.56[N/cm]$, effective mass in Y direction: $\tilde{m}_2 = \frac{1[kg]}{0.085^2} = 138.4[ton]$, effective stiffness in Y direction $\tilde{k}_2 = (1[kg] \cdot (2\pi/1.1[seg])^2)/0.085^2 = 45.07[N/cm]$

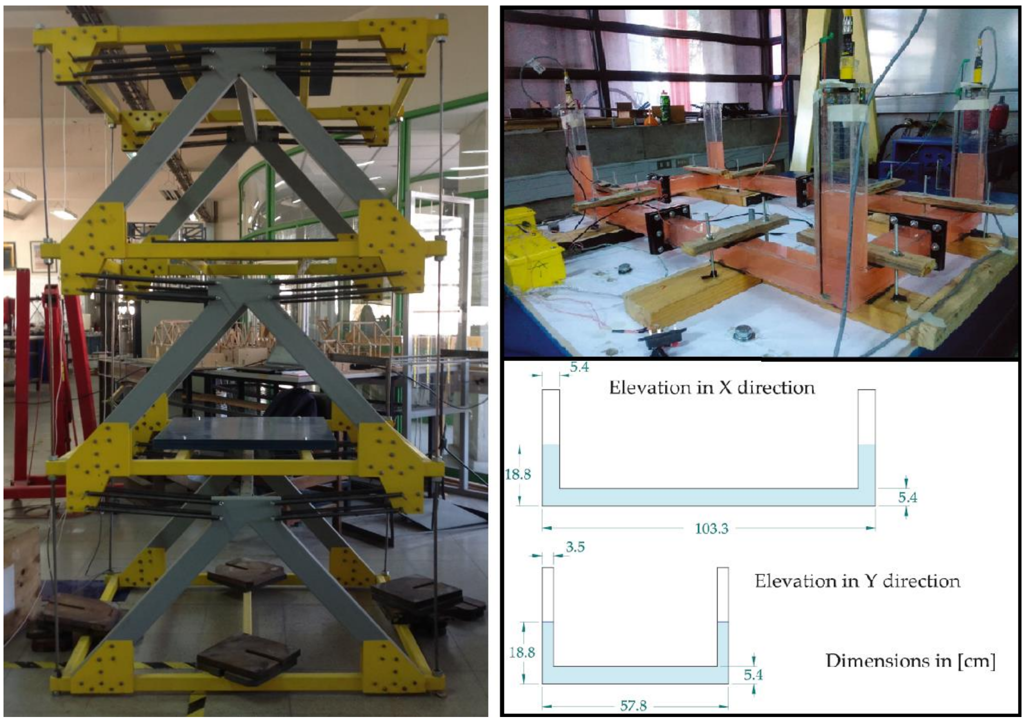

Fig. 9 – Left figure shows the 3-story scale model used for the experimental analysis(left). Right figure shows the BTLCD along with its main dimensions.

The BTLCD for controlling the first and second mode of the building example is shown in the right side of Fig.9. The actual total liquid mass inside the BTLCD reach the $8[kg]$ and the optimal critical damping ratios can be calculated using Equation (12), which leads to $\xi_{dx} = 0.071$ and $\xi_{dy} = 0.08$. In order to validate these damping values, shaking table test were performed. The BTLCD was subjected to three different filtered white noise processes, in which the duration varies between 10 and 15 min. For each test, empirical damping ratios were identified using the Multivariable Output Error State Space (MOESP) method, and theoretical damping ratios were obtained by Equation (5), where it is consider the standard deviation of the liquid velocity calculated for each one of the time ranges analysed. These results are shown in Figure 10, and it can be seen the good agreement between the mean of the theoretical damping values and the damping values measured experimentally.

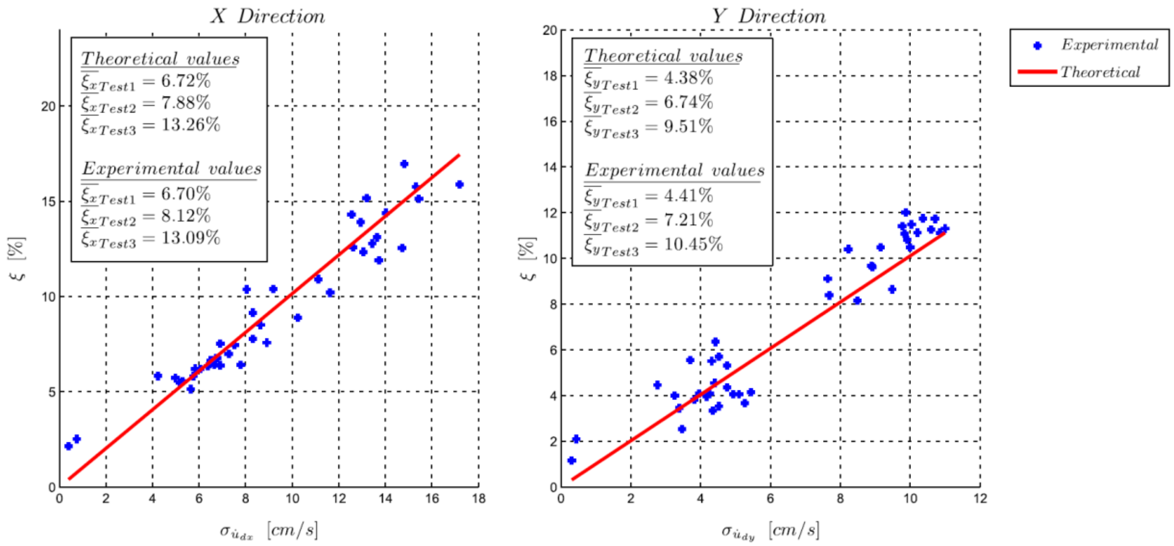

Fig. 10 – Experimental damping versus damping obtained by Equation (12).

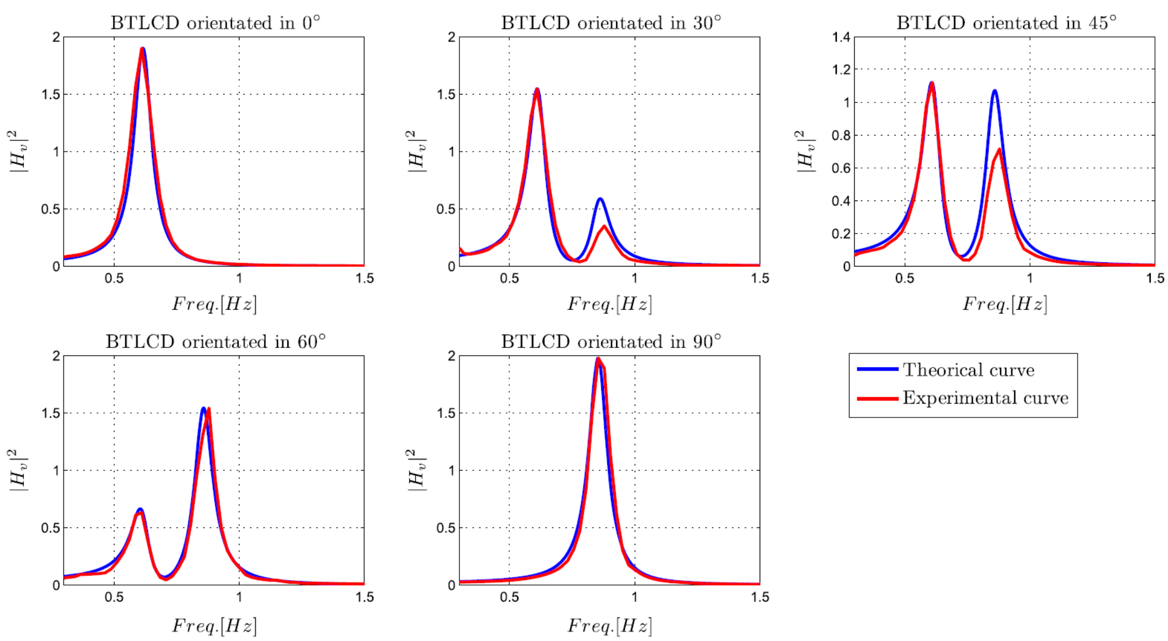

Fig. 11 – Experimental transfer functions from shaking table acceleration to BTLCD.

Theoretical and experimental transfer function of the device are also compared and shown in Figure 11. The device is subject to the action of a filtered white noise applied on its base with energy in the $0.4[Hz]-5[Hz]$ band, and which peak displacement, velocity and acceleration are as follows: $0.054[m]$, $0.24[m/seg]$ and $1.89[m/seg^2]$, respectively. To measure the coupled effects, the BTLCD was inclined relative to the direction excited by the shaking table, where five inclination angles are investigated, $\theta = 0^{\circ}, 30^{\circ}, 45^{\circ}, 60^{\circ}, 90^{\circ}$. The periods and critical damping ratios of the BTLCD can be obtained from the transfers functions between the base acceleration and the liquid displacements inside the device. After applying the Fourier transformation to Equation (18) and the fact that the total volume of liquid shal be conserved, the transfer functions can be expressed as follows:

$$H_z(\omega) = \pm\frac{\cos(\theta)}{\upsilon_x}H_x(\omega) \pm \frac{\sin(\theta)}{\upsilon_y}H_y(\omega), \qquad H(\omega) = \frac{-\alpha\upsilon}{\omega_d^2 - \omega^2 + i\cdot 2\xi_d\omega_d\omega} \tag{21}$$

Where $H_z(\omega)$ is the transfer function of the vertical liquid free surface and $H_x(\omega)$ and $H_y(\omega)$ are the transfer functions of the liquid displacements inside the horizontal conduits of the device, which is indicated in the right expression of Equations (21) (notice that the directional subscript have been removed for clarity). The measured natural periods and critical damping ratios were $T_x = 1.622[seg]$ and $T_y = 1.161[seg]$, which are very close to the theoretical values $T_x = 1.618[seg]$ and $T_y = 1.167[seg]$.

Once analyzed and verified dynamic properties the BTLCD, ten seismic records were applied to the structure with its configuration with and without BTLCD, in order to compare the structural response, hoping verify reductions in the response of the building model that includes the seismic control device. Records tested were Concepción Centro, Constitución, Llolleo, Maipú and Valparaíso horizontal records of Maule 2010 earthquake, Valparaíso record of Algarrobo 1985 earthquake, El Centro 1940 earthquake, Gilroy and Yerba Buena Island records of Loma Prieta 1989 and Arleta Station record of Northridge 1994 earthquake. The most remarkable test was the one developed with the Concepción acceleration record from the Maule 2010 Earthquake, because the structural response in both principal directions to this record was the one that was mainly given by the first translational modes of vibration, not like most of the results, because upper vibration modes were excited easily due to the high structure flexibility. The results from these experimental tests are shown in the following figures.

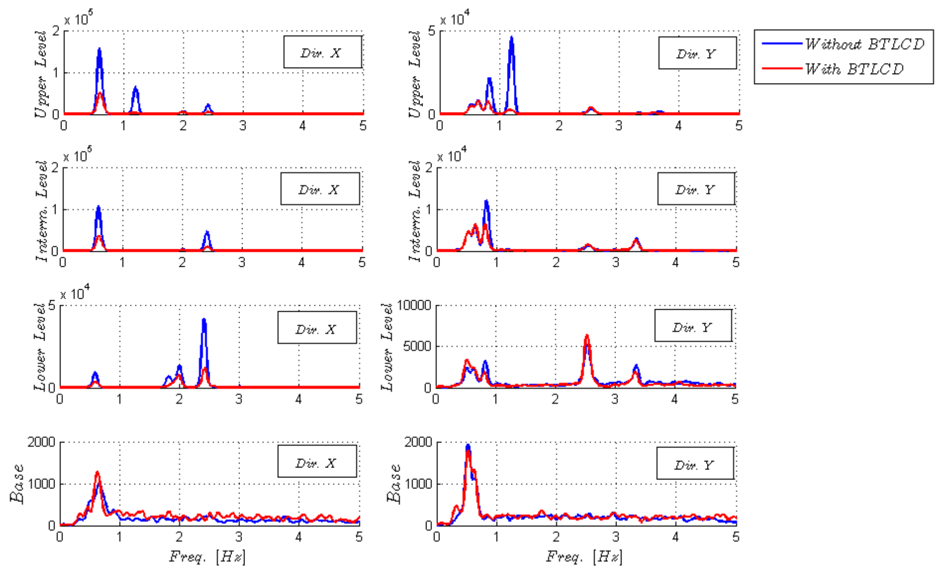

Fig. 12 – Power Spectrum for the displacement response, Concepción 2010 record.

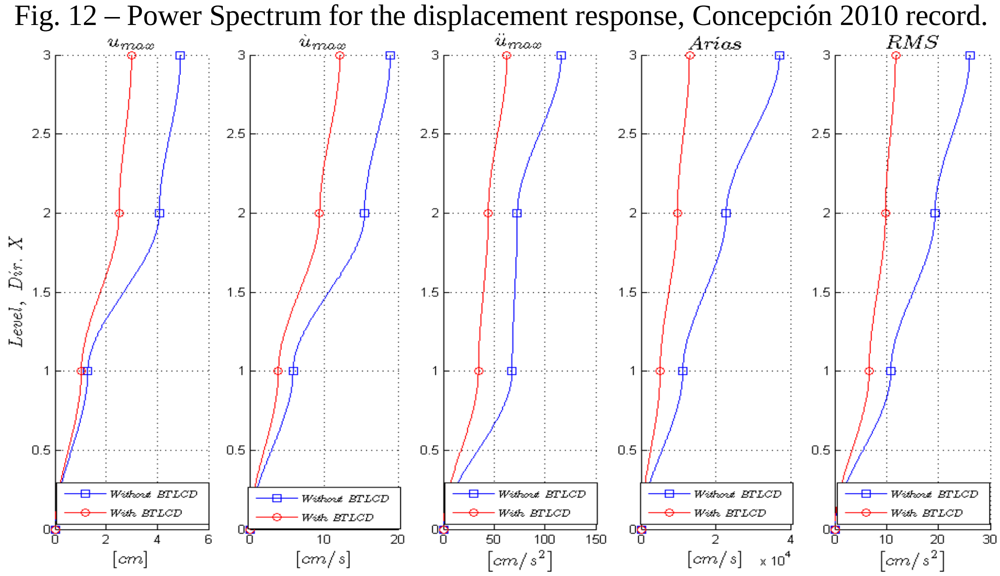

Fig. 13 – Maximum responses, Arias intensity and RMS in X Direction, Concepción 2010 record.

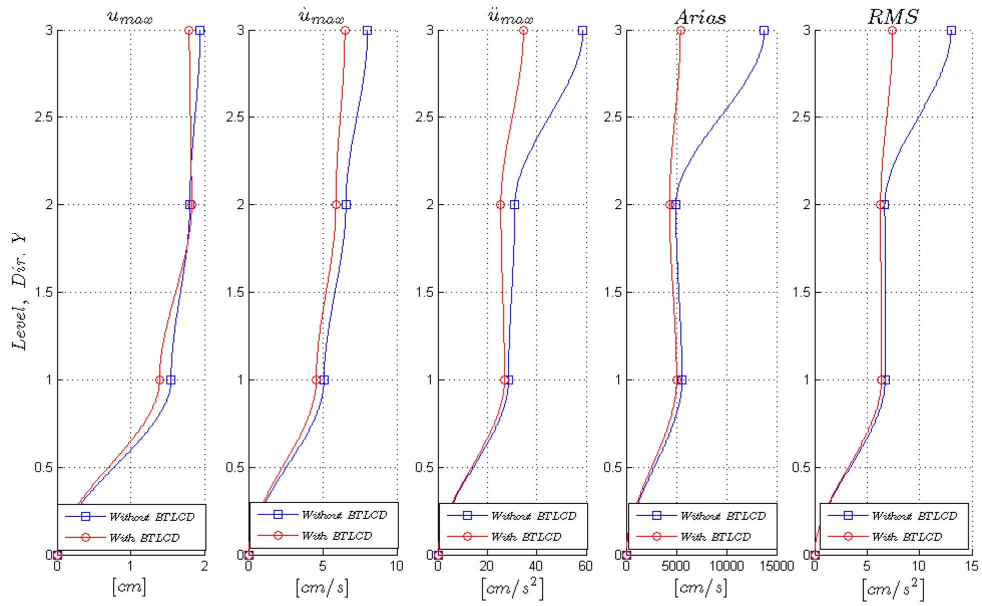

Fig. 14 – Maximum responses, Arias intensity and RMS in Y Direction, Concepción 2010 record.

7. Conclusions

In the present study, we have proposed the use of a new device that acts as two independent and orthogonal TLCDs combined in one single BTLCD unit, for controlling the seismic response of structures that have vibrations occurring essentially in two mutually perpendicular directions. First, the BTLCD was used as a seismic control device for two DOF structures. Using an equivalent linear formulation of the nonlinear forces from the liquid flow inside the device, by means of Lagrangian dynamics it was possible to write a set of linear equations of motion of the BTLCD and the two DOF primary structure to be controlled. The optimal tuning parameters of the BTLCD were then obtained by minimizing the response of the primary structure when subject to white noise base acceleration. The reductions in the mean square value of the primary structure displacement show that the effectiveness of the BTLCD is greater when it is used to control low damped structures. As the damping of the structure increases the reductions become smaller; however, in these cases the use of energy dissipation devices is usually unnecessary. The application of the BTLCD in structures with several degrees of freedom was also studied. In this case the equations of motion of the BTLCD and the primary structure were written using the vector formulation of Lagrangian dynamics, which leads to a system of equations that can be reduced if the response of the primary structure occurs mainly in two perpendicular modes. Using this consideration, the system of equations was transformed into a system which is similar to the system of equations for the BTLCD and the two DOF primary structure. The optimal tuning parameter found can then be used to design the BTLCD as a seismic control device for multiple DOF structures. An iterative method of rapid convergence to facilitate the design of the device is proposed. Finally, the experimental analysis of a 3-story structure with and without BTLCD was developed for ten seismic records and here it is shown the analysis under the action of Concepción 2010 seismic records (Maule 2010 Earthquake). First it was design the BTLCD for controlling the structure response and its dynamic properties were verified experimentally. Then the comparison results of the structure response with and without BTLCD show that the device performs well, and the reduction of the structure displacement and the rapid response decay obtained revealed that the device increases the damping of the controlled structure. From the analysis of all experimental results, it can be noticed that the higher vibration modes of the structure without BTLCD were excited several times, which meaned that the first and stronger assumption (structural response in each direction controlled by the first mode) was not fulfilled. Therefore, when this was the case, consequences of BTLCD implementation could not be foreseen and there were cases where it helps to reduce the excitation of higher modes and situations where not. On the other hand, it should be remarked that minimization of the expression $\bar{E}\{x^2\} = E\{x^2\}/E^*\{x^2\}$ does not guarantees the reduction of maximum displacement, but what it does is to reduce the dispersion of the displacements in comparison with the average displacement, which is cero. In other words, the amplitude of the displacements decreases faster when a BTLCD is incorporated to the system. Therefore, increase the damping ratios associated to the first translational modes is what it is expected from implementation of BTLCD and, if the structural response is mainly controlled by these vibration modes, the same effect will be seen in the global response.

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9. References

[1] Ahsan Kareem, Tracy Kijewski, and Yukio Tamura. Mitigation of Motions of Tall Buildings with Specific Examples of Recent Applications. 1999.

[2] F Sakai, S Takaeda, and T Tamaki. Tuned Liquid Column Damper New Type Device for Suppression of Building Vibrations. Proceedings of International Conference on Highrise Buildings, pages 926-931, 1989.

[3] H. Gao and K.C.S. Kwok. Optimization of Tuned Liquid Column Dampers. Engineering Structures, 19:476-486, 1997.

[4] K.C.S. Kwok & P.A. Hitchcock K.M. Shum. Closed-Form Optimum Liquid Column Vibration Absorber Parameters for Base-Excited Damped Structures. Advances in Structural Engineering, 14:489-497, 2011.

[5] Jong-Shyong Wu and Mang Hsieh. Study on the Dynamic Characteristic of a U-type Tuned Liquid Damper. Ocean Engineering, 29:689-709, 2002.

[6] Jong-Cheng Wu, Ming-Hsiang Shih, Yuh-Yi Lin, and Ying-Chang Shen. Design Guidelines for Tuned Liquid Column Damper for Structures Responding to Wind. Engineering Structures, 27:1893-1905, 2005.

[7] Aparna Ghosh and Biswajit Basu. Seismic Vibration Control of Short Period Structures Using the Liquid Column Damper. Engineering Structures, 26:1905-1913, 2004.

[8] Aparna Ghosh and Biswajit Basu. Seismic Vibration Control of Nonlinear Structures Using the Liquid Column Damper. Journal of Structural Engineering, 134:146-153, 2008.

[9] K.M. Shum, Y.L. Xu, and W.H. Guo. Wind-Induced Vibration Control of Long Span Cable-Stayed Bridges Using Multiple Pressurized Tuned Liquid Column Dampers. Journal of Wind Engineering and Industrial Aerodynamics, 2007.

[10] Fahim Sadek, Bijan Mohraz, and H. S. Lew. Single and Multiple Tuned Liquid Columns Dampers for Seismic Applications. Earthquake Engineering and Structural Dynamics, 27:439-463, 1998.

[11] K.S.C. Kwok & B. Samali H. Gao. Characteristics of Multiple Tuned Liquid Column Dampers in Suppressing Structural Vibration. Engineering Structures, 21:316-331, 1999.

[12] K.M. Shum and Y.L. Xu. Multiple Tuned Liquid Column Dampers for Reducing Coupled Lateral and Torsional Vibration of Structures. Engineering Structures, 26:745-758, 2004.

[13] P. A. Hitchcock, K. C. S. Kwok, and R. D. Watkins. Characteristics of Liquid Column Vibration Absorbers (lcva) ii. Engineering Structures, 19:135-144, 1997.

[14] Sung-Kyung Lee, Kyung-WonMin, and Hye-Ri Lee. Parameter Identification of New Bidirectional Tuned Liquid Column and Sloshing Dampers. Journal of Sound and Vibration, 330:1312-1327, 2010.

[15] Leonard Meirovitch. Analytical Methods in Vibrations. Macmillan Publishing Co, 1967.

[16] I.E. Idelchik. Handbook of Hydraulic Resistance. Research Institute for Gas Puri_cation, Moscow, Russia, 1986.

[17] J. B. Roberts & P. D. Spanos. Random Vibration and Statistical Linearization. Dover, 1999.

[18] Finn Rüdinger. Modelling and Estimation of Damping in Non-linear Random Vibration. PhD thesis, Technical University of Denmark, 2002.

[19] Stephen H. Crandall and William D. Mark. Random Vibration in Mechanical Systems. Academic Press, 1963.

[20] Luis Rozas and Rubén Boroschek. Reduccion de la Respuesta Estructural por Medio del uso de Disipadores de Masa Sintonizada y Disipadores de Columna Líquida Sintonizada. Master's thesis, Universidad de Chile, 2009.

[21] S. Yalla and A. Kareem. Optimum Absorber Parameters for Tuned Liquid Column Dampers. ASCE Journal of Structural Engineering, 126(8):906–915, 2000.