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Development of a methodology for damping of tall buildings motion using TLCD devices

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Abstract. One of the most common solutions adopted to reduce vibrations of skyscrapers due to wind or earthquake action is to add external damping devices to these structures, such as a TMD (Tuned Mass Damper) or TLCD (Tuned Liquid Column Damper). It is well known that a TLCD device introduces on the structure a nonlinear damping force whose effect decreases when the amplitude of its motion increases. The main objective of this paper is to describe a Hardware-in-the-Loop test able to validate the effectiveness of the TLCD by simulating the real behavior of a tower subjected to the combined action of wind and a TLCD, considering also the nonlinear effects associated with the damping device behavior. Within this test procedure a scaled TLCD physical model represents the hardware component while the building dynamics are reproduced using a numerical model based on a modal approach. Thanks to the Politecnico di Milano wind tunnel, wind forces acting on the building were calculated from the pressure distributions measured on a scale model. In addition, in the first part of the paper, a new method for evaluating the dissipating characteristics of a TLCD based on an energy approach is presented. This new methodology allows direct linking of the TLCD to be directly linked to the increased damping acting on the structure, facilitating the preliminary design of these devices.

Keywords: TLCD; Hardware in the Loop; passive damping system; experimental tests; tall building

1. Introduction

The study and design of skyscrapers and of slender buildings generally goes through various phases, from the architectural concept, to structural verification, dimensioning of the facades, up to the analysis of comfort. In these phases of the design process, an increase of structural damping could be needed for safety and comfort specifications. One of the most common solutions adopted in the civil engineering field is to add external damping devices to the structures, such as TMD (Tuned Mass Damper) and TLCD (Tuned Liquid Column Damper).

Tuned liquid column dampers (TLCDs) are a class of tuned liquid dampers that impart external damping to a structure through an oscillating liquid column in a U-shaped container. One of the first papers to investigate the application of TLCD for reducing the along-wind response of wind-sensitive structures, which presented the equivalent linear equation of motion of the liquid column and the equations for the coupled TLCD-tower systems, is Xu *et al.* (1992). In the past two

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decades, other interesting research has also been conducted on the performance or application of single and multiple TLCDs (Sadek *et al.* 1998, Gao *et al.* 1999, Hitchcock *et al.* 1997, Balendra *et al.* 1995, Sun 1994, Xue *et al.* 2000). Some research focused mainly on the definition of optimal design parameters (Yalla *et al.* 2000) under external forcing, the most common of which is the stochastic one (Won *et al.* 1996). Many buildings and towers have been successfully equipped with such control devices (One Wall Centre in Vancouver, Comcast Center in Philadelphia, One Rincon Hill South Tower in San Francisco) thanks to the development of accurate building-device interaction models, able to predict the whole system's behavior and support its design.

More recent studies have been focused on different subjects concerning system modeling, analytical solutions and TLCD effectiveness validation. In 2008 a closed form for the analytical solution of the TLCD equation of motion was presented (Shum 2008) as an alternative to the iterative method used in paper (Sadek *et al.* 1998), allowing an analytical expression for the optimal head loss coefficient of a TLCD. Also many studies have used experimentally determined TLCD parameters in order to evaluate its effectiveness using both numerical and experimental methodologies (Chaiviriyawong *et al.* 2007). In 2010 the numerical evaluation of the effectiveness of a TLCD is evaluated considering uncertain but bounded structure parameters subjected to a stochastic earthquake (Debbarma *et al.* 2010), a useful analysis of structure parameters variability that has to be considered during TLCD design before the real building has been actually built.

Because real structures, subjected to earthquakes or wind, often have a two-dimensional displacement of the top of the building where TLD (Tuned Liquid Damper) are usually placed, many works face this kind of problem considering bidirectional TLD devices. In 2010 an identification of bidirectional TLD properties was produced considering both column and sloshing solutions on the two different directions of the imposed motion (Lee and Min 2010); this device (TLCD plus TSD) has been modeled and experimentally tested in different operating conditions. An interesting alternative to this device was described in 2009, with a TLCD coupled to a TMD device (Heo *et al.* 2009) using water motion to damp the motion of the structure in one direction (TLCD), and its weight, coupled with a spring and a damper, in the other direction (TMD); this construction seems to be more effective than the previous one and easier to design; the performance evaluation methodology used was previously proposed by the same authors for a TLD device (Lee *et al.* 2007).

Moreover many active and semi-active controlled solutions have been studied (Symans and Constantinou 1999, Yalla *et al.* 2001, Chen and Ko 2003), in an attempt to improve TLCD effectiveness for different motion amplitudes, as passive TLCD devices typically decrease their damping effect on the structure as motion amplitude increases.

The present paper traces previous works and presents a new method for evaluating the dissipating characteristics of a TLCD based on an energy approach and a TLCD effectiveness evaluation methodology based on a Hardware in the Loop (HiL) test.

In particular, the new methodology based on the energy approach leads to the evaluation of the TLCD parameter effects in terms of variation of damping associated with the structure, facilitating the preliminary design of these kind of devices, eliminating the need to solve complex analytical equations (Shum 2008) or to implement time-expensive iterative methods (Sadek *et al.* 1998). By using this approach, a TLCD device has been designed for a specific application where a tall building is forced by wind

Moreover, in this paper a numerical-experimental methodology, based on a Hardware in the Loop (HiL) test, is presented for evaluating the effectiveness and the possible instability behavior of the overall system (building + TLCD device) subjected to wind action. As is well known, TLCD dynamics are described by a nonlinear equation (Sadek *et al.* 1998); as a consequence, the damping force transmitted by the TLCD has nonlinear dependence on its oscillation amplitude and, in particular, it will be shown that the TLCD damping force reduces its beneficial effect, increasing the displacement of the top of the building. Many recent studies (Lee and Min 2010, Heo *et al.* 2009, Lee *et al.* 2007) describe HiL validation tests, trying to detect the system's response when subjected to arbitrary or random eternal forces. In any case, this kind of test cannot be conclusive for the effectiveness and, in particular, for the possibility of instability effects associated with the designed TLCD in all its potential applications; as a consequence, all the conclusions principally validated in earthquake test conditions cannot be extended to a building forced by wind.

In this application, thanks to experimental tests carried out on the building considered in the Politecnico di Milano wind tunnel (Diana *et al.* 2009, Rosa *et al.* 2012a, b, Rosa *et al.* 2013, Giappino *et al.* 2012), the external forces, due to the wind action, have been determined by a standard approach (Cheli *et al.* 2010, Cheli *et al.* 2011a, b, Cheli *et al.* 2012, Tomasini and Cheli 2013). By simulating, in the time domain, the motion of the structure subjected to the simultaneous action of wind and (TLCD) damping forces, by means of the HiL procedure presented, it will be possible to evaluate not only the effectiveness of the designed TCLD (as found in some previous papers), but also the potential instability phenomena that can arise on the building considered under particularly strong winds (case study involving real wind forces).

A test bench for a scale model of a TLCD system has been designed with the objective of set up an HiL procedure, where a scaled TLCD physical model represents the hardware component while the building dynamics is reproduced through a numerical model based on a modal approach. In this test the TLCD is moved according to the real displacement of the top of the building, subject to measured wind action and, simultaneously, the building dynamics are affected by the damping force generated by the TLCD device. In this way, realistic time-histories of the building top displacement are reproduced and the non-linear effects associated with the TLCD are correctly taken into account.

Moreover the TLCD designed for this particular application also has the interesting property of being a modular square-section TLCD (Diana *et al.* 2012), whose parameters (such as the loss coefficient function of the orifice shape) make it easy to get from the numerical TLCD model and its optimal parameters, determined with the energy approach, to the characteristic dimensions of the full scale prototype.

2. The nonlinear dynamic of TLCD system: problem setting and equivalent damping parameter

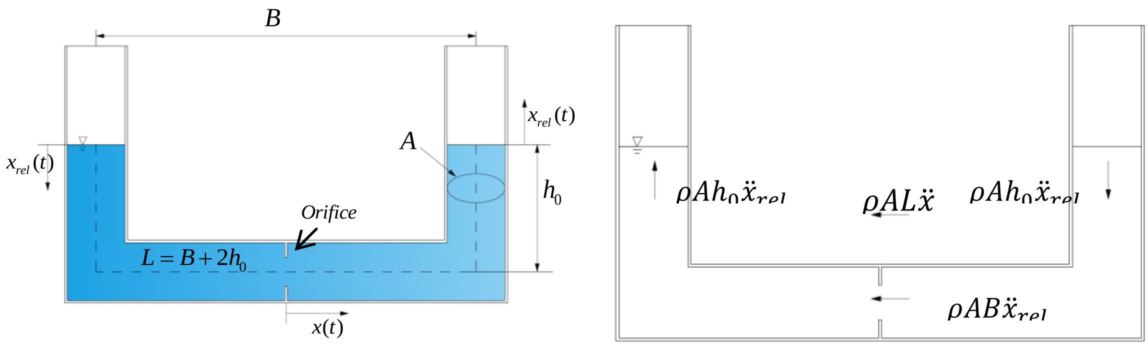
Fig. 1 shows a sketch of a TLCD device: a U-shape container where the liquid column is oscillating. The damping effect of the device is due to the passage of the liquid through an orifice with head-loss characteristics (Fig. 1).

The dynamics of the TLCD, induced by a movement x along the horizontal direction (Fig. 1), is expressed as a function of the coordinate x_{rel}. The nonlinear equation of motion of the system is Eq. (1)

$$\rho AL\ddot{x}_{rel} + \frac{1}{2}\rho A\delta\left|\dot{x}_{rel}\right|\dot{x}_{rel} + 2\rho Ag\, x_{rel} = -\rho AB\ddot{x} \qquad (1)$$

where ρ is the fluid density, g the gravity acceleration and δ the dimensionless orifice head-loss coefficient (Blevins 1984). The natural frequency of the TLCD, for low damping levels, is given by the following equation

$$\omega_{TLCD} = \sqrt{\frac{2\rho Ag}{\rho AL}} = \sqrt{\frac{2g}{L}} \tag{2}$$



(a) (b)

Fig. 1 (a) Scheme of the dimension parameters of the TLCD and (b) corresponding inertial components

In Eq. (1), the damping coefficient is constituted by a non-linear function of the velocity ($\dot{x}_{rel}$) of the fluid and represents the concentrated head loss due to the orifice. The coefficient δ depends on the ratio between the total area of the container section and the orifice area; experimental data can be found for particularly simple sections, such as circular ones (Blevins 1984). For civil application a rectangular section is the most common, unfortunately any application has particular sides dimension and particular δ coefficient that cannot be generalized. For this reason a particular modular square has been chosen for the experimental valuation of the head-loss coefficient by means of a scaled model, as described in section 3.

When the TLCD system is connected to a vibrating structure (i.e., building), the TLCD behaves as a passive dynamic absorber where the effect of the TLCD on the structure dynamics is associated to the inertia forces acting on the fluid: considering the motion of the fluid, it is possible to separate the contribution to the displacement of the fluid imposed by the structure (x, drive motion) and the motion of the fluid with respect to the container (x_{rel} relative motion). As represented in Fig. 1(b), the inertial component associated to the drive motion is equal to $-\rho AL\ddot{x}$. The relative motion x_{rel}, on the other hand, generates two inertial components (Fig. 1(b)): an horizontal one, equal to $-\rho AB\ddot{x}_{rel}$, associated with the motion of the liquid in the horizontal part of the tube, and a vertical one, related to the vertical motion of the fluid columns, which doesn't work on the horizontal displacement of the structure x. This consideration underlines how the effect of the TLCD on the structure is expressed through two terms:

- an added mass term ρAL, due to the inertial component of driven motion;
- an added force defined as Eq. (3)

$$F_T = -\rho AB\ddot{x}_{rel} \tag{3}$$

This component, if suitably dimensioned and phase shifted, can produce a dissipating effect on the motion of the structure. The maximum effect is reached when the frequency of the TLCD is tuned with the first natural frequency of the structure and when the δ coefficient is close to its optimum value.

As an example, Fig. 2 shows the frequency response of a single degree of freedom vibrating system x (representing the building, natural frequency $f_1 = 0.177$ Hz) to an external harmonic input F_{ext} acting on the vibrating system†: the comparison is carried out between the configuration without the TLCD (only 1 dof vibrating system) and the configurations with the TLCD characterized by different values of the damping parameter δ (vibrating system + TLCD, ratio between water mass ρAL and vibrating system mass equal to 5%). Fig. 3 shows the corresponding frequency response between the relative motion of the fluid x_{rel} and the motion of the vibrating system x. It is possible to see that, when the movement x of the vibrating system is in quadrature with the external force (Fig. 2), the relative displacement of the fluid x_{rel} and, hence, the force transmitted by the TLCD F_T, are in quadrature with the movement of the vibrating system (Fig. 3): in other words, the force F_T acts as a damper added to the system.

Considering these introductory remarks, it is possible to transfer to this application the know-how developed within other sectors where passive dissipating devices have been developed (i.e., TMD for cable dynamics: Diana *et al.* 2003) in order to perform a preliminary dimensional study. Frequently design specifications, system characteristics and laboratory tests (as wind tunnel tests) can underline the necessity of increasing structural damping. In these cases, a preliminary design of the damping device allows to perform useful analysis as a comparison between cost-effective solutions before the real design of the device begins.

To predict the effectiveness of the TLCD, a dimensionless equivalent damping parameter h_{eq} can be defined, neglecting its nonlinear effects. Since, as previously observed, the TLCD operates as a dissipating viscous force, the equivalent damping parameter is defined as the ratio between the dissipated energy E_d and the maximum kinetic energy of the system $E_{c\,max}$ (Diana *et al.* 2003)

$$h_{eq} = \frac{1}{4\pi}\frac{E_d}{E_{c\max}} \tag{4}$$

The dissipating function is defined as

$$E_d = \int_0^T F_T \dot{x}\,dt = \int_0^T -\rho AB\ddot{x}_{rel}\,\dot{x}dt \tag{5}$$

indicating with T the period of the motion.

Considering an harmonic motion at an assigned frequency Ω and amplitude X for the vibrating system to be damped and the relative motion of the fluid X_{rel}, the energy dissipated in a given period is

$$E_d = -\rho AB\Omega^2 X_{rel}\Omega X\frac{T}{2}\sin\varphi = -\rho AB\Omega^2 X_{rel} X\pi\sin\varphi \tag{6}$$

† It is important to underline that this external force F_{ext} does not coincide, in general, with the force F_T (Eq. (3)) transmitted between the TLCD (column water) and the vibrating system on that the TLCD is linked.

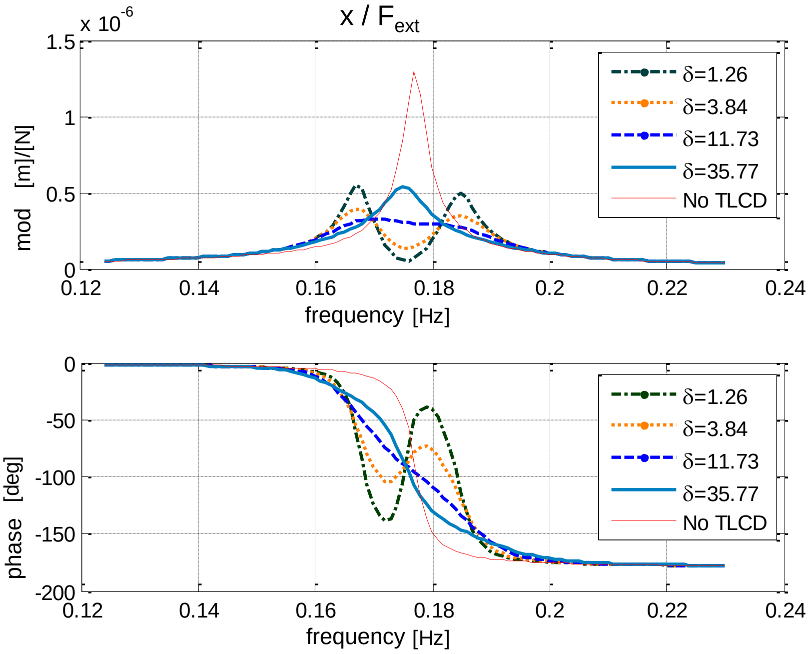


Fig. 2 Frequency response between the oscillation x of the vibrating system and external force F_{ext}: module (above) and phase (below)

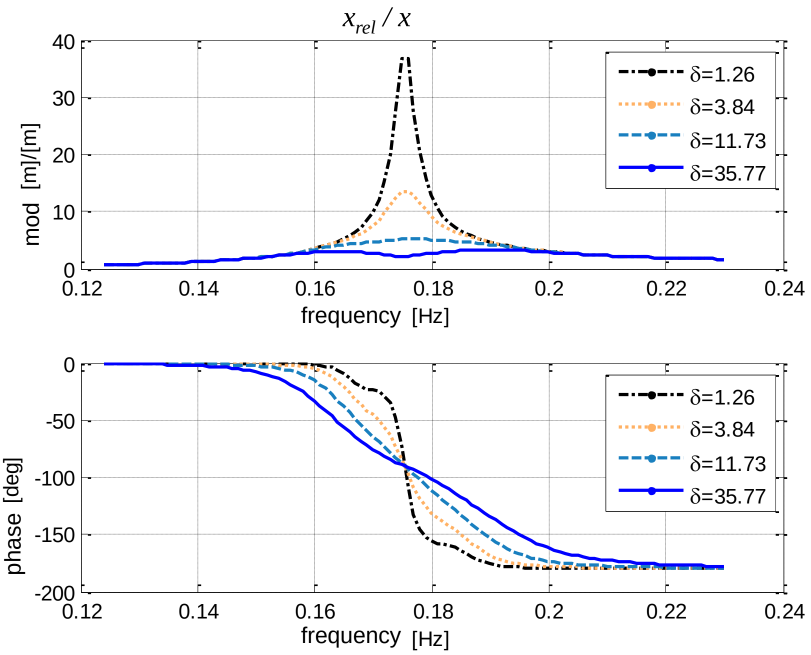


Fig. 3 Frequency response between the relative motion of the fluid x_{rel} and the oscillation x of vibrating system: module (above) and phase (below)

where φ is the relative phase between X_{rel} and X. As highlighted in Fig. 3, in correspondence of the resonance, the dissipating force F_T is in quadrature with the movement of the vibrating system (φ=π/2). The dimensionless damping factor is thus

$$h_{eq} = \frac{1}{4\pi}\frac{E_d}{E_{c\max}} = \frac{1}{4\pi}\frac{\rho AB\Omega^2 X_{rel} X\pi}{\frac{1}{2}(M+\rho AL)\Omega^2 X^2}\sin\varphi = \frac{1}{2}\frac{\rho AB}{(M+\rho AL)}\frac{X_{rel}}{X}\sin\varphi \tag{7}$$

where M is the generalized mass of first mode (normalized to one at the top of the building) and (M+ρAL) the total mass of system.

In the introductory paragraph it was underlined how the optimal design of a TLCD device has to follow two important steps. The first step concerns the choice of head-loss coefficient δ. Previous works have been done with the aim of calculating optimum parameters for TLCDs, using perturbation techniques, numerically through sinusoidal excitations (Gao *et al.* 1999) or by means of closed-form solutions that minimize the variance of the structural displacement (Yalla *et al.* 2000, Yalla *et al.* 2001).

Using the formulation reported in Eq. (7), it is possible to evaluate, as a first approximation, the efficacy of the system in terms of increasing of structural damping due to the TLCD device. This formula does not concern the identification of the optimal TLCD parameters but it is useful in giving preliminary indications about the effects of the different TLCD properties on the equivalent damping factor. From Eq. (7), it can be noted that the device efficacy depends on the ratio between the weight of the volume of fluid present only in the horizontal container over the mass of the structure, multiplied by the frequency response function (FRF) between the relative motion of the fluid and the motion of the structure.

The system is effective in a range of frequencies around the frequency in which the ratio X_{rel}/X has a maximum and the dissipating force is in quadrature (φ=π/2): Fig. 3 shows how increasing the module of this FRF (as an example decreasing the coefficient δ) produce a narrower range, while decreasing the modulus of the FRF (increasing the coefficient δ) and, hence, the equivalent damping parameter h_{eq}, produce a wider frequency range. It is a good rule in designing dynamic absorbers to set the module of the transfer function at a value that represents a good compromise between additional damping on one hand, and amplitude of the frequency band in which the system is effective on the other.

The second analysis concern the effects due to the nonlinear behavior of the TLCD. As an example, Fig. 4 shows, for different values of the input applied to the vibrating system, on the top the modulus of the FRF between x and the external input, on the bottom the modulus of the frequency response between the force F_T and the displacement x numerically calculated Eq. (1).

It is so possible to notice how, as the external input force increases, the response of the system also increases while the force transmitted by the TLCD to the vibrating system is less effective. This aspect assumes particular relevance if a civil structure subject to wind forces is considered: in the presence of increasing wind loads the behavior of the TLCD, which reduces its efficacy, could lead to increasingly large and less damped oscillations, with undesired effects on comfort and safety.

The behavior here described reveals the necessity to simulate realistic transitory force conditions, in which the motion of the device effectively reproduces the motion of the top of the tower subjected to the action of the wind, in order to consider the nonlinear effects associated to the TLCD model. For this reason an HiL test procedure was set up, in which the prototype of the TLCD device is subjected to realistic imposed motion, calculated using a numerical model that simulates the response of the structure to the wind loads measured in wind tunnel (Rosa *et al.* 2009, Rosa *et al.* 2012). In order to correctly evaluate the combined effects of TLCD device and building motion, in the HiL test procedure the numerical model is represented by means of a modal approach which accounts for the first six vibration modes. In fact, in general, the applied TLCD force has effect on all the modes (virtual work not zero), and not only on the 1st damped mode.

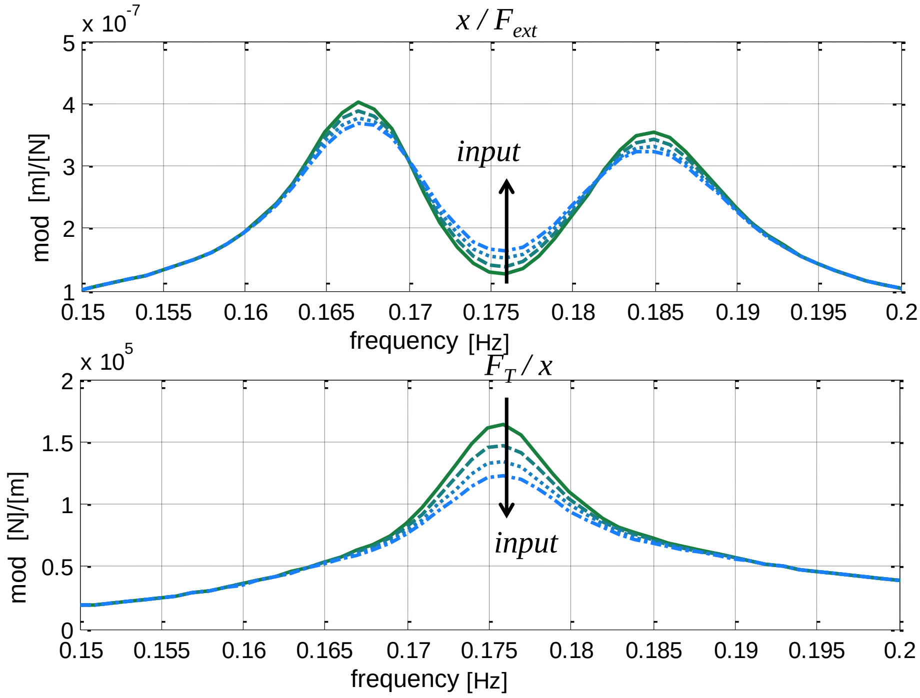


Fig. 4 Frequency response function between the displacement x of the vibrating system and the external input force (top) and frequency response between the transmitted force F_T and the displacement x for different values of the external force (bottom)

3. Experimental test bench for a scale model of the TLCD

As mentioned in section 2, from a theoretical point of view, it could be possible to design a TLCD device on the basis of the formulation reported in Eq. (7). However, in order to verify the nonlinear numerical model, its approximations and experimentally estimate the correlation between the head-loss coefficient δ and the geometry of the orifice, a test bench for a scale model of TLCD system has been set up. To make the considered configuration as general as possible and in order to provide an experimental head-loss characteristic formula for square section TLCDs, a modular device has been designed using a series of square section modules of side L_q. In each module, a square orifice of side l has been introduced.

Fig. 6 shows a sketch and a photograph of the used test bench. The bench has a base, on which the TLCD rests, fixed by cables to a supporting structure. This fixing system allows movement along the x direction where the motion is imposed by means of an hydraulic actuator. An LVDT transducer integrated in the actuator control measures the imposed motion x of the base while a load cell positioned between the cylinder and the base measures the force F_{ext} transmitted from the cylinder to the system (which is different from F_T due to the inertial and damping forces which arise on the base). The relative displacement of the fluid x_{rel} is measured by a capacitive depth gauge. As will be better specified in the next section, the force transmitted from TLCD to the base F_T (Eq. (3)) is then obtained from this displacement measurement.

Because, as specified in the introductory paragraph, this damping device was studied for a real application, it was decided to build it as large as possible in order to easily measure even the damping effect associated to the specific geometry of the duct; for this reason, a scale factor λ=1:5 with respect to the full scale was used. With this scale factor and the consequent Froude relation, the scaled-TLCD is characterized by the following frequency

$$\omega_{TLCD}^{(\lambda=1:5)} = \sqrt{\frac{2g}{\lambda L}} = \frac{1}{\sqrt{\lambda}}\omega_{TLCD}^{(full-scale)} = \frac{1}{\sqrt{1/5}}\omega_{TLCD}^{(full-scale)} \tag{8}$$

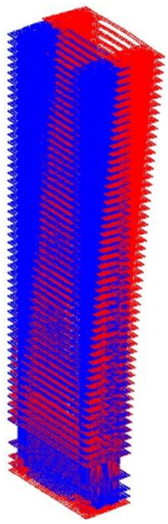
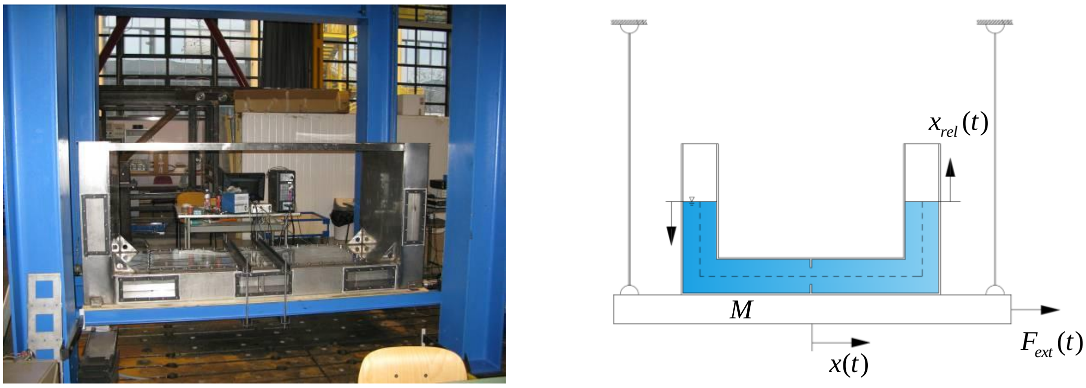


Fig. 5 First natural frequency of the tower: f_1=0.177 Hz

Starting from this parameter, the design of the TLCD, concerning parameters L, A, h_0, B (see Fig. 1), is quite simple. Given the first frequency of the tower (Fig. 5), verified as the most critical one according to wind actions, the L parameter is determined by Eqs. (2) and (8). Because of design constraints also the maximum mass of the whole TLCD system to be installed on the top of the tower is defined and, as a consequence, the total area of the section of the duct A is determined, since L is already fixed.

The parameter h_0 is chosen in order to guarantee the maximum oscillation of the fluid without the vertical duct being emptied during the water motion and, as a result, the horizontal length of duct B is limited. As a first approximation, in order to calculate the maximum water motion amplitude (and so h_0) the maximum top of the tower displacement (according to wind loads) can be used. The resulting TLCD parameters according to this example are summarized in Table II. The loss of load is produced through a reduction of section, defined by the ratio between the side of the square orifice l and the side of the square section L_q.

One of the main purposes of the experimental tests was to verify the model of the TLCD (see Eq. (1)) and identify the coefficient δ associated with the loss of load introduced by different orifices (with different closure ratios).



(a) (b)

Fig. 6 A picture of the test bench with one of the TLCDs tested resting on suspended frame (a) and a sketch of the test bench (b)

Table 2 Characteristics of the TLCD

Symbol	Value	Unit
f(scaled-TLCD)	0.395	Hz
L	3.1	m
B	2.3	m
h_0	0.4	m
A	0.16	m^2
L_q	0.2	m

To this end, tests were carried out using different amplitude and frequency of imposed motion (x), varying the level of the fluid in the TLCD and the ratio l/L_q of the orifice. As an example, Fig. 7 shows the relation between the amplitude of oscillation of the water X_{rel} and the amplitude of the base motion X as a function of the frequency (l/L_q=0.60, h_0=450 mm and X=10 mm); in the same figure the curve obtained with the numerical model described in paragraph 2 is shown. Minimizing the error between the experimental and numerical data at all frequencies, the value of the damping parameter δ that guarantees the best fit can be obtained. It can also be seen that the peak of the function in correspondence with the frequency of 0.39 Hz is clearly shown by the numerical model and the correspondence described is also visible in the slope of the phase of the FRF, which indicates that the estimate of damping too can be held to be fully satisfactory.

Collecting the results of all these kind of tests, Fig. 8 shows the damping parameter δ as a function of the l/L_q ratio of the orifice introduced in the TLCD for all the different tested amplitudes of the relative motion X_{rel}. The complete results of these experimental tests, for different TLCD systems, are described in Diana *et al.* (2012).

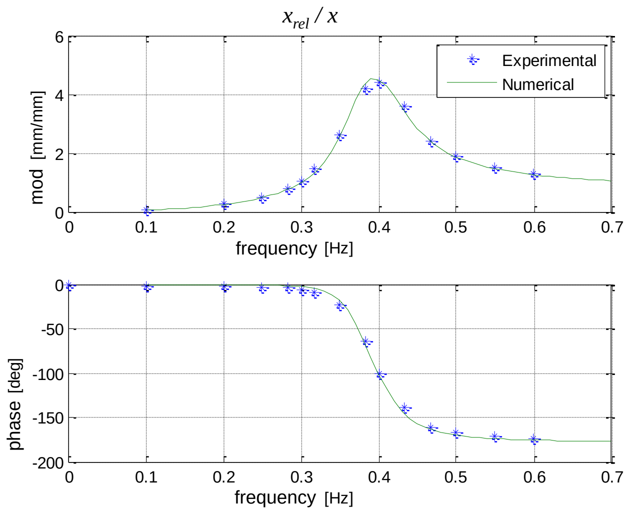


Fig. 7 Experimental and numerical module and phase values of the transfer function between the movement of water and of the plate; experiment conducted with l/L_q =0.6 , h_0 =450 mm, X=10 mm

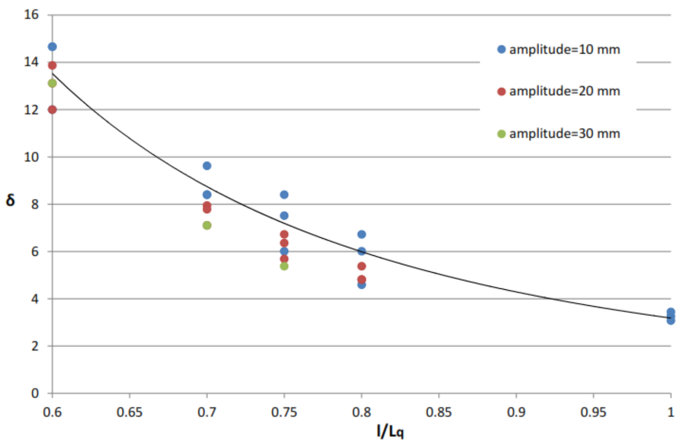


Fig. 8 Experimentally obtained damping parameter at various amplitudes of motion imposed (x) as a function of the characteristic ratio l/L_q (square section)

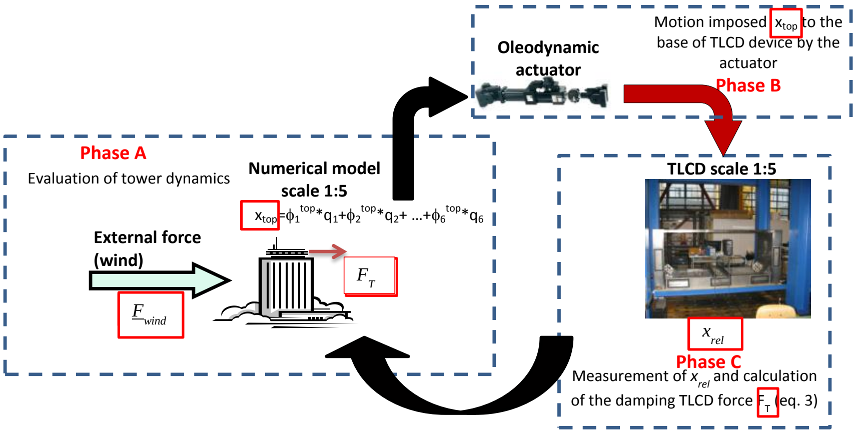


Fig. 9 Working diagram of the Hardware in the Loop test: inputs and outputs of different phases are highlighted by red rectangles.

4. Hardware in the loop test

In the HiL bench, the building dynamics are reproduced using a numerical model based on a modal approach (software component) while the experimental part is represented by the scaled 1:5 TLCD model (hardware component). The physical connection between the building (numerical model) and the absorber (physical model) is made by a hydraulic actuator that, on the basis of structure dynamics and of the dissipative force generated by the TLCD, defines the interactions, thus creating a HiL system.

The numerical model, within this loop, receives the same inputs and supplies the same outputs as the real system it represents. The input and output of the model constitute the interface between the numerical model and the physical component to be tested (in this case, the TLCD). Fig. 9 shows the logical structure of the HiL procedure for this application. The way it works can be summed up in the following steps:

- phase A: starting from the forces due to the wind F_{wind} (input 1, calculated from pressure measurements taken in wind tunnel tests, Rosa *et al.* 2009, Rosa *et al.* 2012) and from the damping force due to the TLCD action F_T (input 2, measured from the physical model of TLCD, see phase 3), the numerical model (modal approach) is used to calculate the tower dynamics. In particular, the output of phase A is represented by the displacement of the top of the tower x_{top} in correspondence with the point where the TLCD is connected. The dynamic model of the tower is implemented in a real-time board.
- phase B: for every time-step, the movement of the top of the tower x_{top} is imposed on the base of the TLCD prototype by the controlled hydraulic actuator. The force measured by the inline load cell of the actuator, needed to generate the imposed motion on the base of the TLCD, depends on the inertial and damping properties of the test rig but it is an internal force and it does not influence the final results.
- phase C: the motion of the fluid inside the TLCD x_{rel} is measured with a depth gauge, and thanks to this, the force exchanged between the TLCD and the tower (F_T) is calculated by Eq. (3) and passed to the model of the tower.

By applying this procedure, the dynamics of the TLCD is directly influenced by the simulated motion of the top of the tower which, in its turn, is conditioned by the action of the TLCD.

With relation to phase A, the modal model used to calculate the dynamic response of the tower, is described by 6 uncoupled differential equations in the modal variables q_i. If the first six vibration modes are considered

$$m_i\ddot{q}_i + c_i\dot{q}_i + k_i q_i = Q_{i,wind}(t) + Q_{i,TLCD} \qquad i = 1:6 \tag{9}$$

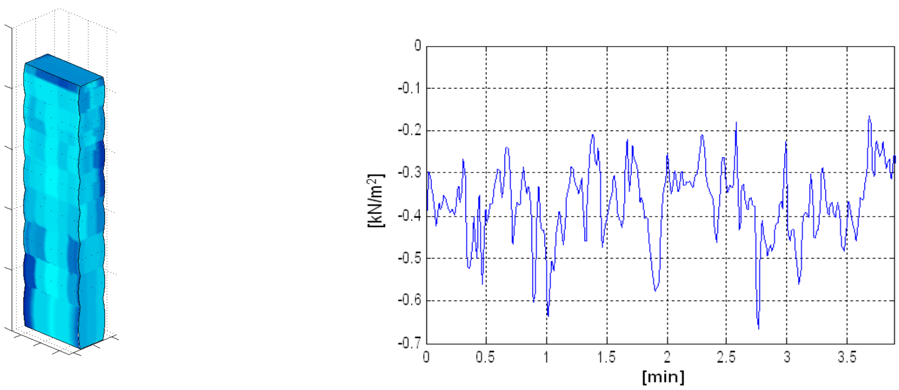
where m_i , c_i e k_i indicate the mass, damping and modal stiffness, while $Q_{i,wind}(t)$ and $Q_{i,TLCD}(t)$ indicate the Lagrangian components on the i-th mode of the force due to the wind F_{wind} and to the TLCD F_T.

To calculate the Lagrangian component of the forces due to the wind, the measurements of pressure recorded during wind tunnel tests (on a 1:100 scale model of the tower) have been used. Fig. 10 shows, as an example, on the left, the position of the "pressure taps" (pressure measurement points) of the building model and, on the right, the time history of the pressure measured in correspondence with one of these points; according to the model scale this measurement has been transformed in a full-scale pressure time history. When the pressure is known in a sufficient number of points, it is possible to evaluate the overall force of the wind acting on the tower F_{wind} by calculating, for every M-th tap, the corresponding contributing area $\vec{\chi}_M$ (Rosa *et al.* 2009, Rosa *et al.* 2012)

$$F_{wind} = \sum_{M=1}^{N_{TAPS}} \left(\tilde{p}_M(t) * \vec{\chi}_M\right) \tag{10}$$

where $\tilde{p}_M(t)$ represents the time history of the pressure measured in correspondence with the *M*-th tap. The virtual work done by the aerodynamic force relating to the *M*-th tap is then calculated as (Rosa *et al.* 2009, 2012)

$$\delta L_{wind} = \sum_{M=1}^{N_{TAPS}} \left(\tilde{p}_M(t) * \vec{\chi}_M\right) \times \delta\vec{s}_M \tag{11}$$



(a) (b)

Fig. 10 Position of the taps on the 1:100 scale model of the tower (a) and time-history and (b) of the pressure measured in correspondence with a tap (full-scale)

By applying the modal approach, the virtual displacement of the M-th tap is written as a linear combination of the vibrating modes

$$\delta s_M = \sum_{i=1}^{N_{modes}} \phi_{i,x}^M \times \delta q_i \vec{i} + \sum_{i=1}^{N_{modes}} \phi_{i,y}^M \times \delta q_i \vec{j} + \sum_{i=1}^{N_{modes}} \phi_{i,z}^M \times \delta q_i \vec{k} \tag{12}$$

where $\phi_{i,x}^M, \phi_{i,y}^M, \phi_{i,z}^M$ represent the projections along the two longitudinal directions and the vertical one of the *i*-th vibrating mode in correspondence with the *M*-th pressure tap. Considering the first six vibrating modes, the Lagrangian component of the forces of the wind for the *i*-th mode is thus calculated as in Eq. (13) where the single contribution along the *j*-th direction is calculated as in Eq. (14), and χ_M^j indicates the contributing area corresponding to the *M*-th tap projected in direction *j*.

$$Q_{i,wind}(t) = Q_{i,wind}^x(t) + Q_{i,wind}^y(t) + Q_{i,wind}^z(t) \qquad i = 1:6 \tag{13}$$

$$Q_{i,wind}^j(t) = \sum_{M=1}^{N_{TAPS}} \left(\tilde{p}_M(t) \bullet \chi_M^j \bullet \phi_{i,j}^M \right) \qquad j = x, y, z \tag{14}$$

The Lagrangian component of the force transmitted by the TLCD (F_T), which is considered to be applied in direction *x* in correspondence with the top of the tower, writing the virtual displacement of the top of the tower as in Eq. (16), where $\phi_{i,x}^{top}$ indicates the i-th vibrating mode calculated in correspondence with the top in direction *x*.

$$Q_{i,TLCD}(t) = F_T(t) \cdot \phi_{i,x}^{top} \qquad i = 1:6 \tag{15}$$

$$\delta x_{top} = \sum_{i=1}^{N_{modes}} \phi_{i,x}^{top} \quad \delta q_i \tag{16}$$

In phase *B*, the actuator, through displacement control, imposes the movement x_{top} on the base of the TLCD, so, in this phase, the imposed movement x_{top} applied by the actuator is not an external input applied to the system (as in paragraph 3) but the result of the calculation of the response of the building to incident wind and the damping action of the TLCD. Finally, in phase *C*, the force transmitted by the TLCD F_T is calculated by measuring the displacement of fluid x_{rel}.

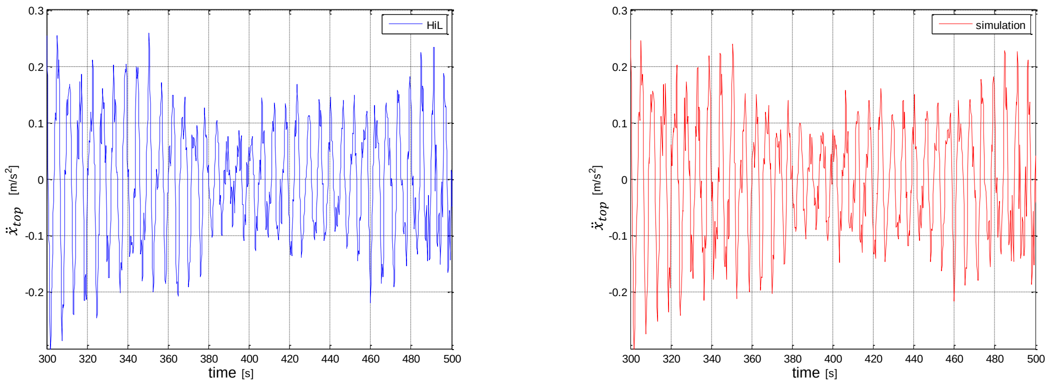
4.1 The complete numerical model

To validate the numerical model of the TLCD also in real transient conditions, where non-linear effects are more evident, the results of the HiL test were compared with those obtained through a numerical model in which, according to the HiL model, the physical scaled-TLCD was substituted by its numerical model. Assembling the modal model of the tower (a system of six uncouple differential equations) and the non-linear differential equation that describes the motion of the fluid inside the TLCD device, the system reported in Eq. (17) is obtained, where the acceleration of the top of the building, as it was for the displacement x_{top} (Eq. (16)), is written as a linear combination of the modal coordinates q_i.

$$\begin{cases} m_i\ddot{q}_i + c_i\dot{q}_i + k_i q_i = Q_{i,wind}(t) + Q_{i,TLCD} & i = 1:6 \\ \rho AL\ddot{x}_{rel} + \frac{1}{2}\rho A\delta|\dot{x}_{rel}|\dot{x}_{rel} + 2\rho Ag\, x_{rel} = -\rho AB\ddot{x}_{top} = \sum_{i=1}^{N_{modes}} -\rho AB\phi_{i,x}^{top}\ddot{q}_i & \end{cases} \tag{17}$$

4.2 Results

On the following the results obtained with the HiL test and with the complete numerical model are reported in terms of motion of the tower subjected to the damping action of the TLCD and to a wind time-history characterized by a return time of 10 years (average speed at a height of 100 m, V=31m/s, Rosa *et al.* 2009). The TLCD was considered to have the geometrical characteristics described in section 3, synchronized to the frequency of the scaled tower (h_0 =0.55 m), using a closing ratio for the orifice l/L_q =0.6. Fig. 11 shows that the two time histories (HiL versus complete numerical model) are very similar: this means that the numerical model is able to correctly reproduce the behavior of the tower even under transitory forces associated to the incident wind. So this numerical model could be used to verify the efficiency of TLCD devices, for any possible orifice geometry, in real working conditions, finding the optimum solution for the specific application.

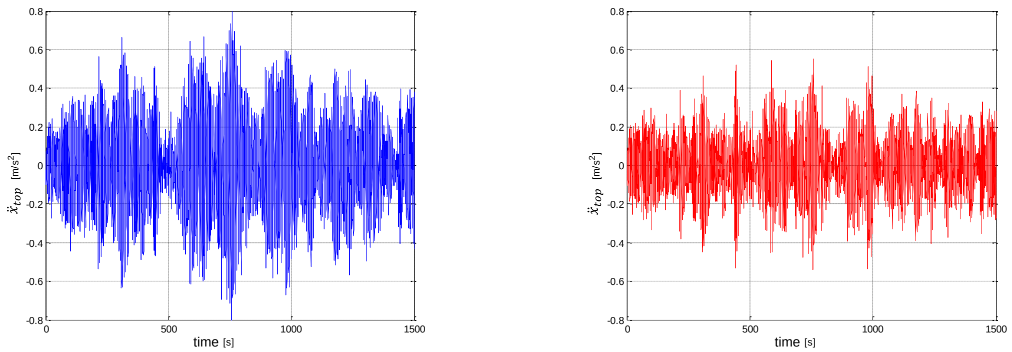


(a) (b)

Fig. 11 Acceleration of the top of the tower taken to full scale with HiL test (a) and calculated in the presence of a TLCD with the complete numerical model (b) Average wind speed V=31 m/s.

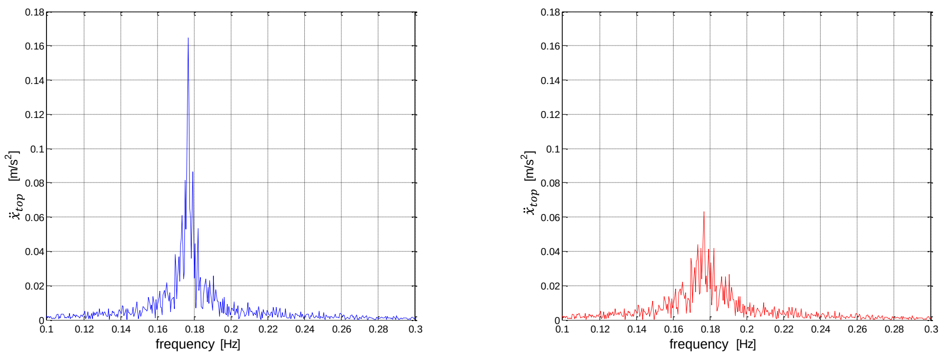
For a wind characterized by a return time of 100 years the building dynamic was simulated with the complete model. Fig. 12 shows a comparison between the acceleration of the top of the tower considering the TLCD device (b) and without it (a). It can be seen that the presence of the damping device helps the reduction of the amplitude of motion during the simulation.

Fig. 13 highlight the effect of the TLCD on the dynamics of the system showing the spectrum of the acceleration of the top of the tower; it is thus possible to see how the response of the system is considerably reduced around the frequency on which the TLCD was set, while there is no substantial effect on the remaining range of frequencies.



(a) (b)

Fig. 12 Comparison of the full-scale acceleration of the top of the tower without TLCD (a) and with TLCD (b) Average wind speed *V*=38 m/s



(a) (b)

Fig. 13 Comparison of the spectrum of the full-scale acceleration of the top of the tower without TLCD (a) and with *TLCD* (b)

5. Conclusions

This article has described a methodology for optimizing a *TLCD* liquid based damping device. In the first part of the work, starting from energy considerations, a dimensionless damping parameter (h_{eq}), that represents the equivalent damping introduced by the *TLCD* on the vibrating system, has been derived. This formulation allows a preliminary analysis of the system and underlines the most significant parameters in the definition of the damping effect of the *TLCD* device.

In the second part, an experimental test bench for a 1:5 scale *TLCD* model has been set up. By means of the bench, the following objectives have been reached:

- the nonlinear numerical model presented in the paper has been validated and the coefficient δ associated with the loss of load introduced by the orifice has been experimentally identified for a square section, with different $1/L_q$ ratios;

- an HiL procedure has been set up in order to reproduce the nonlinear effects associated to the TLCD model when a realistic time-history of the wind force is applied on the building. With respect to previous studies, where the effectiveness of the *TLCD* was evaluated for general cases, this procedure permits direct verification of the possibility of potential instability conditions on a specific tower, subjected to real wind actions (thanks to the pressures measured by means of wind tunnel tests on scale models) and equipped with the designed *TLCD*.

The HiL test is based on a modal model of the tower, able to simulate the response of the building subjected to realistic wind loads, using pressure measurements carried out during wind tunnel tests on a scale model. The HiL tests also validate a complete model simulating the movement of the tower when subjected to the simultaneous action of the wind and the damping system, accounting its nonlinear effects. This complete numerical model constitutes the effective tool, in the design stage, to evaluate displacements and accelerations of a building equipped by the TLCD damper and subjected to real wind conditions.

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