Assessment of the performance of tuned liquid dampers for vibration mitigation in structures

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SUMMARY:
The inclusion of passive energy dissipation devices is seen as a cost effective way to improve protection against seismic loads. In recent years, devices, such as Tuned Liquid Dampers (TLD), have received increasing attention as a simple but effective way of reducing building response to dynamic loads. The paper describes an experimental study and includes the results obtained from tests performed on TLDs installed in a SDF structural system with varying frequencies. The system was designed and constructed to work in a range of frequencies between 0,6 to 1,4 Hz, achieved by means of a set of air-cushions with different stiffness, depending on the initial pressure and on the deformation during the tests. The main results and conclusions obtained from the tests performed on TLDs with varying geometries as well as from the tests performed on the SDF + TLD system are presented.

Keywords: Tuned Liquid Dampers, Passive devices, Energy dissipation, Vibration mitigation, Shaking table tests

1. INTRODUCTION

Recently, passive devices, such as tuned liquid dampers (TLDs) have drawn special attention, because they are a simple and effective way of reducing structural response in buildings, bridges and other structures to dynamic loads, such as wind and earthquakes [Yalla, 2001]. TLDs are just tanks with a liquid inside (normally water); both their geometry and the water height define the natural sloshing frequency. When coupled to structures, their fundamental sloshing frequency is adjusted to the fundamental frequency of the structure, so that, for a given seismic load, the structure response to that frequency is reduced, due to the coupling of the water sloshing.

Additionally, they also present an ideal optimal cost-effectiveness, are easy to install and their sloshing frequency can be easily changed by varying the water height. Other properties can also be altered to improve their performance, such as: i) using another liquid different from water with different density and viscosity, ii) inclusion of networks or vertical grids iii) varying the roughness of the device walls, etc. ...When in service, TLDs present good performance in tall buildings and low-frequency flexible structures, such as bridges and towers.

The design and implementation of TLDs, as well as other passive energy dissipation devices, require experimental tests (full scale or reduced scale) for validation of their main features. The main objectives of the set of tests developed were: i) understand in more detail, the operation of TLDs, in order to allow the use of mathematical and mechanical models in the simulation of linear and nonlinear phenomena occurring inside them. The performance of the devices in the presence of large amplitude excitations is an important point of this work, ii) Define how the change of some parameters associated with each TLD tested; such as the fluid height at rest, the geometry of the device, the presence of suspended particles, the damping level; or with the load itself, such as the type of action, its intensity, frequency and duration; can influence their performance and iii) Determine the efficiency associated with the introduction of TLDs in structural systems of well-defined frequency.

2. EXPERIMENTAL TESTS ON THE REFERENCE STRUCTURE

2.1. Testing device

The testing device used to assess the interaction between the TLDs and the transmission structure included the use of the LNEC uniaxial seismic platform, to which different horizontal loads generated artificially were imposed [Falcão Silva, 2010]. Fig. 2.1. shows a schematic representation of the testing device [Oliveira e Morais, 2006].

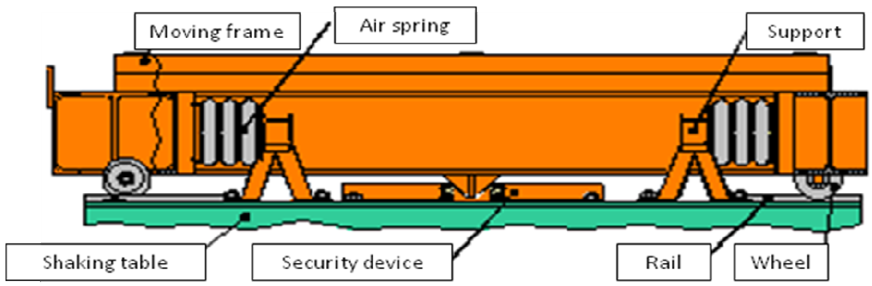

Figure 2.1. Testing device: SDF transmission structure

In addition to a displacement sensor and an accelerometer placed on the uniaxial seismic platform, in order to record its movements, the SDF transmission structure was instrumented with two pressure transducers, to continuously monitor the internal pressure in the two set of springs, three displacement transducers (LVDT), to record the relative motion of the transmission structure and two accelerometers (PCB), to measure its acceleration. Fig. 2.2. presents the plan of the instrumentation used in the tests to characterize the dynamics of the transmission structure.

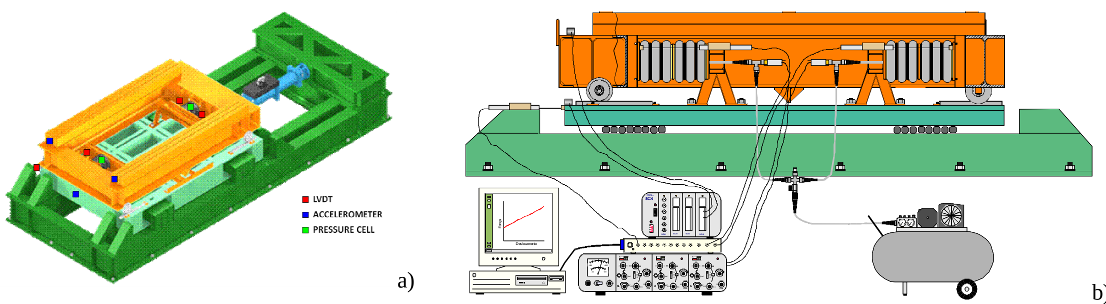

Figure 2.2. Instrumentation placed in the transmission structure: a) Perspective of the testing device and b) detail with connection to acquisition system and pneumatic circuit

2.2. Preliminary tests

Each air spring used as an elastic element in the transmission structure was subject to quasi-static tests, in order to validate the theoretical models proposed by the manufacturer, and define mathematical models enabling to relate the force, as a function of pressure in the springs and their deformation.
Based on the results obtained, it was possible to tune a mathematical model for the operation of the air springs and obtain empirical relationships, relating the force in the spring, F, with the spring deformation, d, on the basis of well-defined initial pressures imposed to the springs.

It was considered that the initial pressure in the springs can vary between 1.5 and 7 bar and that in the SDF transmission system tested with and without TLDs, three configurations can be considered: i) Two parallel sets of two springs in series (CASE 1), ii) Two springs in parallel (CASE 2) and iii) Two parallel sets of two springs in parallel (CASE 3). The configurations presented in CASES 2 and 3 enabled to obtain values of stiffness and therefore frequencies higher than those intended for the experimental program, as representative of structural systems in the existing Portuguese housing park. Thus, CASE 1 emerged as the simplest and more economical way to meet stiffness and frequency requirements (Fig. 2.3.).

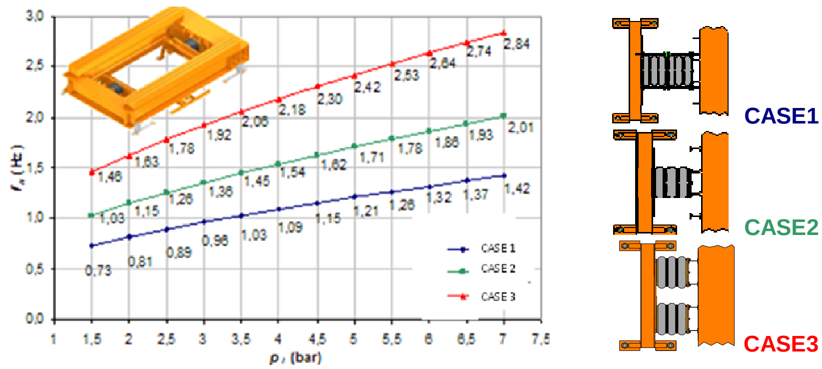

Figure 2.3. Frequencies for different air spring configurations, adapted from [Morais et. al., 2010]

Taking into account the values obtained, an extensive program of experimental tests was outlined, in order to actually identify the dynamic characteristics of the SDF transmission structure considered, for subsequent use in tests with TLDs included.

2.3. Analysis of experimental results obtained

The SDF transmission structure was mounted with the air-springs placed in accordance with the provisions of CASE 1, with varying pressures between 1.5 bar and 4.5 bar, and subject to random tests corresponding to 20 white noise series, artificially generated using the LNEC-SPA software [Mendes e Costa, 2007], in order to identify its dynamic characteristics. Based on the instrumentation defined in the testing device, records of displacements, accelerations and spring pressure for each type of test performed were obtained. The results of random white noise tests were analyzed by means of the Modal Analysis - FRF Estimations module and adjusted based on concepts of signal analysis. Frequency response functions (FRF), damping in the structure and coherence between input and output signals, for all initial pressures in the springs tested, were determined in the scope of an experimental study [Falcão Silva, 2010]. As for white noise tests, it is important to note that the results obtained correspond to an average of the 20 series tested and that the frequency response functions refer to relations between input signals in accelerations (acceleration of the shaking table) and output signals also in accelerations (acceleration in the SDF transmission structure).The schematic representations of the frequency and damping variation trends with the initial pressure in the air springs for white noise tests are shown in Fig. 2.4. and Fig. 2.5., respectively.

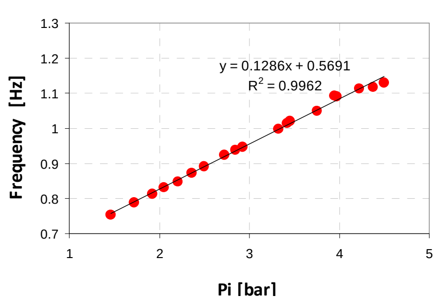

Figure 2.4. SDF system frequency variation

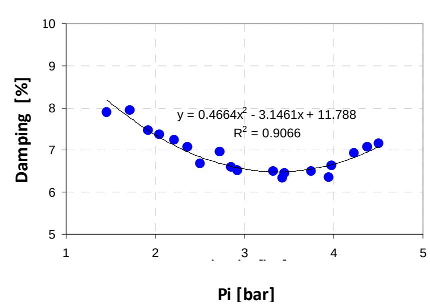

Figure 2.5. SDF system damping variation

The SDF transmission structure presents a clearly linear frequency evolution and a clearly nonlinear damping evolution (second degree) with the variation of the initial pressure. The nonlinearity of damping can be justified by eventual phenomena occurring in the springs and which are not adequately identified in the specifications of the elements.

3. EXPERIMENTAL TESTS ON TUNED LIQUID DAMPERS (TLD)

The experimental program held at NESDE - LNEC, enabled the characterization of the dynamic behaviour of water tanks with specific TLDs characteristics. These individual TLDs, with geometry identical to those that compose the TLDs sets which were subsequently tested coupled to the SDF transmission structure, were designed and constructed based on the following requirements: i) Adjustment to the fundamental vibration frequency and to the mass of the SDF transmission structure, as verified that the devices are more effective as more the frequency vibration approaches the fundamental frequency of the structure in which they are included, and also the more the relationship between the water mass inside the set of TLDs devices and the mass of the transmission structure is kept between 1 to 5% [Gardarsson, 1996] [Yu, 1991]; ii) Geometrical limitations of the structural system built for installation of multi TLDs set; iii) Easiness to conduct the TLD tests in both main operation directions, thus allowing to cover a wider range of frequencies and iv) Selection of a non opaque material, to allow the visualization of the wave(s) formed within the devices during the experimental testing program.

3.1. Testing device

To carry out the tests to characterize the dynamic behaviour of rectangular TLDs an uniaxial seismic platform was used. In fact, to better understand the behavior and dynamic characteristics of TLDs when not included in structures, it was necessary to carry out tests in which these devices operated by themselves, reason why the assemblage of devices and accessories was carried out according to what is shown in a the scheme on Fig. 3.1. and Fig. 3.2 [Falcão Silva, 2010].

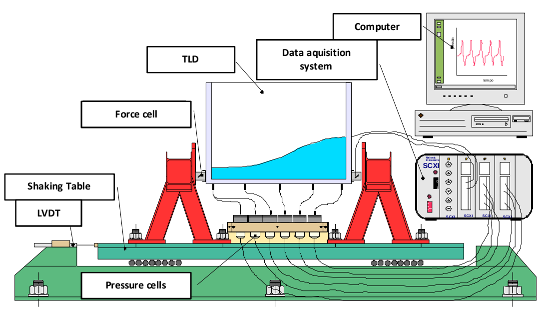

Figure 3.1. Testing device

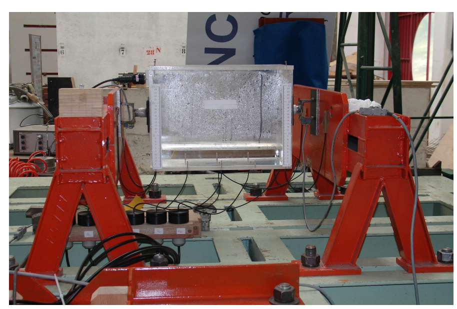

Figure 3.2. Assemblage in-situ of the testing device

With the testing device defined, it was possible to register not only the movements transmitted to the devices, but also the forces associated with linear and nonlinear phenomena that occur inside the fluid in motion during imposed dynamic loads, as well as the elevation of the fluid surface. The variables measured during the tests were the relative displacement on the seismic platform, the height of the water column at different points and the force transmitted to the side walls of the tank. For that purpose, it was used: i) a displacement LVDT sensor (Linear Variable Differential Transformer); ii) 6 KELLER 46R pressure sensors and iii) two force transducers, using technology developed in CIC-NSM [Morais et. al., 2010].

It was decided to test TLDs, when isolated, subject to random white noise excitations, in order to complement the research investigation works previously developed [Sun, 1991] [Yu, 1991] [Gardarsson, 1996] [Yalla, 2001]. For that purpose, were used 20 white noise series with a frequency content between 0.5 Hz and 1.5 Hz, artificially generated using software LNEC-SPA and previously used in the dynamic characterization of the SDF transmission structure. The reason for choosing the indicated frequency range is because it is representative and compatible with real existing structures, for example, in the Portuguese housing park, in which were intended to be applied. Thus, the referred series were imposed on TLDs as horizontal translation excitation with different peak amplitude values, ranging from low to high values. These tests enabled, among other things, to obtain the experimental vibration frequencies as well as damping values for each situation tested, for comparison either with the corresponding theoretical values [Yalla, 2001] [Yu, 1991] and with the values obtained from the numerical simulations developed and proposed in a PhD thesis [Falcão Silva, 2010].

3.2. Analysis of experimental results obtained

In all tested cases, records of displacements, accelerations and water surface elevation were obtained. The natural vibration frequency associated with the sloshing phenomenon that occurs on a fluid in motion inside TLDs is similar to what happens in ordinary tanks, conditioned by their geometry and fluid height at rest.

During the experimental program carried out, the study focused on rectangular TLDs with a certain well-defined water height at rest and compatible with the frequencies to be adjusted. FRF obtained for each situation tested during the experimental program allowed the identification of objective modal frequencies corresponding to each test developed, i.e. for different water heights at rest as well as for increasing excitation amplitudes. As an example, the average variation trends of the experimental frequency in function of the excitation amplitude for shallow and deep TLDs are shown below (Fig. 3.3. and Fig. 3.4.). The blue points reflect the results for all series tested and allow us to have a clearer perception of the variability of response for the different series tested. Average values appear in red.

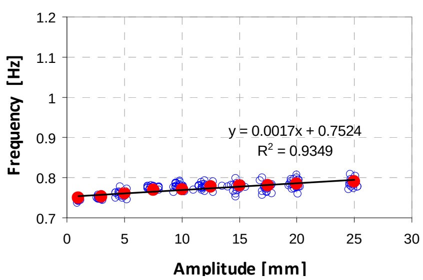

Figure 3.3. Frequency variation in shallow TLD

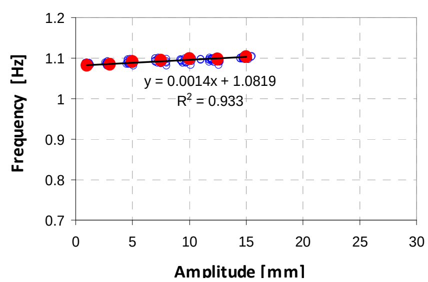

Figure 3.4. Frequency variation in deep TLD

The variation trend of the fundamental vibration frequency of TLDs is clearly linear with the peak value of excitation amplitude. The behaviour identified by visual observation of the waves formed within the device, also shows the emergence of other phenomena, responsible for the gap between the theoretical and experimental frequency values.

Based on the results obtained for the 20 series tested, it was possible to establish empirical relationships between the fundamental vibration frequency of the TLD and the peak amplitude of the load imposed. Based on these results, it was also verified that regarding the fundamental frequency of the fluid inside TLDs, besides the imposed load amplitude, A, there is a clear dependence on the water height at rest, h, and the length of device itself, L. Thus, when higher loads emerge, for example, during a particular seismic action, the phenomena that occur inside TLDs cease to be primarily linear, and therefore the existing formulation has a more restricted scope of application. However, in possession of experimental results, such as those presented in this study, it is possible to propose some adjustments on the models.

Damping was another parameter which showed a clear variation during the tests. The effect of fluid damping is significant at the resonance frequency and should be carefully considered when modelling the behaviour of TLDs, whatever their geometry. The modal damping associated with shallow sloshing waves, also called shallow water waves, is difficult to determine theoretically, especially when nonlinear breaking wave phenomena occur

As a summary of the results obtained, are presented below the graphical representations of the average variation trends of modal damping with the load amplitude (Fig. 3.5. and Fig. 3.6.). As for the fundamental vibration frequencies, points in blue reflect the results obtained for the different series tested and allow a clear perception of the response variance, for the different tests included in the experimental program. The red points represent the average values.

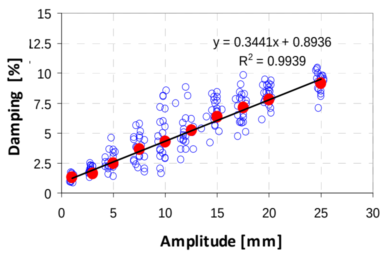

Figure 3.5. Damping variation in shallow TLD

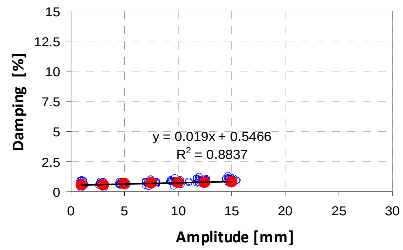

Figure 3.6. Damping variation in deep TLD

As can be seen, the values of damping coefficients estimated on the basis of the experimental results obtained for the different water heights at rest show a great variability. The experimental results obtained also led to the conclusion that the variation trend of damping is fairly linear, and that it increases with the peak value of the excitation amplitude. The behaviour of the wave formed inside the TLD during the tests, identified by visual observation, also shows the emergence of other phenomena, especially non-linear ones. In addition to what has been presented for frequency and damping, a more comprehensive analysis on TLD, when isolated, was developed [Falcão Silva, 2010]; and included: i) A more comprehensive analysis of linear and nonlinear phenomena arising inside TLDs, when subject to sinusoidal excitations of increasing amplitude; ii) Determination of the dynamic mass of the mobilized water; iii) Determination of the stiffness equivalent to the dynamic mass of the mobilized water; iv) Determination of the phase angle; v) Determination of the wave height and normalized wave height; vi) Determination of shear forces and normalized shear forces; vii) Determination of energy balance; viii) Identification of breaking wave nonlinear phenomena; ix) Identification of transverse waves and stationary waves.

4. EXPERIMENTAL TESTS ON THE REFERENCE STRUCTURE WITH TLDS INCLUDED

After completion of the first phase of the experimental tests, which focused on isolated rectangular TLD devices, that were, directly mounted on the seismic platform, the work stepped to the second phase, in which a set of these devices was tested, when included in structures with varying frequency.

The reason for placing a set of TLDs and not just one TLD unit is because it was necessary to reach a mass relation between 1 and 5%, so that vibration mitigation in a given well-defined frequency structure is optimized, without negative side effects introduced by a high amount of mass, for which the structure in question may not be dimensioned. During the study, mass percentages varying between 2% and 7%, slightly higher than the values mentioned above, were tested. The test results described and presented in this section allow us to obtain very valuable conclusions about the performance of such devices in representative structures of existing structures, regarding the reduction of the dynamic loads imposed.

4.1. Testing device

The transmission structure, with varying frequency, was tested under the action of the 20 artificially generated series [Mendes and Costa, 2007], but now with the 33 rectangular TLD placed on it (Fig. 4.1. and Fig. 4.2.). To facilitate the fixation of the tank sets to the oscillator, a wooden base was designed, equipped with four steel supports, one at each corner, which allowed the fixation of the set with two orientations, i.e. with the devices longitudinally or transversely aligned. The instrumentation used was the same as for the situation in which only the transmission structure (Fig. 2.2.) was tested.

In addition, one of the tanks was instrumented according to what has been presented in section 3 (Fig. 3.1. and Fig. 3.2.).

Figure 4.1. Set of rectangular TLDs placed on SDF reference structure

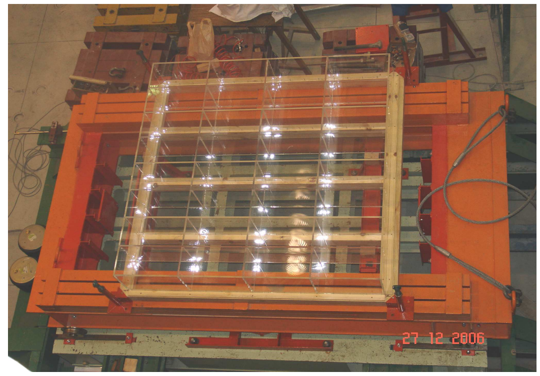

Figure 4.2. View from the top of the set of rectangular TLDs placed on SDF reference structure

4.2. Analysis of the experimental results obtained

In all tested cases, were obtained records of: i) Displacements and accelerations in the seismic platform; ii) Displacements and accelerations in the transmission structure; iii) Pressure in the two air springs responsible for the stiffness of the structural system, and therefore for the variation of the respective fundamental frequency and iv) Water surface elevation inside the devices.

In tests carried out, new FRF for the whole reference "structure + TLD" were obtained, considering different excitation amplitudes and water heights at rest inside the devices. In addition, for the same reference structure, what corresponds to a given initial pressure in air springs, were also tested several water heights at rest, corresponding to different frequencies around the fundamental vibration frequency of the structure, whose movements are intended to be mitigated, in order to evaluate the best relationship between frequencies of the structure and of the device and optimize its performance. Fig. 4.3. and Fig. 4.4. show some FRF obtained during the tests.

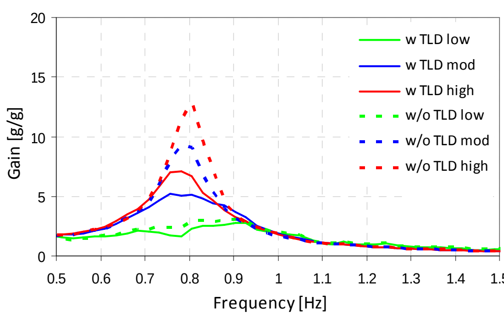

Figure 4.3. FRF for SDF structures with shallow TLDs

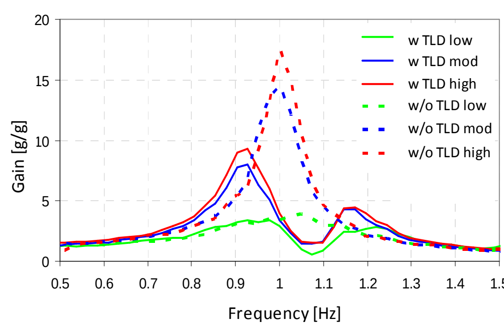

Figure 4.4. FRF for SDF structures with deep TLDs

As can be seen, when introducing TLD in a certain SDF structure and for any situation presented, two fundamental vibration modes can be identified: i) One associated with the main structure and ii) Another corresponding to the devices which were included in it, in order to mitigate vibrations resulting from dynamic loads imposed.

The separation of the two modes is more evident as the dynamic load amplitudes imposed are higher. There is a reduction of the system response in the fundamental frequency, while the new FRF peaks deviate from this value. It should be noted, for example, that reductions observed at the peak FRF values on the main systems with rectangular TLDs range between 50 to 80%, for low to high dynamic excitation amplitudes, what corresponds to a very considerable reduction.

Globally, RMS values are variables that seem to be more suitable for comparisons and even for determining the efficiency of the devices, once they take into account not only the peak values occasionally reached during a given occurrence, but also the whole time histories recorded.

It can also be concluded that, for these levels of dynamic load amplitudes, the response presents no major difference, when considering simple TLDs or with suspended particles. However, it appears that when the fluid height at rest increases, that is, when the TLDs turns from shallow to deep, the situations in which devices with polystyrene particles in suspension were introduced behave better.

5. PERFORMANCE OF TUNED LIQUID DAMPERS

Finally, and based on what has been presented during the analysis of results, it is possible to define the criteria of efficiency and performance that can be applied and generalized to this kind of devices. The proposed criteria allow evaluating the performance of TLDs, when included in different structural systems for different adjustment levels of operation frequency and mass ratios.

5.1. Experimental efficiency criteria

An extremely important point, to be taken into account when analyzing TLD performance, whatever their geometry, when included in structural systems, corresponds to the relationship between device and structure frequencies [Gardarsson, 1996] {Yalla, 2001] [Yu, 1991]. Thus, and according to previous work carried out, it is possible to define a coefficient γ corresponding to the so-called frequency adjustment coefficient, given by the expression:

$$\gamma = \frac{f_{TLD}}{f_{est}} \tag{5.1}$$

The situations in which this coefficient is equal to unity correspond, in theory, to ideally tuned situations. However, based on previous experimental results [Gardarsson, 1996] [Yalla, 2001] [Yu, 1991], it has been observed that, in fact, the higher efficiency does not exactly correspond to the value 1, but rather to a broader range between 0.9 and 1.1 and clearly dependent on the load amplitude. Besides what has been mentioned, it should not be forgotten that, for the performance analysis presented below, another very important parameter should be considered, corresponding to the relation between the fluid mass inside the device and the structure whose vibrations we intended to mitigate:

$$\mu = \frac{m_{TLD}}{m_{est}} \tag{5.2}$$

This coefficient has values defined as optimal between 1 and 5%. However, devices that express higher values of this coefficient may be used, as long as the structural safety of the structure is ensured. However, given the safety factors used in the design of structures, values up to about 10% of the mass of the main structure can be implemented, thus allowing to successfully reach considerable amounts of dynamic vibration mitigation.

Based on the experimental tests carried out, we defined efficiency criteria, taking into account for each case the γ and μ indexes previously indicated:

$$Ef\_\mathbf{X} = \frac{X_{est\_ref} - X_{est\_ref\_TLD}}{X_{est\_ref}} \tag{5.3}$$

where the variable X can be taken as peak value of displacement, as peak value of acceleration, as RMS value of displacement and as RMS value of acceleration.

In addition to these criteria directly obtained by comparing the records obtained from the instrumentation, a reference criterion related to the analysis of the obtained response functions in frequency can also be defined. The indexes obtained, when implementing the equation (5.3) for the considered variables, are expressed as a percentage.

5.2. Performance analysis based on experimental efficiency criteria

After completion of the equation (5.3) for each identified variable, were obtained various levels of efficiency [Falcão Silva, 2010]. As an example, are presented in this section (Fig. 5.1. and Fig. 5.2) the RMS displacement ratios obtained for shallow and deep TLDs. For shallow TLDs, it appears that, in general, efficiency increases with the increasing load amplitude imposed.

The relationship between the optimized frequencies for each situation was also identified. Thus, for reduced load amplitudes, except in some rare cases, the optimal relationship between frequencies is around 0.86-0.91, while maximum values obtained for the RMS_desl rate were about 14%. For moderate amplitudes, the maximum efficiency rate reaches 20% for a relationship between frequencies of 1.01. Considering high dynamic load amplitudes, an efficiency rate of 35% in RMS_displ is reached.

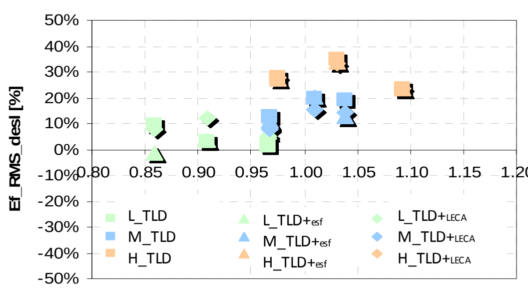

Figure 5.1. Efficiency rate of Ef_RMS_displ for shallow TLD

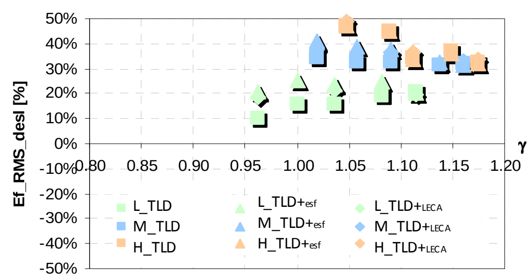

Figure 5.2. Efficiency rate of Ef_RMS_displ for r deep TLD

Overall, was observed an efficiency increase with the excitation amplitude for deep TLD. For low amplitudes, were achieved efficiency rates of about 25% for RMS values of displacements. With the increase of the dynamic load amplitude imposed, efficiency rates varying between 10 and 41% were obtained. In what concerns higher load amplitudes, the behaviour of deep TLD is undoubtedly very good with varying efficiency rates reaching 50%.

6. CONCLUSIONS

The extensive experimental program developed made it possible to obtain several conclusions enumerated below:

i. The experimental frequencies and damping were approximated with reduced errors by theoretical expressions, only for low excitation amplitudes, and as such only when linear phenomena (linear sloshing) were involved. The difference observed for amplitudes varying from low to high reaches almost 10%. The observed difference corresponds to the emergence of nonlinear phenomena (breaking waves), which with increasing excitation amplitudes begin to be evident and frequent;

ii. For the relationships between the masses of the SDF transmission structures and of the TLD devices tested, optimal frequencies were determined. The values obtained made it possible to confirm what has been proposed by previous works presented in the literature [Gardarsson, 1996] [Yalla, 2001] [Yu, 1991];

iii. TLDs are a very effective kind of passive device to mitigate dynamic loads. In certain cases regarding excitation amplitude and frequency adjustment, in the resonance frequency of the structure, whose action is intended to be mitigated, reductions in the peak values of the FRF reaching 80% can be observed;

iv. Very significant reductions of the RMS displacement values of the different SDF transmission structures tested we obtained, which, in some cases, reached up to 50%. This value shows that, in fact, using only water, a cheap and easily obtainable substance, it is nowadays possible to significantly reduce the effect of seismic actions on structures. An analysis of the performance and efficiency of the devices based on peak values appears to be more conservative, when compared with an analysis based on RMS values;

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