EXPERIMENTAL STUDIES ON THE CHARACTERISTICS OF TUNED LIQUID DAMPERS FOR REDUCING VIBRATION IN STRUCTURES

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ABSTRACT :

Traditional design approaches usually consider seismic actions as equivalent static actions. Recent research has shown that adopting a dynamic approach where the real characteristics of seismic actions are taken into account may lead to reach significant behavior improvements.
The inclusion of energy dissipation passive devices is nowadays seen as an effective way of improving structures protection towards seismic actions. A significant number of this kind of devices is already placed in real structures all over the world.
Vibration mitigation of the seismic actions imposed to the structures is being more and more taken into account in structures design. In order to get more effective systems, structure's designers are using more and more passive devices. Systems like Tuned Liquid Dampers (TLDs) have drawn some attention to the scientific and designing community as an effective, easy to implement and economic solution for vibration mitigation.
In order to validate TLDs properties a 3.7 ton one degree of freedom transmission system with adjustable dynamic characteristics has been developed to simulate structures natural frequencies between 0.7 and 2 Hz. The variation of frequency in the referred range is achieved by means of a system of air-springs placed in the transmission system.
The present paper reports the results of experimental tests made on the air springs in order to characterize them as well as develop a model which rules its mechanical behaviour and that will be very useful for the definition of the characteristics of the transmission system and its response to dynamic actions.
Furthermore dynamic tests performed over TLDs to characterize its behaviour and validate theoretical models are described and the corresponding preliminary results presented. This work aims at preparing the testing device to perform parametric studies in order to evaluate the dynamic characteristic of the transmission system with and without TLDs included and its performance for each situation.
This paper also describes the equipment and instrumentation used during the experimental programme performed..

KEYWORDS: Passive Energy Dissipation Devices, Tuned Liquid Dampers, Vibration Mitigation, Dynamic tests, air-springs

1. INTRODUCTION

Recently, passive devices like Tuned Liquid Dampers (TLDs) have drawn special attention as they are a simple and effective way of reducing structures response (buildings and bridges) towards dynamic actions (wind and earthquakes). TLDs are just tanks with a fluid inside (usually water), in a way that its geometry and water height define the natural frequency of sloshing. When added to structures their sloshing frequency is adjusted to the structure's fundamental frequency, so that during an earthquake the structure response to that frequency is reduced due to the dissipative effect of water sloshing.
TLDs present an optimal cost-effectiveness relationship, are easy to install and their sloshing can be easily altered by varying the water height. Other properties can be also altered in order to improve the TLDs performance, such as: i) using another fluid (with different density and viscosity); ii) using vertical grids; iii) varying the rugosity of the TLD walls, etc…
When in service, TLDs present a good performance in high buildings and low frequency flexible structures (bridges and towers).
In Portugal and mainly due to the fact of the reduced height of Portuguese constructions this type of devices is not quite known or used. Nevertheless the Portuguese modern constructions (housing, offices and commerce) are increasing in height that is why the use of TLDs should certainly be a good option, considering the reduced costs associated to the construction, placement and maintenance of the referred devices. The design and implementation of TLDs as well as the other passive energy dissipation devices require experimental tests (real scale or reduced scale) for validation of the main characteristics.
The aim of the study that is being developed under a PhD thesis is to evaluate de dynamic behaviour of TLDs and their performance when include in structures. For that purpose was developed in LNEC, a transmission system with one degree of freedom and adjustable dynamic characteristics [Oliveira and Morais, 2006] have been developed in order to simulate the behaviour of low frequency typical structures. The referred transmission system (Figure 1) is composed by a 3.7tons mobile mass and several air springs allowing the simulation of vibration modes with frequencies identical to the ones desired (0.7 to 2.0 Hz)
In order to achieve a greater accuracy in the determination of the transmission system frequency, some tests were performed on the air-springs responsible for the definition of the stiffness (rigidity) of the system. After these preliminary tests the springs were characterized by means of an empirical model relating force (as a function of the internal pressure on the air-springs) and deformation obtained. These results are showed in the present paper.
To better understand the dynamic behaviour of the TLDs set to be used in vibration mitigation of the transmission system, one of the tanks (TLD) was tested for different intensities random vibration. The definition of geometric characteristics of the TLDs tested as well as the instrumentation used is also described.
Some preliminary results on dynamic tests performed on the TLD prototype will also be showed as well as the definition of the future developments previewed for the testing set-up with a set of 32 TLDs (Figure 2).

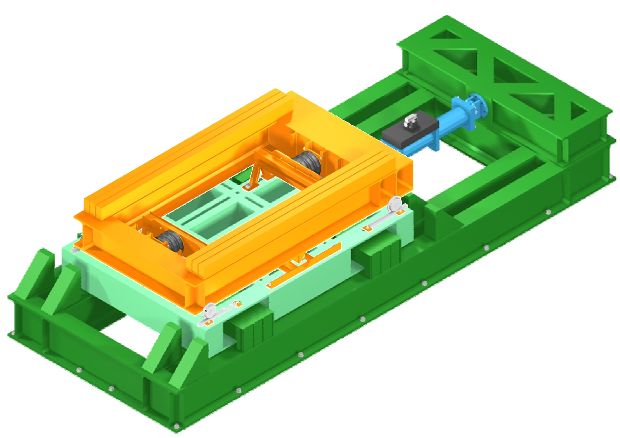

Figure 1. Schematic view of the placement of the single degree of freedom transmission system over the uniaxial shaking table

Figure 2. Testing set-up of the transmission system with 32 TLDs included [Falcão Silva et. al, 2007]

In the end will be stated some preliminary remarks and conclusions referring the work done until the moment. The development of the experimental program over the transmission system with and without TLDs included will be object of a future publication.

2. METHODOLOGY

To perform the previously mentioned tests, some equipment has been developed and the necessary instrumentation for each situation installed. Firstly the air-springs were tested to define a global model for their behaviour and afterwards the TLDs were tested for the definition of their main characteristics. These two types of tests will be used in future for the definition of the behaviour of the transmission system with and without the set of 32 TLDs for vibration mitigation.

2.1. Air springs experimental tests

Tests have been performed on each one of the four air-springs (Firestone W01-M58-6128), submitting them to a cycle of charge-discharge ranging from 300 to 200mm height (of the spring) starting from initial conditions of pressure and constant deformation velocity.
To carry out the tests, a Baldwin/Schenck press with 100kN force cell calibrated in Laboratório de Ensaio de Produtos Metálicos (LPM) was used, together with a data acquisition system and some support equipment. The description of the tests was presented in [falcão Silva et. Al., 2007].

2.2. Tuned Liquid Dampers (TLDs) experimental tests

These tests allow the characterization of the dynamic behaviour of the water tank (TLD). This TLD (with only one chamber) was designed on the basis of the following: i) dynamic behaviour of the transmission system to be tested because the TLDs are effective when their sloshing frequency is tuned (or close) to the fundamental frequency that is intend to mitigate and simultaneously when the relation between the mass of the set of TLDs and the structure's mass is between 1 and 5% [Banerji et. al, 2000]; ii) geometric limitation of the transmission system for the installation of the set composed by 32 TLDs; iii) tests easy to perform in both directions; iv) use of a non-opaque material in order to allow the visualization of the waves formed during the tests.
The natural frequency of sloshing in a TLD is determined by its geometry. In the present case, research focused in rectangular TLDs. According to [Sun, 1991] the natural frequency of sloshing of rectangular TLDs is calculated by means of:

$$f_n = \frac{1}{2\pi}\sqrt{\frac{2n-1}{2a}\pi g \tanh\left(\frac{2n-1}{2a}\pi h\right)} \quad (2.1)$$

Where n corresponds to the vibration mode, 2a is the length of the TLD and h corresponds to the water height. It must also be referred that is intended to mitigate the structures vibrations by using the oscillation energy of waves in the TLD associated with the fundamental mode.

Considering all the previously mentioned requisites, a tank with 422x211mm2 basis and 300mm height has been chosen. With this solution it may be tested more configurations, still taking into account the mass relation previously mentioned.
By varying the water height between 40 and 100mm and according with the expression (1), values of fundamental frequency between 0.6 and 1.8 Hz can be obtained considering that the TLD can be aligned in the length direction of 422 or 211mm. Figure 4 shows the evolution of the fundamental frequency of the TLDs depending on its length. To perform the experimental program the testing set-up was installed as showed in a simplified scheme in Figure 5.

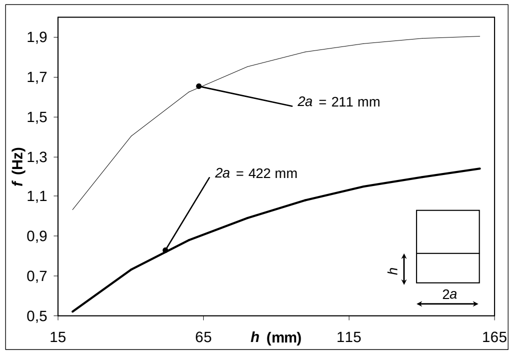

Figure 3. Evolution of the fundamental frequency with the water height in the rectangular TLD in both directions [Falcão Silva et. al., 2007]

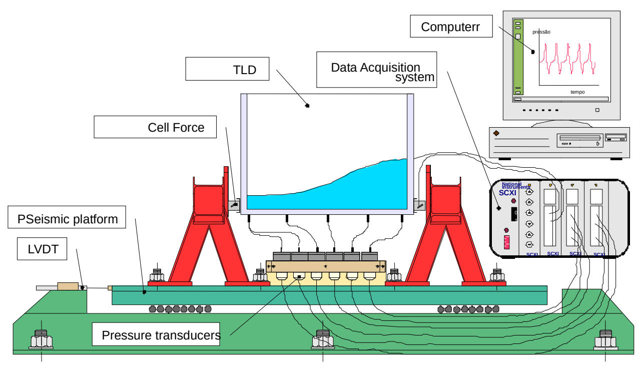

Figure 4. Schematic view of the testing set-up used during the experimental programme [Falcão Silva et. al, 2007]]

During the experimental program were measured: i) relative displacement in the seismic platform by means of a LVDT; ii) water height in different points of the TLD by means of 6 submersible pressure sensors (Keller 46R) and iii) forces in the TLD walls by means of .cell forces developed in LNEC Scientific Instrumentation Centre. It is important to notice that the 6 pressure sensors, which were adapted for this test [Falcão Silva et. al., 2007] were preferably used along the central lines because in this configuration they are less affected by the effects of wall proximity.
For the tests performed were used random white noise excitations artificially generated by the software LNEC-SPA [Mendes and Costa, 2007]. Twenty series of 300s duration each were generated, which were afterwards used for each considered water height (between 40 and 100mm) and for each displacement's amplitude imposed to the shaking table (between 1 and 25mm). These tests enable to obtain experimental vibration frequencies for comparison with the corresponding theoretical values [Sun, 1991], as well as the damping values for each situation tested. It will be obtained medium values based on the results of the twenty series imposed to the shaking table.

3. RESULTS

3.1. Air springs experimental tests

Based on the results obtained experimentally it was possible to define empirical models for each one of the air-sprins tested. These empirical models may be defined as exponential relations between forces (F) and deformation (x) observed in the spring during the tests, considering well defined initial pressures imposed
These empirical relations will be:

$$F(P_i, x) = C(P_i)e^{m(P_i)x} \tag{3.1}$$

With C and m linearly dependent on the initial pressure (Pi) and x corresponding to the spring deformation referred to the initial undeformed position.
The results obtained during the experimental tests for air-spring 2 are presented in Figure 5.

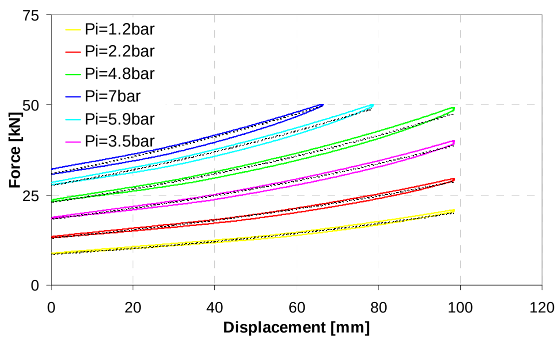

Figure 5. Experimental results for spring 2 and corresponding regressions

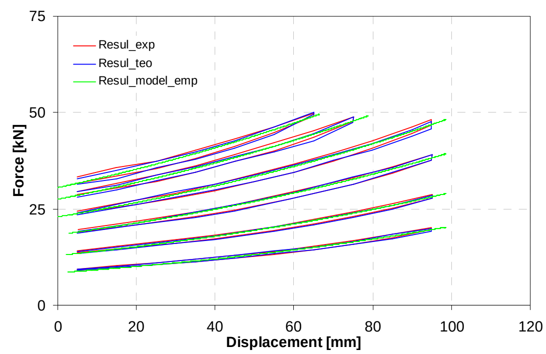

Figure 6. Experimental, theoretical results and empirical models for spring 2

It was obtained the following empirical models for the forces in all four air-springs as function of deformation and initial pressure (Table 1).

Table 3.1 Empirical models for the forces in the air-springs

Air-spring	Model
1	$F_1(Pi,x) = (3.903Pi - 1.9332)e^{[-0.0003Pi+0.0098]}$
2	$F_2(Pi,x) = (3.9548Pi - 2.2518)e^{[-0.0003Pi+0.0091]}$
3	$F_3(Pi,x) = (3.7751Pi - 1.4418)e^{[-0.0001Pi+0.0088]}$
4	$F_4(Pi,x) = (3.8214Pi - 1.5858)e^{[-0.0002Pi+0.0089]}$

These models correspond to good approximations both for the experimental results as well as for the theoretical models defined by the manufacturer. These good relations between results are presented in Figure 6 also for spring 2. The results obtained for other springs are included in [Falcão Silva and Costa, 2008].
The determination of the stiffness (K) of each air-spring (and of the transmission system) is made by means of differentiation of the expressions for each force, being the expected value for the transmission structure's frequency obtained based on the stiffness of the set of air springs for the mass of the structure (about 3.7tons). Considering that the initial pressure of the experimental tests may vary between 1,5 and 7 bar and that in the one degree of freedom transmission system to be tested with and without TLDs included for vibration mitigation may be considered two configuration: i) four air-springs (set of two springs in series, parallel) – CASE 1; ii) two air-springs (parallel) – CASE 2 it may be achieved natural frequencies between 0.7 and 2.0Hz, which cover the frequencies previewed for this particular study.

3.2 Tuned Liquid Dampers (TLDs) experimental tests

The values measured during the experimental programme enabled the characterization of the TLD studied to be

included in the set of 32 TLDs to be placed on the transmission system for vibration mitigation.
Analysis of the experimental results was made using the Analysis and Modal analysis modules of the software LNEC-SPA [Mendes and Costa, 2007]
Modal frequencies were identified using the Frequency Response Functions estimated and the Peak Picking Method. The FRF estimated relates the water height (pressure sensors) to the relative displacement measured in the shaking table (LVDT).
In all the tests only one translation mode has been identified as, for the considered excitations, the higher modes did not present representative amplitudes.
The modal frequencies identified for the tests performed for several water heights and 1mm excitation amplitude (only linear phenomena) are included in Table 3. In the referred table are also present the theoretical values for the fundamental frequency obtained by the expression (2.1). As it may be observed the differences observed are reduced proving that the theoretical models are able to simulate with accuracy the frequency in a linear range (for small amplitudes of excitation)

Table 3.2 – Experimental (fexp) and theoretical (fteo) modal frequencies

h (mm)	fexp (Hz)	fteo (Hz)	error (%)
40	0,747	0,73	2,3
50	0,809	0,81	0,12
70	0,937	0,94	0,32
85	1,021	1,02	0,10
100	1,084	1,08	0,37

Figure 7 shows the FRF obtained for 50mm water height and excitation amplitude varying between 1 and 20mm. In spite of variations observed the trend is clearly linear (Figure 6).
As it may be observed from both Figures 7 and 8 only frequencies corresponding to low excitation amplitudes, 1 and 2mm, are in accordance with the values obtained from expression (2.1), what may be an indicator of the occurrence of non-linearities for higher excitation amplitudes which are not being considered in the theoretical expression. When the excitation amplitude increases, it can be noticed some alterations of the fundamental frequency (increase) what confirms the existence of some other phenomena (non-linear) inside the TLD.

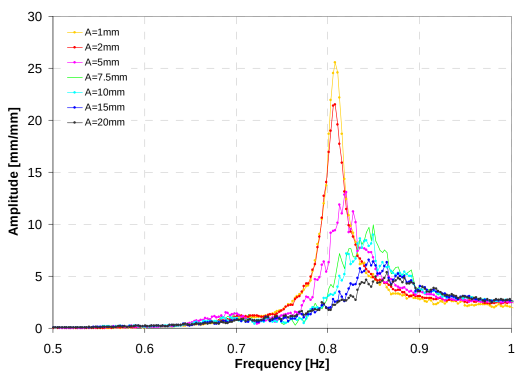

Figure 5. Experimental results for spring 2 and corresponding regressions

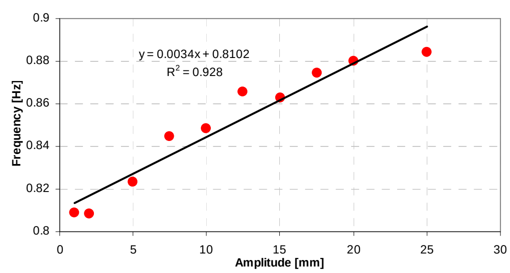

Figure 6. Experimental, theoretical results and empirical models for spring 2

Damping was another parameter that presented a clear variation during the tests. The effect of fluid damping is significant near the resonance frequency and must be carefully considered when modelling the TLDs behavior [Sun, 1991]. Damping of the sloshing that occurs inside the TLD for shallow water waves is difficult to determine in an analytical way, especially when breaking waves occurs. However the damping (ξn) can be approximated according to what was expressed in [Sun, 1991]. The expression (3) is suitable for rectangular TLDs facing small excitation amplitudes.

$$\xi_n = \frac{1}{\eta + h_0} \frac{\sqrt{2}}{2} \frac{\sqrt{\omega\nu}}{2\omega_w}\left(1 + \frac{2h_0}{b} + S\right) \quad (3)$$

Where η corresponds to the elevation of water surface; h0 is the fluid height at rest; ω is the long wave natural frequency in accordance with linear wave theory [Lamb, 1932]; ν is the cinematic viscosity, ωn is the frequency of the water vibration mode in the TLD, b corresponds to the TLD length in order to account the dissipation due to friction on the side walls; S is a surface contamination factor that assesses damping on the contaminated liquid surface (ranges between 0 and 2, and according to [Miles, 1967] was considered a value of 1, which corresponds to a completely contaminated surface. Table 4 presents the theoretical and experimental values obtained for the damping considering different water heights and 1mm excitation amplitude.

Table 3.2 Experimental (ξ_{exp}) and theoretical (ξ_{teo}) damping

h (mm)	ξexp (%)	ξteo(%)	error (%)
40	1,08	0,89	+22
50	0,89	0,72	+25
70	0,62	0,52	+20
85	0,55	0,44	+25
100	0,46	0,38	+21

Differences observed between the values shown on the previous table can be justified by an alteration of the contaminated liquid surface (S). This way is thought that for the conditions of the tests performed during the experimental program developed it is not a completely contaminated surface and therefore, in order that the theoretical model can be representative, S must be adjusted to values above 1. These studies, considering increasing S values, will be developed in future and will allow the validation of the model for the particular conditions present during the tests.
Similarly to what has been done for the experimental frequencies it is showed (Figure 7) the graphical presentation of the evolution of the experimental damping with the excitation amplitude.

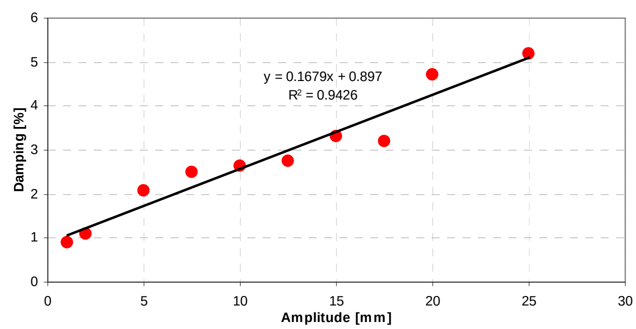

Figure 7. Evolution of the damping coefficient with excitation amplitude

The results presented in the Figure demonstrate that the trendline is linear (with r2=0.94) proving that when the excitation amplitude increases the theoretical model is not suitable for simulating the damping, due to the occurrence of highly non-linear phenomena in the water that are not considered in the expression (3). For these non-linear situations is advisable to use other models for the damping determination.

4. FUTURE PERSPECTIVES

Despite the results shown in the present paper the study on the effectiveness of TLDs for vibration mitigation is far from being completed. It is important to refer that there are some additional work that is already previewed: i) Conclusion of the tests over the rectangular TLDs, namely different water heigths and excitations (sinesweeps and records of earthquakes); ii) Characterization tests of the transmission structure (Figure 1) for validation of the empirical models (air-springs) that allow an indirect calculation of the structure's stiffness (and frequency),

iii) Experimental tests over the transmission system with the set of 32 TLDs mounted (Figure 2) considering different water heights and effective water masses; iv) Tests performed for different tank shapes (circular). These other tanks are already under construction being previewed their conclusion by the end of 2008

5. CONCLUSIONS

Preliminary tests aiming at developing and implementing a system to protect and reduce vibration in flexible structures are being concluded.
The adequate choice of equipment and implementation allowed that, so far, tests have been developed with sucess.
To validate air-spring characteristics tests were performed. These tests enabled the achievement of a model that simulates adequately the springs mechanical behaviour. This will be useful to determine the transmission system characteristics as well as to obtain the reaction force in the springs.
Experimental frequencies in the TLD have been obtained with reduced errors when compared with theoretical expressions, as long as the excitation amplitudes are low and therefore only linear phenomena are involved. The differences obtained for a range of excitation amplitude between 1 and 25mm almost reached 10%, as can be observed in Figure 6.
The theoretical damping coefficient is dependent on a factor so called "contamination factor of the free surface – S". Increasing values of excitation amplitude correspond to a variation of the damping coefficient associated to the occurrence of non-linear phenomena (breaking waves among others).
It was also observed a good correspondence between the records of the forces on the TLD walls obtained directly (force cells) or indirectly (pressure sensors placed on the bottom wall of the TLD), which proves that, for the studied cases, the shear force in the TLD is not affected by any hydrodynamic component.

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