Proceedings of the 5th WSEAS International Conference on Applied Computer Science, Hangzhou, China, April 16-18, 2006 (pp682-687)

Experimental Investigation on Sloshing Water Dampers Attached to Rigid Blocks

O. CORBI
Department Structural Mechanics
University of Naples Federico II
Via Claudio 21, 80125, Napoli
ITALY

Abstract: - The paper focuses on the possibility of coupling Sloshing Water Dampers with rigid blocks moving on a foundation base subject to a horizontal ground motion.

One considers pure rocking of blocks, moving according to a dynamic excitation inferred by means of a shaking table facility; experimental data are derived in order to compare the dynamic response of the blocks equipped or not with the devices for various liquid levels of the tanks.

Key-Words: - dynamics, tuned liquid dampers, experimental tests, rigid blocks, shaking table, control devices.

1 Introduction

1.1 Generalities

Techniques devoted to increase the damping characteristics of a structure, may significantly reduce the risk of occurrence of severe damage or structural failures during a catastrophic event (eg. Earthquakes and hurricanes).

Serviceability considerations and other advantages, such as low cost and easiness of installation in existing structures, push toward the adoption of auxiliary damping masses to be attached to the primary structure, like Tuned Mass Dampers (TMDs), Tuned Liquid Dampers (TLDs) and Tuned Liquid Column Dampers (TLCD) [1-3].

TLDs, by attaching multiple liquid-filled tanks to the structures [4], also offer, if properly designed, the benefit of effectiveness even for small-vibrations, thus representing an efficient and simple technique to increase the damping of a structure.

Because of its peculiar character, the evaluation of the performance, in terms of energy dissipation, of a tuned sloshing damper requires the understanding of complex fluid-structure interactions. To this end, numerical and experimental investigations on liquid tanks can provide useful information on the overall device behaviour [5, 6].

In the following one studies a feature that has not been treated in literature very often, i.e. the possibility of coupling liquid dampers to rigid blocks for attenuating its rocking response under dynamic excitation and/or preventing its overturning; actually the rigid block model [7]-[14] is a pretty interesting one, since it is able to capture the essential behaviour of a wide variety of structural (or even not-structural) objects.

To this purpose some laboratory tests are developed on a shaking table facility and the relevant numerical results are herein discussed.

In the following paragraphs one gives a short overview of the main characteristic of the most commonly adopted liquid damping devices.

1.2 Tuned Liquid Dampers (TLDs)

1.2.1 General description

A Tuned Liquid Damper can be synthetically described as an auxiliary liquid mass, whose liquid is a Newtonian fluid with very low viscosity (usually water) moving in a tank.

TLD's action consists in utilizing free-surface liquid motion.

Passive mechanical dampers using this liquid motion have been widely investigated and implemented in the fields of aeronautical engineering and naval engineering.

The first proposals of applications of TLDs for civil engineering purposes date back to late '80s: Sato [15-16] was among the first to suggest their application to civil structures, including buildings and towers, with the specific aim of reducing the dynamic response of the structure to external excitations. The TLD is generally positioned on one floor of the building for mitigating the vibrations induced by dynamic events such as earthquakes or strong wind actions and changes the dynamic characteristics of the structure by the motion of the shallow liquid.

The sloshing liquid exerts a force that damps the dynamic response of the structure to which it is coupled, if the size of the container, its shape and depth of the liquid are properly tuned.

These devices, usually located at the top floors, can, thus, dissipate the external input energy into the system through the sloshing effect of the liquid inside partially filled small containers, suitably mounted on the structure [17].

The interaction between the TLD and the structure takes place through a shear force produced by the difference in hydrodynamic pressure acted upon the TLD walls. More specifically, the basic idea behind the use of TLDs is that the proportions of the TLD are to be determined such that the natural frequency of the liquid is tuned with the fundamental natural frequency of the building so that its dynamic response is reduced.

So the main characteristic tuned liquid damper relies upon consists in a liquid which sloshes forces or moments to change the dynamical properties and to dissipate vibratory energy of a structure. In addition, the shear force caused by the inertia of the liquid mass reduces the structural response. Tuning the natural frequency of liquid sloshing with the natural frequency of structure, results in the optimisation of the effectiveness of the damper.

Actually the knowledge of the rules governing the motion of the liquid in a tank is of basic importance for understanding the behaviour of liquid-based devices and testing the reliability of the relevant simplified mechanical models.

Recently, the popularity of TLDs as viable devices for structural control has prompted study of sloshing for structural engineering applications. The motion of liquids in rigid containers has been the subject of many studies in the past few decades due to its frequent application in several engineering disciplines [18]. Moreover, one should emphasize that the need for accurate evaluation of the sloshing loads is also required for the design of aerospace vehicles, in civil engineering applications for the design of water tanks and dams, for chimney' installations (Figure 1), for problems relating to safety for tank trucks on highways and liquid tank cars on railroads, as well as in maritime applications where the effect of sloshing of liquids present on board, for e.g., liquid cargo or liquid fuel, can cause loss of stability of the ship as well as structural damage.

Up to now, due to their low coast, facility of installation and effectiveness, a big interest has been devoted to many aspects of TLDs, namely, the modelling, design, construction, algorithms, testing and cost and reliability analysis.

Figure 1. Tuned Liquid Dampers (TLDs) installed in chimneys.

TLDs can be basically divided in two main categories: Tuned Sloshing Water Dampers, which are dissipating devices based on the sloshing of water at the inner of containers of various shapes, and Tuned Liquid Column Dampers (TLCDs), which adopt U-tubes like liquid containers to counteract the forces acting on the structure and introduce damping in the oscillating liquid column through an orifice in the liquid passage [5].

1.2.2 Characteristics

As regards the macroscopic description of TLDs, a tuned liquid damper is characterized by several parameters such as the mass ratio, which is the ratio of mass of the damper to the first modal mass of the structure. For civil engineering applications, this is typically of the order of 1-2%. Space requirements dictate the actual mass ratio of the dampers. Typically 1% mass ratio for a well designed damper can provide up to 50% reduction in response. Another parameter is the frequency ratio, which is defined as the ratio of the frequency of the damper to the frequency of the structure. Typically, auxiliary devices are tuned to the first modal frequency of the structure. A good rule of thumb is for mass ratios of 1% to have a tuning ratio of 0.99 [1].

The effective damping ratio of the damper, for a regular TMD, represents the linear damping ratio. However, for liquid dampers this varies nonlinearly with amplitude. A good rule of thumb is to have about 4.5% damping ratio for mass ratios of 1%. In case the TLD is not able to provide that much damping at the design speed, one can add baffles, beads and other protrusions to artificially add damping [1]. However, too much of damping again leads to non-optimal damping and reduces the damper performance.

1.2.3 Installations

A number of full-scale TLDs have been designed and implemented for real structures. As an example one can mention the Australian 105 m. Hobart Tower in Tasmania that was equipped with 80 TSWD units after the tower was cloaked in a protective cylindrical shell. The shell, while shielding the transmission antenna from the harsh conditions, unfortunately increased the wind-induced response, necessitating the installation of the TSWD units.

In addition, Japanese installations of TLDs include six shallow TSWDs, one deep TSWD, and five TLCDs. The TSWDs primarily utilize circular containers for shallow configurations and rectangular ones for deep water TSWDs,

while the TLCDs rely on the traditional U-shaped vessel. Such applications work best for buildings with small vibrations and have been observed to reduce the structural response to 1/2 to 1/3 the original response in strong winds [19].

One Japanese TSWD application in the top floor of the 158 m. Gold Tower in Kagawa features 16 units. The installation of 10 tons. of TSWDs was found to reduce the response to 1/2 to 1/3 of the original response. The tank, in the form of a cube, is filled with water and equipped with steel wire nets to dissipate the motion of the liquid.

By adjusting these damping nets, the length of the tank, and the depth of water, the device may be appropriately tuned. There are many advantages to applications such as these: there is no mechanical friction in the system so it is effective for even the slightest vibrations, failure of the system is virtually impossible, it is effective against the strong motion of earthquakes and winds, the period is easy to adjust, and the system is inexpensive and easy to maintain [20]. However, there are drawbacks as well: all the water mass does not participate in counteracting the structural motion. This results in extra premium in terms of added weight to the structure without the benefit of commensurate response control.

An alternative TSWD configuration of multi-layer stacks of 9 circular (2 m diameter) fibre reinforced plastic containers, each 22 cm. high, was installed in 1991 in the 149 m. Shin Yokohama Prince Hotel (SYP) in Yokohama, Japan (Figure 2). Each layer of the TSWD was equipped with 12 protrusions installed in a symmetric radial pattern to preclude the swirling motion of the liquid and to get adequate additional damping.

Similarly, another multi-layer configuration of 25 units was installed in the 42 m. Nagasaki Airport Tower in 1987.

Figure 2. Shin Yokohama Prince Hotel and TSD units installed [18].

Twelve cylindrical, multi-layered vessels of vinyl chloride measuring 50 cm high and 38 cm in diameter were installed on the air-traffic control room floor and the remaining thirteen distributed on each stair landing. Each vessel is divided into 7, 7 cm high layers each containing 4.8 cm of water and weighing 38 kg. Thus a total of 950 kg of TSD units was installed in the tower. Run down tests conducted to calculate the frequency and damping ratio of the tower revealed that there was more displacement due to the across wind component than the along wind component and uncovered the presence of beat phenomena which was eliminated through the use of floating particles that helped to dampen the liquid motion in the containers. An examination of the tower response has shown, once again, the performance of the TSD appears to improve at even higher velocities with the response in wind reduced 35% in winds of 20 m/s [17]. Another airport tower has also been equipped with a TSWD system. Consisting of approximately 1400 vessels containing water, floating particles, and preservatives, the device was installed in the 77.6 m Tokyo International Airport Tower at Haneda in 1993 (Figure 3).

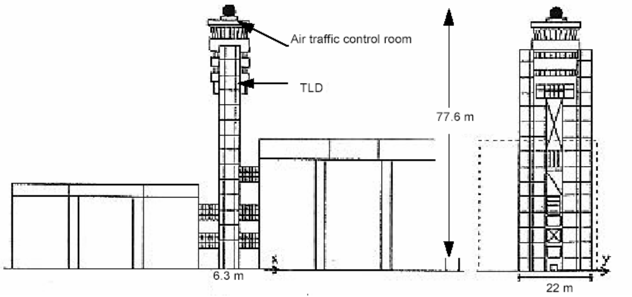

Figure 3. Tokyo International Airport Tower (TIAT) at Haneda and views of TLD units installed [17].

The 1400 shallow circular cylindrical vessels with 60 cm. diameter and 12.5 cm. height had injection taps and handles to serve as projections and 4 conical dents on the upside and base [17].

2. Experiments on Rigid Blocks Equipped with Water Tanks

2.1 Generalities

The rocking response of rigid bodies has attracted the interest of many researchers all over the world [7]-[14], since it is related to the possibility of predicting failures of a wide variety of structures, due to rocking and overturning.

Therefore, even in its apparent simplicity, this may be considered a still open problem, to be carefully deepened both under the experimental and numerical points of view.

On the other side, the possibility of preventing collapses of structures by means of additional masses suitably tuned to the basic characters of the structure itself is a widely studied problem, and devices based on sloshing liquids have now been recognized desirable damping properties [1]-[6], as discussed in the above.

In the paper the two features are coupled and the possibility of mitigating the dynamic rocking response of standard models of rigid blocks by simple liquid dampers devices is investigated from an experimental point of view.

2.2.Experimental Campaign

Experiments were performed using some facilities available at the Laboratory of Materials and Structural Testing of the University of Naples “Federico II”, in details a unidirectional shaking table whose motion is purely transactional in the horizontal direction (Figure 4).

In order to obtain experimental data on blocks’ motion due to pure rocking, the blocks are suitably fixed on the moving table and an accelerometer is placed on the top of each block, measuring its accelerations. A special device is adopted for fixing the blocks in such a way to avoid any rotation around z–axis and sliding along the shaking table surface (Figure 5).

For evaluating the dissipation of energy due to the sloshing action of liquid in containers, some liquid dampers (LDs) are mounted on the upper surface of the rigid blocks.

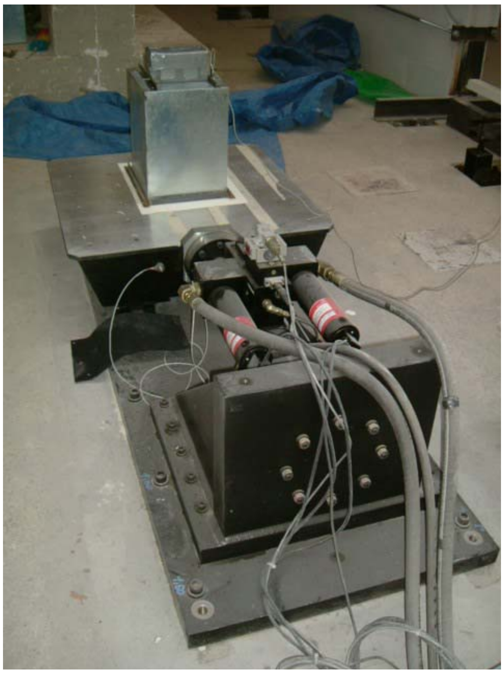

Figure 4. The shaking table located at the Laboratory of the University of Naples “Federico II”.

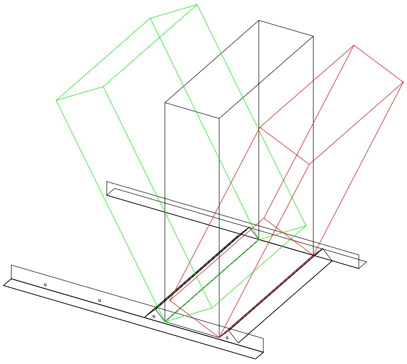

Figure 5. Device for fixing the blocks on the shaking table and allowed motion of the blocks.

The adopted LDs simply consist of some tanks with different shapes to be filled with a liquid (in the specific case, water) at various levels.

Actually, in the experimental campaign, one executed tests on a number of block prototypes; in the following one only reports some results relevant to a prismatic block in aluminium with dimensions 30×30×40 cm, in order to synthetically discuss the results.

As regards to the liquid containers, one considers three tanks, as shown in the resuming scheme of Figure 6, one of which has a simply parallelepiped shape (vertical lateral sides), and will be referred to as 0° tank. The remaining two tanks have a trapezoidal shape with 30°- or 45°-inclined lateral sides; these will be referred to in the following as 30° and 45° tanks.

The monitoring equipment simply consists of an accelerometer placed on the top of the blocks in order to read their accelerations.

Experimental investigation on coupling water tanks and rigid blocks is useful in understanding the merits and disadvantages of each device.

During dynamic tests, the input signal driven by the shaking table consists of a horizontal sine acceleration with fixed amplitude and frequency.

Actually one fixes the span of the table at 0.5 cm and executes a number of tests by varying the excitation frequency between 1 Hz and 10 Hz, which can be considered the most significant frequency range if one refers to the maximum power concentration of a seismic motion.

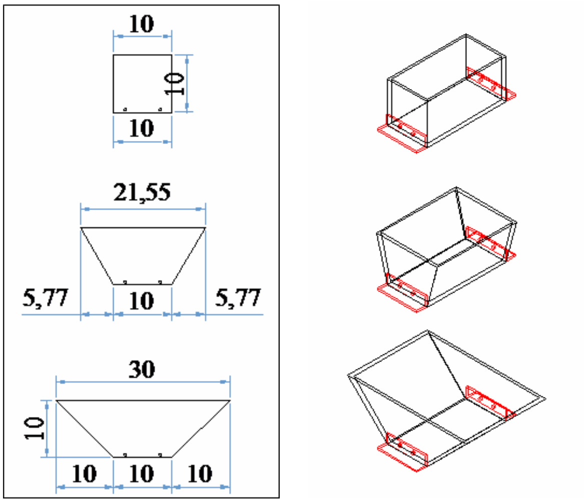

Figure 6. Resuming scheme of adopted tanks for LDs.

The experiments are executed filling tanks with water up to 4 and 8 cm of depth and comparing the results with the ones of the block with empty tanks, which is referred to by the 0 cm notation.

Results of experimental tests on the considered block are reported in Figures 7-9, where Figure 7 refers to the prismatic (0°) tank, while Figures 8 and 9 refer to the trapezoidal tanks, respectively 30° and 45°. In details the set of Figures 7-9 represents peak accelerations (m/s^2) of the block versus frequencies (of the unidirectional base acceleration) (Hz) for a span level o 0.5 cm and for the mentioned (8cm, 4cm and 0 cm) liquid levels in the tanks: in every graphic one has three curves relevant to the depth of the water (0, 4, 8 cm) ; the data allow to read the benefit of adopting a higher or lower level of liquid for the same tank.

Generally speaking, one can observe that comparison between the three liquid depth levels reveal the potential efficiency and advantage of the liquid damper system in damping the vibrations of the structural model, even if the benefit by the liquid damper is not homogeneous on the frequency range, but it is strongly dependent on the frequencies at which the power of the excitation is lumped.

In all the cases that have been tested the benefit has been found to be potentially very significant (attenuation ratio larger and also much larger than 5 in some cases) but some cases have been encountered where the device increases the risk (attenuation ratio smaller than 1).

3. Conclusions

The paper deals with the possibility of coupling sloshing water devices with rigid blocks moving on a foundation base subjected to a horizontal ground motion.

An experimental investigation is developed on aluminium blocks moving by pure rocking, according to the base excitation inferred by the shaking table facility.

Experimental tests are performed in order to compare the dynamic response of the blocks equipped or not with tanks filled with water at various levels (basically liquid dampers), devoted to dissipate the incoming energy.

The potential benefits induced by addition of such devices are appreciated, even if the need of properly designing the liquid damper devices is emphasized.

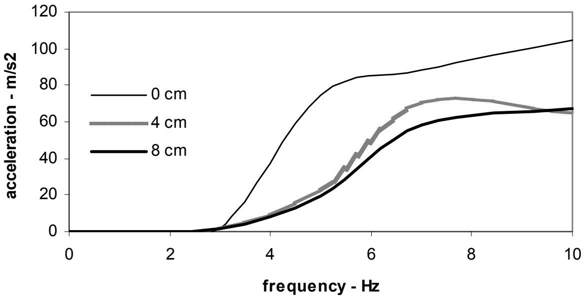

Figure 7. Block equipped with 0° water tank. The three curves refer to liquid levels (0 cm, 4cm and 8cm).

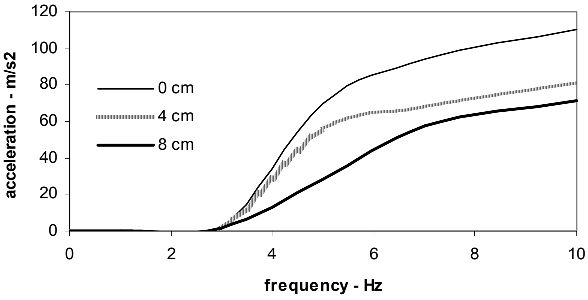

Figure 8. Block equipped with 30° water tank. The three curves refer to liquid levels (0 cm, 4cm and 8cm).

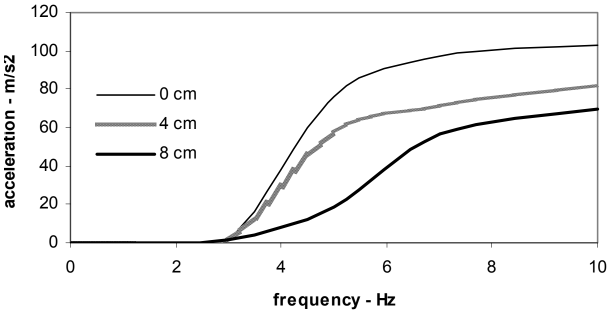

Figure 9. Block equipped with 45° water tank. The three curves refer to liquid levels (0 cm, 4cm and 8cm).

Acknowledgments

The paper has been developed within a research project funded by Regione Campania (project L.5, year 2002).

References

[1] Kosaka H, Noji T, Yoshida H, Tatsumi E, Yamanaka H, Agrawal AK, Damping Effects of a Vibration Control Damper Using Sloshing of Water, *Proceedings of the 10th World Conference on Earthquake Engineering*; Madrid, 1992; 4, pp.2435-2440.

[2] Fujino Y, Tuned Liquid Damper (TLD) for Suppressing Horizontal Motion of Structures, *International Journal of Engineering Mechanics*, 1992; 118, n. 10, pp. 2017-2030.

[3] Kareem A, Next Generation of Tuned Liquid Dampers, *Proceedings of the 1st World Conf. on Structural Control: International Association for Structural Control*; Los Angeles, 1994; 3, pp. 19-28.

[4] Sun LM, Fujino Y, Koga K, Model of Tuned Liquid Damper for Suppressing Pitching Motions of Structures, *International Journal of Earthquake Engineering and Structural Dynamics*, 1995; 24(5), pp. 625-636.

[5] Chaiseri P, Fujino Y, Pacheco BM, Sun LM, *Interaction of Tuned Liquid Damper (TLD) and Structure: Theory, Experimental Verification and Application, Structural Engineering/Earthquake Engineering*, 1989; 6(2), pp. 273-282.

[6] Baratta A, Corbi O, Orefice R, Tuned Liquid Dampers for structural Applications: Experimental Evidence, *Proceeding of the 4th International Conference on Engineering Computational Technology*, Lisbon, 2004.

[7] Aslam M, Godden WG, Scalise DT, Earthquake rocking response of rigid bodies, *International Journal of Engineering Mechanics Division ASCE*, 1980; 106(2), pp. 377-392.

[8] Corbi I, Orefice R, Study of rocking rigid blocks using shaking table experiments, *Proceedings of the 4th International Conference on Engineering Computational Technology*, Lisbon, 2004.

[9] Hogan SJ, The many steady state responses of a rigid block under harmonic forcing, *International Journal of Earthquake Engineering and Structural Dynamics*, 1990; 19, pp. 1057-1071.

[10] Milne J, Experiments in observational seismology, *Trans. Seism. Soc.* Japan, 1881; 8, pp.12-64.

[11] Perry J, Note on the rocking of a column, *Trans. Seism. Soc.* Japan, 1881; 3, pp. 103-106.

[12] Tso WK, Wong CM, Steady state rocking response of rigid blocks. Part 2: Experiment, *International Journal of Earthquake Engineering and Structural Dynamics*, 1989; 18, pp. 107-120.

[13] Yim CS, Chopra AK, Penzien J, Rocking response of rigid blocks to earthquakes, *International Journal of Earthquake Engineering and Structural Dynamics*, 1980; 8(6), pp. 565-587.

[14] Zhang J, Makris N, Rocking response of free-standing blocks under cycloidal pulses, *International Journal of Engineering Mechanics*, ASCE, 2001; 127(5)L 47383.

[15] Sun LM, Fujino Y, Chaiseri P, Pacheco BM, The properties of tuned liquid dampers using TMD analogy, *International Journal of Earthquake Engineering and Structural Dynamics*, 1995; 24, pp. 967-976.

[16] Sato T, Tuned sloshing dampers, *Japan Journal of Wind Engineering*, 1987; 32, pp. 67-68.

[17] Tamura Y, Kohsaka R, Nakamura O, Miyashita K, Modi V, Wind-induced responses of an airport tower- efficiency of tuned liquid damper, *Journal of Wind Engineering and Industrial Aerodynamics*, 1996; 65, pp. 121-131.

[18] Yalla SK, Kareem A, Modeling of TLDs as sloshing-slamming dampers, *Proceedings of the 10th International Conference on Wind Engineering*, Copenhagen, 1999.

[19] Maebayashi K, Tamura K, Shiba K, Ogawa Y, Inada Y, Performance of a hybrid mass damper system implemented in a tall building, *Proceedings of International Workshop on Structural Control*, 1993, pp. 318-328.

[20] Noji T, Yoshida H, Tatsumi E, Kosaka H, Hagiuda H, Verification of vibration control effect in actual structures (Part 2), *Journal of Structural and Construction Engineering*, Transactions of the AIJ, 1991, pp. 145-152.