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Objekttyp: **Article**

Zeitschrift: **IABSE congress report = Rapport du congrès AIPC = IVBH Kongressbericht**

Band (Jahr): **14 (1992)**

PDF erstellt am: **21.06.2024**

Persistenter Link: https://doi.org/10.5169/seals-853207

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Vibration Control of Structures by Tuned Liquid Column Dampers

Amortissement de vibrations des constructions par colonnes de liquide

Tilgung von Bauwerkschwingungen mittels Flüssigkeitssäulen

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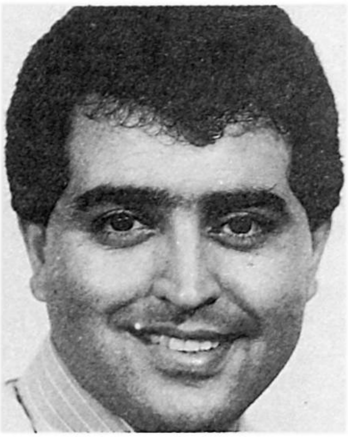

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SUMMARY

The effectiveness of Tuned Liquid Column Dampers (TLCD) in suppressing wind and earthquake induced vibrations of structures is investigated both analytically and experimentally. Random vibration analysis of a 40-storey building subjected to earthquake loading confirms the effectiveness of the system in reducing building response. The experimental work investigated the effectiveness of the proposed damper system for a single degree of freedom structure in terms of additional damping displayed by the structure when equipped with the TLCD system. The study also included a parametric study of the TLCD system resulting in an optional system.

RÉSUMÉ

En se basant sur l'utilisation d'amortisseurs à colonne de liquide à effet direct, l'article examine, tant du point de vue analytique qu'expérimental, la suppression efficace des vibrations induites dans les structures par les effets du vent ou des tremblements de terre. Le calcul des vibrations aléatoires produites dans un bâtiment de 40 étages par des secousses sismiques confirme l'efficience de ce système d'amortissement, par suite de la réduction de la réponse de l'ouvrage. L'étude expérimentale a porté sur une structure à un seul degré de liberté, en fonction d'un amortissement additionnel enregistré par la structure équipée du système d'amortisseurs à colonne de liquide à effet direct.

ZUSAMMENFASSUNG

Die Wirksamkeit von Tilgern auf der Basis abgestimmter Flüssigkeitssäulen wird analytisch und experimentall für wind- und erdbebeninduzierte Bauwerkschwingungen untersucht. Die stochastische Schwingungsanalyse für ein vierzig-stöckiges Gebäude unter Erdbebeneinwirkung bestätigt die Wirksamkeit auf die Bauwerksantwort. Die experimentellen Studien umfassten die erreichbare Zusatzdämpfung in Systemen mit einem Freiheitsgrad und die optimale Abstimmung eines solchen Tilgers.

1. INTRODUCTION

Control of excessive vibrations of tall buildings and other structures subjected to severe environmental loads such as wind and earthquake is of particular importance to structural engineers and has received considerable attention in recent years.

Tuned Mass Dampers (TMD) and visco-elastic dampers have been found effective in reducing the response of structures subjected to dynamic loads [1-4]. Recently liquid dampers such as sloshing dampers and Tuned Liquid Column Dampers (TLCD) are found effective in suppressing structural motions with definite advantages over other damping devices including low cost, easy handling and virtually no maintenance requirements. In this paper the effectiveness of the TLCD system in suppressing building vibrations is investigated both analytically and experimentally.

In the TLCD system the vibration energy of the structure is dissipated through the motion of liquid mass in a tube-like container, the restoring force due to the gravity acting upon the liquid and the damping effect as a result of loss of hydraulic pressure due to orifices installed inside the container.

The TLCD system is a versatile and simple system. The shape of the container tube is arbitrary and can assume any shape to suit its accommodation in buildings and towers. The vibration frequency of the liquid is only a function of the length of the liquid inside the tube. This would allow the system to be tuned (or retuned) to the frequency of the structure by simply altering the length of the liquid. Changing the damper frequency for tuned mass damper systems is rather difficult as it involves the change of damper mass or its spring stiffness, or the length of the supporting cables in the case of a pendulum type TMD.

TLCD systems are most suited for tall buildings and towers for which a water tank is usually installed for fire fighting or water supply. The proposed idea is to design the afore-said water tank as a TLCD system and hence absorb some of the vibration energy induced by wind and earthquake excitations. For this reason inclusion of a TLCD system does not impart a cost or extra weight penalty as has been the case for some TMD systems. A typical liquid column tube is shown in Fig.1.

2. ANALYTICAL FINDINGS

The effectiveness of the system has been investigated analytically following the random vibration analyses of three typical tall buildings subjected to earthquake excitations with an intensity equivalent to that of the Housner's average response spectra. The analysis uses the governing equation of motion for TLCD systems given by Sakai, et al [5] as

$$\rho AL\ddot{x} + 0.5\ \rho A\xi|\dot{x}|\dot{x} + 2\rho Agx = -\rho AB\ddot{y} \qquad (1)$$

in which y is the displacement of the tube, x is the elevation change of the liquid and ρ, L, B, and A are, respectively, the density, length of the liquid, the width, and cross-sectional area of the tube. ξ is defined as the coefficient of headloss (constant) governed by the opening ratio of the orifice(s) and g is the acceleration due to gravity. The natural frequency ω_1 and the natural period T_1 of the liquid column tube of Fig.1 are given in the following equations:

$$\omega_1 = \sqrt{2g/L} \quad ; \qquad T_1 = 2\pi\sqrt{L/2g} \qquad (2)$$

As seen from Eq. 1, the damping term in the fundamental equation of tuned liquid damper is non-linear. This is treated by an equivalent linearization technique as shown by Xu, et al [6]. The equivalent linear equation corresponding to Eq.1 may be written as

$$\rho AL\ddot{x} + 2\rho AC_p\dot{x} + 2\rho Agx = -\rho AB\ddot{y}_n \qquad (3)$$

in which C_p is the equivalent damping coefficient which is related to the coefficient of headloss as well as the velocity of the liquid column.

In this paper the effectiveness of the TLCD system is demonstrated on a 40-storey building equipped with a TLCD system with first natural vibration frequency of 0.17 Hz. The mass of the water is 2 % of that of the building. The required water column length for optimum tuning was found to be 18.7 meters. The required cross-sectional area of the tube is then 55.1 m^2. Maximum damping would be achieved when the ratio of the horizontal portion of the liquid to its total length is maximised in static position. Hence, 90 percent of the total liquid length was positioned horizontally. It is also found that maximum response reductions are achieved when the tuning ratio, ie, the ratio of the liquid column frequency to the frequency of the structure, is about 0.95. This ratio however is a function of mass ratio as well as the orifice opening ratio. Fig.2 illustrates the effectiveness of the TLCD system in reducing the top floor displacement of the forty storey building when subjected to earthquake loading with an intensity equivalent to that of the Housner's average response spectra. Fig. 2 also shows the sensitivity of the system to tuning ratio and the opening ratio of the orifice installed inside the tube. It is observed that a TLCD system with a tuning ratio of about 95 percent, and an orifice opening ratio of 46 percent is capable of reducing the building response by about 25 percent. The ordinate in Fig.2 represents the response ratio which is the response of the building with the TLCD system to the same response quantity in the absence of the damper system.

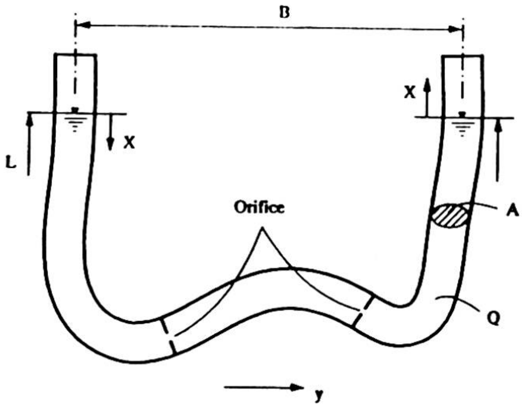

Fig. 1 A typical liquid column tube

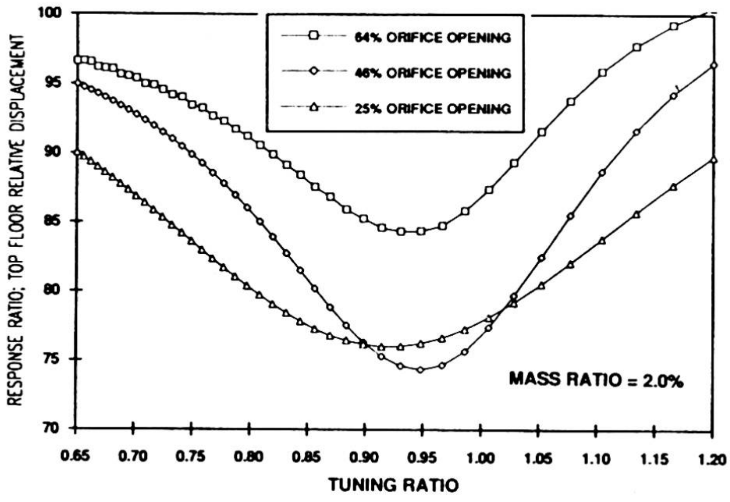

Fig. 2 Response of the 40-storey building equipped with TLCD system

3. EXPERIMENTAL WORK

In order to verify the effectiveness of the proposed TLCD system and to identify the parameters which affect its performance, a series of free vibration tests were performed in the structures laboratory of the School of Civil Engineering at the University of Technology, Sydney. The structure was modelled as a single degree of freedom system possessing a natural period of vibration of 3 seconds. The effect of orifice opening ratio and mass ratio was investigated. The effectiveness of the system was measured in terms of system overall damping ratio ie system damping as percentage of the critical value.

3.1 Test Set-up

In order to study the effects of the above-said parameters in relation to the performance of the TLCD system, a pendulum with variable mass was chosen as the single degree of freedom structure. A fixed volume of water passing through a tube, fitted with a variable orifice, was located at the centre of mass of the pendulum. The water was to pass through a 50 mm diameter tube with 90% of the total volume of water contained within a horizontal length of this tube and the remaining 10% in the vertical arms. Tuning ratios of 110%, 100% and 90% were tested. To simulate different water/pendulum mass ratios, the mass of the pendulum was varied for each tuning to represent different mass ratios of 1%,2%,3% and 4%, respectively. The initial amplitude of the pendulum and the decay, together with the velocity and quantity of water flow in the pipe, was measured.

The length of the pendulum was calculated using Eq. 4.

$$T = 2\pi \sqrt{(L/g)} \tag{4}$$

For the required period of oscillation of 3 seconds, the pendulum length, L, was therefore calculated as 2.24 metres. A 2 x 2 point suspension system has been used.

The height of the water in the vertical arms of the damper was determined by measuring the pressure within a closed vertical tube connected to a pressure tapping mounted close to the end of the horizontal section of the pipe. The velocity of the water flow was determined based on the slope of the pressure/time graph.

As the mass of the pendulum had to vary over a considerable range, and simultaneously support the horizontal length of the water tube, which varied in length for each tuning range, it was decided that two parallel lengths of square hollow steel tubing, (each 55 x 55 x 3.9 mm) connected by welded steel brackets across the bottom flanges, would be structurally adequate to both support the applied extra masses and maintain the masses and water tube at a co-planar centre of gravity.

The mass of the two 5 metre lengths of steel tube, together with the PVC 50 mm bore tubing, was 65 kg. Steel saddles, designed to rest on the top of the tubes, and fitted with cylindrical solid rod outrigger arms, provided additional mass to the frame to bring the mass of the total unloaded pendulum to 100 kg. The eight steel saddles were each capable of supporting six 22.5 kg lifting weights, thus providing a theoretical upper limit of 1180 kg.
The centre section of the damper pipe was fitted with a double flange piece machined to accept flat pre-drilled plates with apertures of 100%, 80%, 60%, 40% and 20% of the pipe cross-sectional area. Fig. 3 illustrates the test set-up.

4. TEST RESULTS AND CONCLUSIONS

Free vibration test results for mass ratios of 1,2,3, and 4%; tuning ratios of 100, 90, and 110% and orifice opening ratios of 20,40,60,80, and 100% were analysed in order to obtain the optimum damping level of the system. The recorded amplitudes of the nth and the n+mth vibration cycles were fed into a computer program from which system damping was obtained by calculating log-decrements. The results for 100 percent tuning ratio is tabulated in Table 1 and also illustrated in Fig. 4. The results indicate that the optimum tuning ratio is around 100%. The system damping ratio for 90 and 110% tuning ratios are generally less when compared with the results obtained for 100% tuning ratio. It is also observed that for 90 and 110% tuning the system damping increases monotonically with reducing orifice opening ratio.

Table 1 and Fig.4 clearly indicate that for 100% tuning ratio the largest system damping is achieved when the orifice opening ratio is 40%. This is true for all mass ratios. It was anticipated that the optimum opening ratio would be somewhere between 0 and 100 %, as the former represents full closure and the latter full openness, both of which were known to be non-optimal.

The results further indicate that for orifice opening ratios in the range of 100 to 60%, a larger mass ratio would not necessarily mean more damping. Furthermore, in this range the system damping is not sensitive to mass ratio and choosing a large mass ratio would not increase the system damping greatly. However, for the orifice opening ratios of 40 and 20%, a larger damper/structure mass ratio is associated with a larger system damping.

Test results clearly demonstrated the effectiveness of TLCD systems in suppressing vibration energy. The system is most efficient with tuning and orifice opening ratios of 100% and 40%, respectively. For these optimum values, the effectiveness of the system increases with increasing mass ratio. It must be realized however that there is a practical limit to mass ratio which is governed by architectural and other design constraints. In these experiments an optimal TLCD system with a mass ratio of only 2% increased the system damping by about 4% ie from 0.8% to 4.9% of critical damping.

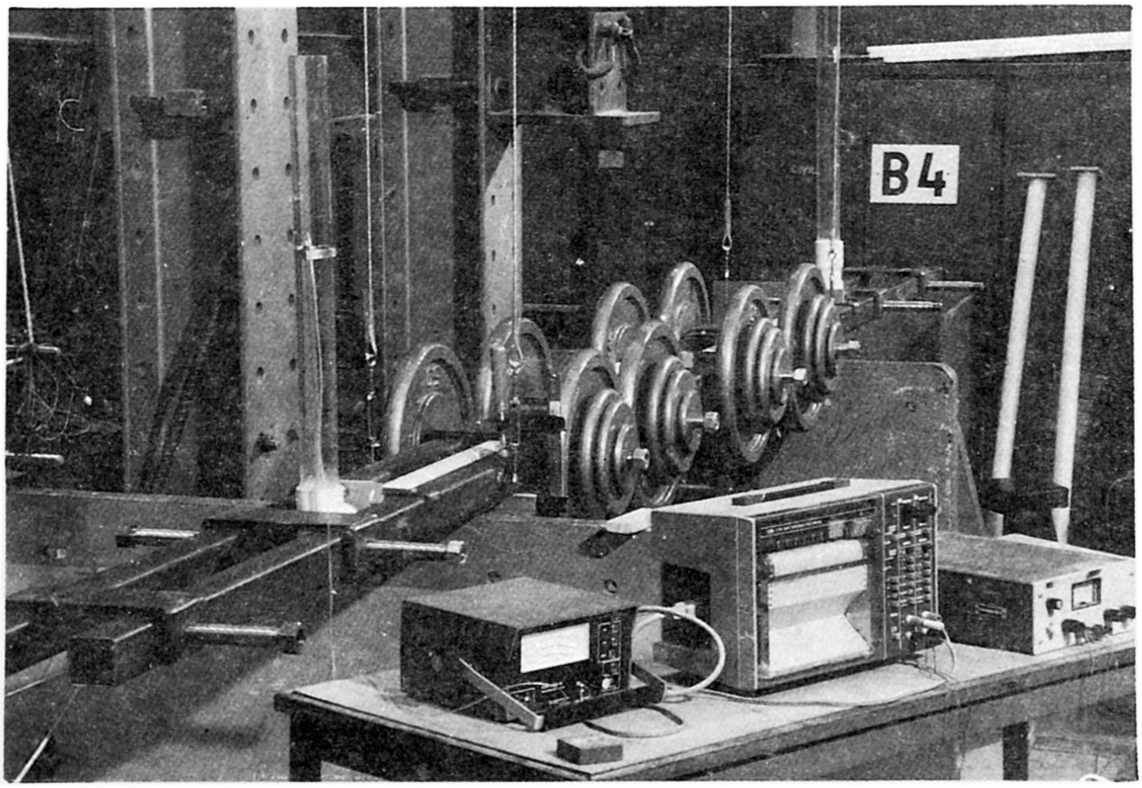

Fig.3 Test set-up

		No TLCD	Orifice Opening Ratio				
			100%	80%	60%	40%	20%
Mass Ratio	1%	0.6	2.4	2.6	3.0	3.3	1.7
	2%	0.8	2.1	2.4	2.8	4.9	3.4
	3%	1.2	3.3	3.5	3.8	6.6	5.4
	4%	1.3	2.7	2.8	3.9	8.5	6.7

Table 1 Damping ratios of the system for 100% tuning

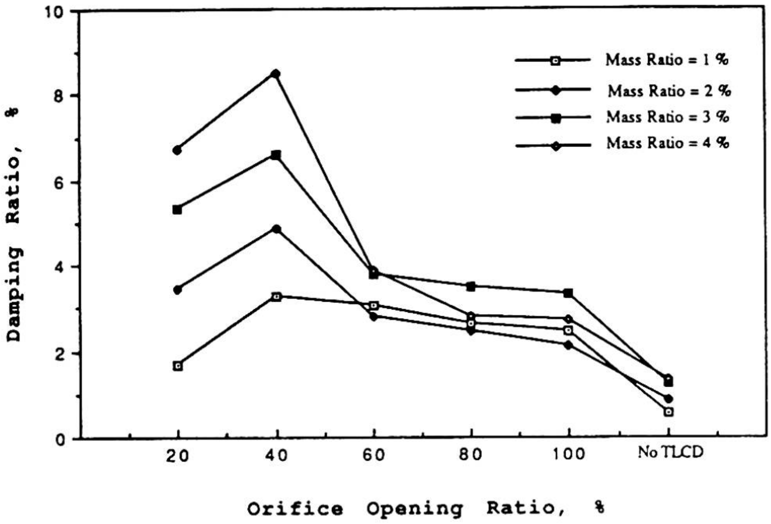

Fig. 4 Variation of damping ratio with orifice opening and mass ratio for 100% tuning

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