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New Damper for Tower of Long-Span Suspension Bridge

Nouveau système amortisseur pour la pile d'un pont suspendu de grande portée

Schwingungsdämpfer für die Türme einer grossen Hängebrücke

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SUMMARY
A new damper, relying on the motion of shallow water in a rigid cylinder, is studied through free vibration tests of a single-degree-of-freedom model of bridge tower with a natural period of 2 sec. For a large damping effect at small amplitude of tower vibration, it is necessary to tune the sloshing period of the liquid to the natural period of the tower; hence the name Tuned Liquid Damper. Breaking of surface waves, while highly dependent on vibration amplitude, is the main mechanism of energy dissipation. There seems to be an optimal TLD size for a given frequency and amplitude of vibration.

RÉSUMÉ
Un nouveau système amortisseur, basé sur le mouvement de l'eau dans un cylindre rigide est étudié au moyen d'essais de vibrations libres dans un modèle à un degré de liberté pour une pile de pont présentant une période naturelle de deux secondes. Afin d'obtenir un important effet d'amortissement pour une faible amplitude de vibrations de la pile, il est nécessaire d'ajuster la période de liquéfaction du liquide à la période naturelle de la pile; d'où le nom d'"amortisseur liquide accordé". Le brisement de la surface des vagues dépend directement de l'amplitude de vibrations, et est le mécanisme principal de dissipation de l'énergie. Il semble exister un "amortissement liquide accordé" pour chaque fréquence et amplitude de vibration.

ZUSAMMENFASSUNG
Ein neuartiger Schwingungsdämpfer, basierend auf der Schwappbewegung von Wasser in einem steifen Zylinder, wird mit Versuchen an einem Modell für einen Brückenturm von 2 Sekunden Grundschwingungszeit studiert. Für eine hohe Dämpfungswirkung bei kleiner Schwingungsamplitude muss die Schwapperiode des Wassers auf diejenige des Turmes abgestimmt werden; daher die Bezeichnung: abgestimmter Flüssigkeitsdämpfer. Das Brechen der Oberflächenwellen ist stark von der Schwingungsamplitude abhängig und bildet die Hauptursache der Energiedissipation. Es scheint für jede Kombination von Frequenz und Amplitude eine andere optimale Dämpfergrösse zu resultieren.

1. INTRODUCTION

With the increase of span length, the wind-induced vibrations of the towers of cable-suspended bridges tend to become a subject of discussion, not only at the free-standing erection stage but also after the completion of the bridge, particularly in case of cable-stayed bridges where the constraint of stay cables on the lateral bending of the tower is unexpectedly small. To increase the structural damping is an efficient way to suppress such vibrations.

This contribution discusses a new kind of mechanical damper, herein named Tuned Liquid Damper (TLD) [Fig. 1] relying on motion of shallow liquid inside a rigid container for absorbing and dissipating structural vibration energy. Liquid dampers have been in use in space satellites and marine vessels. Modi and Sato [1, 2] were among the first to suggest their application to ground structures including towers and buildings. Growing interest in TLD [3-5] is attributable to several potential advantages, including low cost, easy installation even in already existing structures, few maintenance requirements, and adaptability to temporary use. However, adequate modelling and clear explanation of TLD mechanism are lacking despite studies so far indicating its effectiveness. Here are reported some insights and data from an experiment designed to demonstrate the TLD's fundamental mechanism, with emphasis on parameters that immediately relate to practical implementation.

2. EXPERIMENT PROCEDURE

To simulate one mode of a tall flexible bridge tower, a heavy steel platform [Fig. 2] was designed with natural period T_S of 2 sec (or frequency f_S= 0.5 hz), and mass m_S ranging from 116 to 440 kg. The structure, i.e. platform, was given initial displacement while taking care that the liquid in the TLD was quiescent before the structure was released into free vibration. Both structural displacement and liquid surface height at one side of the TLD were recorded.

Unlike in past experiments that employed small models, large prototype-size cylinders (40 cm and 60 cm diameters) were used here as liquid containers, with a view to using multiple identical TLDs in massive actual towers. With mass ratio, dimension, and vibration frequency thus made equal to those of prototype, it was possible to sidestep some dynamic fluid similarity requirements that would be difficult if not impossible to satisfy simultaneously.

3. RESULTS OF EXPERIMENT

Additional damping $\Delta\delta$ (= logarithmic decrement with TLD attached - structural damping) is shown in Fig. 3 for several cases where Φ = 40 cm; m_S = 116 kg; and the liquid is plain water. Figure 4 shows a comparison of TLD for the diameters 40 cm and 60 cm. A = amplitude of structural vibration; h = depth of liquid; a = $\Phi/2$ = radius of cylinder; γ = ratio of fundamental sloshing frequency of liquid to frequency of structure; μ = ratio of liquid mass to mass of structure.

<u>3.1 Effect of frequency tuning</u>: Each curve of $\Delta\delta$ versus A in Fig. 3 corresponds to a different liquid depth h and, accordingly, different frequency ratio γ. It should be noted that the liquid in TLD is generally shallow, e.g. the ratio h/a is below 0.1 in most of the cases where additional damping is significant. As Figs. 3 and 4 show, high additional damping $\Delta\delta$ is obtainable when the frequency ratio is about γ = 1.0, which is the nominal tuning condition for the present system. The additional damping at tuned condition is particularly high when the amplitude A is small. In fact $\Delta\delta$ exhibits strong dependence on A when γ = 1.0, and has a peak at a certain small amplitude. The peak $\Delta\delta$ just

mentioned corresponds to a liquid mass that is only about 1% of structure. On the other hand, additional damping $\Delta\delta$ is rather low at frequency ratios that are very different from $\gamma = 1.0$, despite large liquid mass ratio.

Figure 4 shows that the condition of tuning seems unnecessary, however, for large amplitude A, where the same moderate additional damping $\Delta\delta$ is obtained almost regardless of frequency ratio γ. This may suggest the use of γ less than 1.0, to make the liquid mass ratio μ accordingly lower. Still, γ should be close to 1.0 if high $\Delta\delta$ is to be obtained specially at small A; the name Tuned Liquid Damper is on account of this latter requirement.

3.2 Effect of container size: In tuning the natural frequency of liquid to the frequency of structure, it is possible to choose from among different sizes and their corresponding required liquid depths. The question in practice is whether to use one large TLD or multiple smaller ones. Figure 4 can also compare the efficiency of TLD for different diameters. On comparing the respective peaks of $\Delta\delta$ at about $\gamma = 1.0$ and μ=1.2%, it is seen that the larger TLD gives higher peak $\Delta\delta$. Figure 5 compares one large TLD with five small ones, again showing that the peak $\Delta\delta$ is higher for larger TLD, even as almost equal mass ratios correspond to these peaks. Thus for the present case it is indicated that, for the same mass ratio, the bigger TLD is more effective in producing large $\Delta\delta$.

3.3 Effect of other parameters: As presented in detail in Ref. 5, higher $\Delta\delta$ is produced with: low viscosity of liquid; smooth bottom of container; and adequate gap between liquid and roof of container. Additional damping is practically linearly proportional to liquid mass ratio or number of identical TLDs, provided the frequency ratio is about $\gamma = 1.0$ and the mass ratio is low.

4. DISCUSSIONS

4.1 Liquid motion and additional damping: As Fig. 3 illustrated, the additional damping $\Delta\delta$ due to the TLD depended much on structural vibration amplitude A. In fact the type of liquid motion changed as the amplitude A. It was found that the type of liquid motion consistently corresponding to rather large $\Delta\delta$ (say, $\Delta\delta > 0.03$ in Fig. 3) is that with two waves travelling on half-circles along the wall, as shown in Fig. 6.

Wave height was also measured at a point near the container wall, on a diameter along the direction of structural motion. Figure 7 shows an example wave record and its counterpart structural displacement record, corresponding to curve (3) in Fig. 3. The wave record provided a good estimate, even if the recorded positive peaks included some effect of splashing during the type of liquid motion described in Fig. 6, and even if very low wave troughs could not be recorded at all.

For the case shown in curve (3) in Fig. 3, $\Delta\delta$ had a peak value at around A = 0.25 cm and dropped drastically for still smaller amplitude. Inspection of the wave record showed that for A > 0.25 cm, the wave height H was greater than 1.2 cm which was the depth of liquid h in that TLD. Wave breaking, with the associated turbulence at the wave crest, was to be expected when wave height H reached a value about equal to liquid depth h; indeed turbulence at the wave crest was observed during the experiment.

The same case also showed, however, that while wave breaking occurred the resulting $\Delta\delta$ would not necessarily be larger or the same at larger amplitude A. This could be understood by recalling that $\Delta\delta$ is proportional to the ratio $\Delta E/E$, where the kinetic energy E in the denominator is proportional to A^2. The per cycle energy dissipation ΔE in the numerator turned out to be nearly proportional to A [Fig. 8] rather than A^2, for the range of amplitudes considered. This indicates that $\Delta\delta$ is attributable to energy dissipation rather than mere absorption by the damper. In other words, $\Delta\delta$ is attributable to dissipation by wave breaking instead of mere transfer of energy into the liquid. Should simplified mechanical modelling of TLD in terms of mass, spring, and damping elements be attempted, the almost linear relation between per cycle energy loss ΔE and amplitude A [Fig. 8] in the amplitude range considered suggests a property of coulomb-type damping instead of viscous.

4.2 Choosing the appropriate size of cylinder: Figures 4 and 5 showed that, for the same liquid mass ratio, the bigger (60 cm) TLD was better since higher $\Delta\delta$ was produced. The advantage of the bigger diameter, for given period of TLD vibration, may be associated with the manner of liquid motion [Fig. 6]: two waves develop along half circles and hit together twice per cycle. Each time that the waves meet, the energy dissipated is proportional to the velocity of the converging waves; this velocity is in turn proportional to the length of the half-circle arc that they traverse every half-cycle.

Energy loss per cycle was plotted versus amplitude A in Fig. 8, for 40 cm and 60 cm TLDs at $\gamma = 1.0$. It showed that, at each amplitude A, the energy loss per cycle in the 60 cm TLD was almost 10 times that in the 40 cm TLD. The mass ratio involved in both cases was $\mu = 1.2\%$; but the actual liquid mass in the 60 cm TLD was 4 times as much. The ΔE per unit liquid mass was almost 2.5 higher in the larger TLD.

Other considerations may rule out the use of very large TLD, however. Figure 9 illustrates that for tuning to given period (or given frequency), there is a wide range of possible cylinder sizes; each size Φ has its own corresponding required liquid depth h. The necessary relative liquid depth h/Φ is not constant, however; instead it increases rapidly in the range of large Φ. Very high h/Φ in very large TLD would not be very efficient, as some liquid near the bottom would tend to be immobile and ineffective. Limitations on available space for installation would be another practical constraint.

In any case, the deeper liquid would require a higher wave height H, hence a larger structural amplitude A, before energy dissipation by wave breaking can start. For example, the 40 cm TLD required about A = 0.5 cm [Fig. 3]; the 60 cm TLD required about A = 1 cm. It is indicated that there may be an optimal size of TLD for given structural period (or frequency), amplitude of vibration, and space limitation.

5. SUMMARY

A new kind of mechanical damper, called Tuned Liquid Damper or TLD, which has certain advantages for suppression of vibrations of tower-like structures was investigated experimentally. It is indicated that energy dissipation in TLD is due mainly to wave breaking, which explains various TLD properties.

Within the range of parameters considered in the experiment, the larger TLD is more effective. However, because of changing liquid condition from shallow to deep, for given frequency and amplitude of structure there may be a cylinder diameter that produces optimal amount of additional damping. Limitation of space for installation would be another practical constraint to TLD size. The subject of optimal TLD size still requires further investigation.

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REFERENCES

1. MODI, V.J. and WELT, F. 1987. Vibration control using nutation dampers. Proc Intl Conf Flow Induced Vib, Bowness-in-Windermere, England, 369-376

2. SATO, T. 1987. Tuned sloshing damper. Japan J Wind Eng, 32, 67-68

3. MIYATA, T., YAMADA, H., and SAITOH, Y. 1987. Feasibility study on damping of wind-induced vibrations of structures by breaking of sloshing water. Japan J Wind Eng, 32, 65-66 (in Japanese)

4. NOJI, T. et al. 1987. Study on a vibration damper system using hydrodynamic force of sloshing (Parts 1,2,3). Proc Conf Arch Inst Japan, 867-872 (in Japanese)

5. FUJINO, Y. PACHECO, B.M., CHAISERI, P., and SUN, L.M. 1988. Fundamental study on tuned liquid damper (TLD)- a new damper for building vibrations. Proc Symp/Work on Serviceability of Bldgs, Ottawa, Ontario, Canada, 14pp

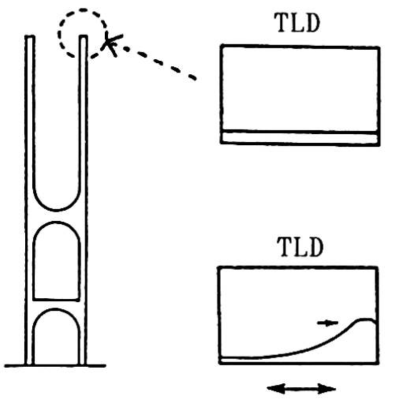


Fig. 1 TLD installed on a bridge tower

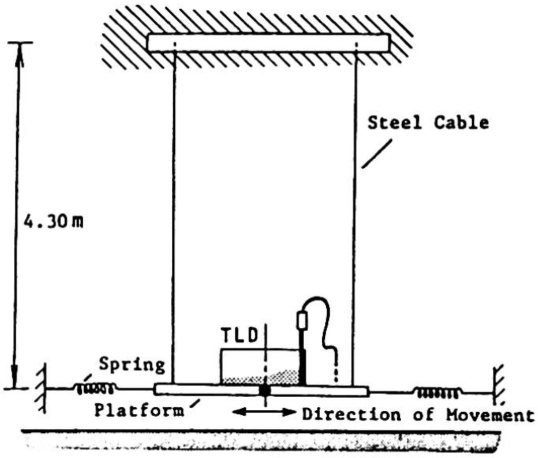


Fig. 2 SDOF structural model with TLD

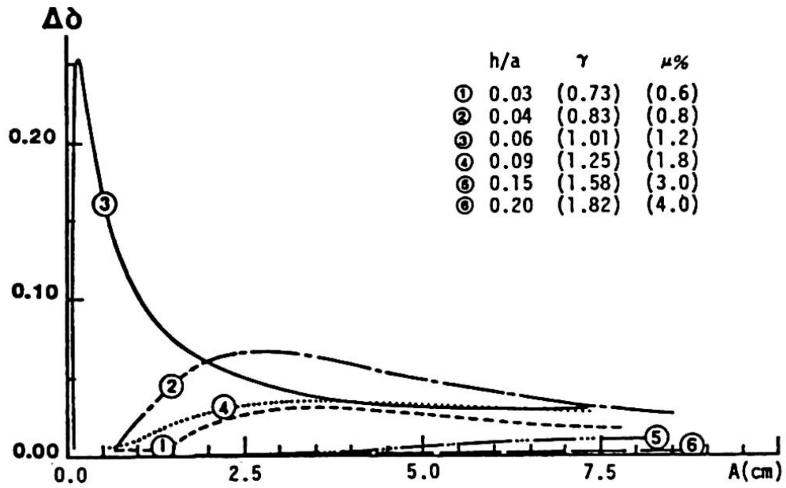
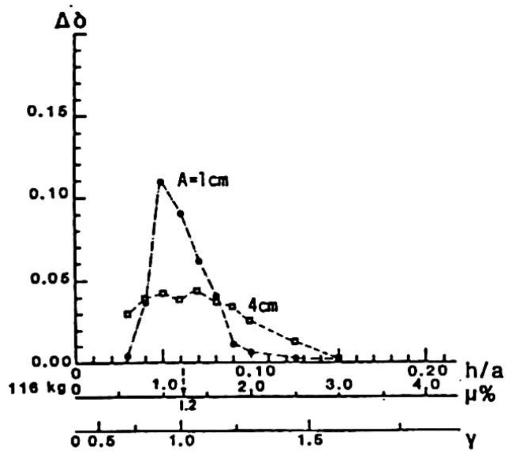
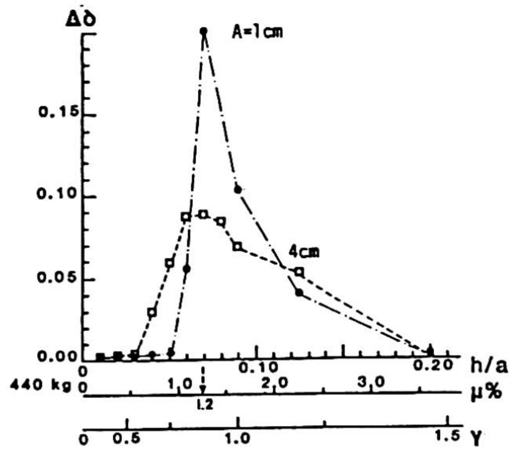


Fig. 3 Additional damping due to TLD



(a) Φ = 40 cm; m_S = 116 kg



(b) Φ = 60 cm; m_S = 440 kg

Fig. 4 Comparison of TLD for the diameters 40 cm and 60 cm

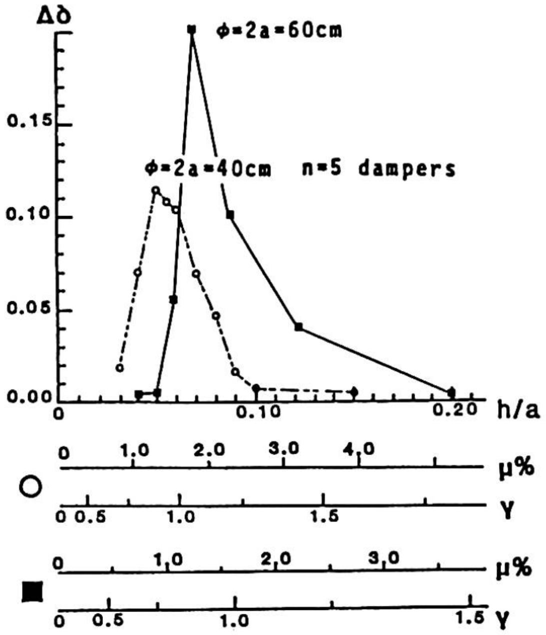


Fig. 5 Comparison of one large and five small TLDs (m_S = 440 kg)

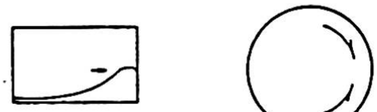


Fig. 6 Liquid motion when $\Delta\delta$ is large

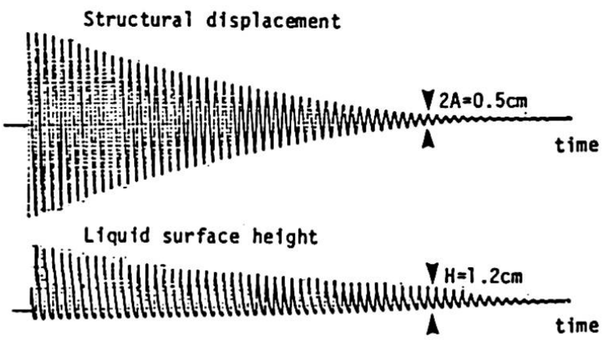


Fig. 7 Time histories for Case (3) in Fig. 3 (γ = 1.0; h = 1.2 cm)

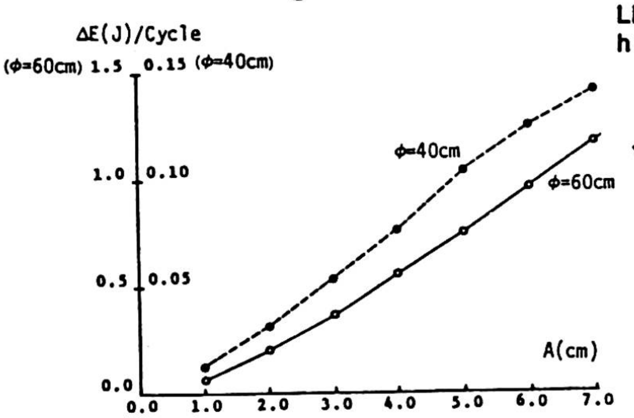


Fig. 8 Energy loss per cycle versus vibration amplitude

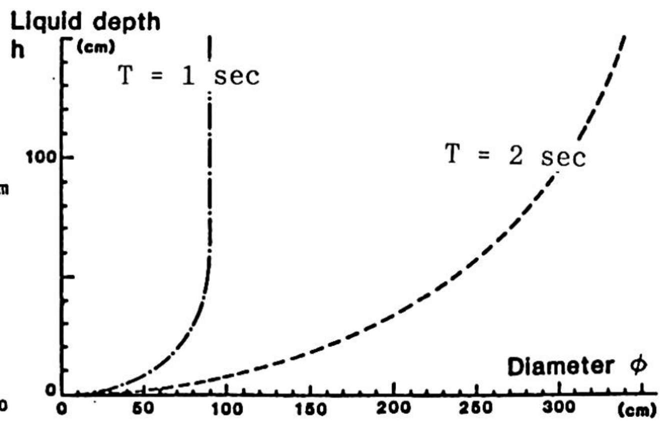


Fig. 9 Required depth versus container diameter