WIND-INDUCED VIBRATION CONTROL OF TALL BUILDINGS BY MULTIPLE TUNED LIQUID COLUMN DAMPERS

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1 INTRODUCTION

Modern high-rise buildings possess relatively little natural damping in the form of masonry walls or cladding. As such they are susceptible to oscillations caused by wind. Conventional methods of increasing mass and stiffness to alleviate excessive motion are costly both in terms of materials and construction time. As a result, a number of different damping devices, such as tuned mass dampers, have been developed to assist in providing vibration control to these structures.

A more recent device is the Tuned Liquid Column Damper (TLCD) first proposed by Saka'i et. al. (1). The damping mechanism for this system is based on the principle of hydraulic head loss by means of water passing through an orifice in a column to dissipate energy. The restoring force due to gravity acting upon the liquid also contributes to the increase in damping of the system. The practical advantages of this device are its ease of tuning and that it can utilise water already required near the top of most tall buildings for fire fighting and water supply purposes.

Previous research by Xu et. al. (2) and Samali (3) has concentrated on using only one TLCD to provide energy dissipation. In this paper, the effectiveness of using Multiple Tuned Liquid Column Dampers (MTLCD) in controlling the cross-wind response is presented. The concept of multiple dampers has been proven effective by Fujino and Abe (4) in relation to tuned mass dampers and by Fujino and Sun (5) in relation to tuned sloshing dampers and the same concept is extended to tuned liquid column dampers in this paper. In a MTLCD system, rather than having just one column tuned to a specific frequency, as is the case for a single TLCD, the MTLCD system used here has seven TLCDs, each tuned to a frequency within the vicinity of a natural frequency of the structure. The effect of varying the design parameters such as the coefficient of head loss (a function of the orifice opening ratio), the tuning ratio (the ratio of the natural frequency of an individual TLCD to that of the building) and the mass ratio (the ratio of total damper mass to the mass of the building) were investigated.

MTLCD has the potential to alleviate much of the sensitivity to tuning ratio that is encountered when using one TLCD. In addition, the control of more than one mode of vibration can be achieved by tuning the MTLCD specifically to the appropriate natural frequencies of the structure.

2 ANALYTICAL PROCEDURE

A 40 storey and 50 storey building were used in the analysis. Both buildings were modelled as lumped mass multi-degree-freedom shear buildings. The problem was formulated in terms of transfer matrices in the frequency domain. The analysis uses the governing equation of motion for a TLCD given by Saka'i et. al. (1) as

$$\rho A L \ddot{x} + 0.5 \rho A \xi |\dot{x}| \dot{x} + 2 \rho A g x = - \rho A B \ddot{y} \qquad (1)$$

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 column, the width and the cross sectional area of the tube. ξ is a constant which is defined as the coefficient of head loss and g is the acceleration of gravity. The natural frequency of the liquid column tube of Figure 1 is given by

$$\omega_1 = (2g / L)^{0.5} \qquad (2)$$

The non linear damping term in (1) is treated by an equivalent linearisation technique as shown by Xu et. al. (2). Thus (1) becomes

$$\rho A L \ddot{x} + 2 \rho A C_p \dot{x} + 2 \rho A g x = - \rho A B \ddot{y}_N \qquad (3)$$

in which C_p is the equivalent damping coefficient which is related to the coefficient of head loss and the velocity of the liquid column.

A random vibration analysis was carried out to determine the response statistics.

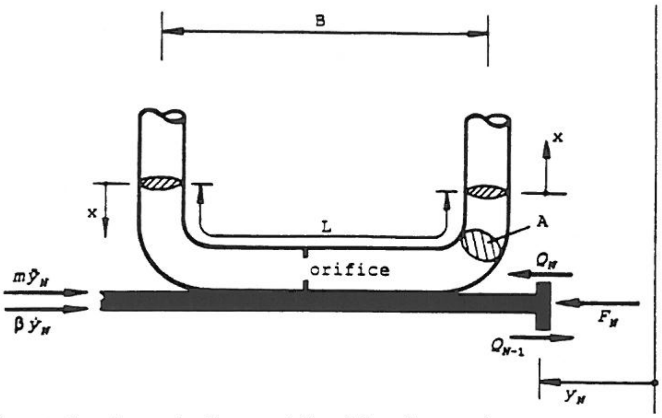

Figure 1: A typical tuned liquid column damper

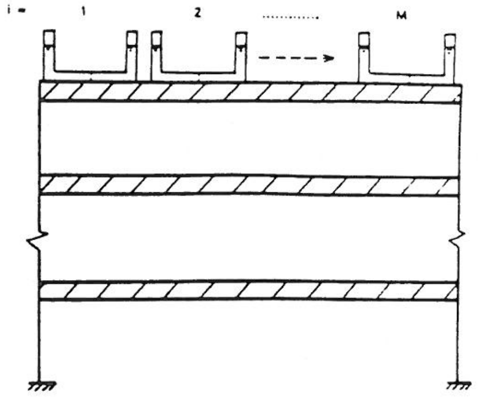

Figure 2: MTLCD model

The first objective of the study was to determine the effect of a MTLCD system upon the structural response by varying the mass ratio, orifice opening ratio and tuning ratio. A MTLCD system was chosen which consisted of seven individual TLCDs located on the top floor of the 40 storey building, as shown in Figure 2. The tuning ratios of the TLCDs were distributed in 1% increments above and below a "central tuning ratio". For example a central tuning ratio of 100% of the first natural frequency of the building would yield the following distribution:

TLCD No	1	2	3	4	5	6	7
Tuning Ratio	97	98	99	100	101	102	103 (%)

An iterative process is required to solve for C_p as it is dependent upon the standard deviation of the liquid velocity. The liquid velocity of the TLCD corresponding to the central tuning ratio was used in this process.

For each orifice opening ratio, the central tuning ratio was varied between 95% and 101% of the first natural frequency of the structure over a mass ratio range of between 0.5% and 4.5%. The mass ratio represented the ratio of the total liquid mass of the seven TLCDs to the structure mass, expressed as a percentage.

An average cross-sectional area was calculated by dividing the total liquid mass by the sum of the column lengths. This area was then used for each TLCD in the MTLCD system.

The 40 storey building possessed a first vibrational period of 5.8 seconds and had the same mass and inter-storey stiffness assigned to all floors. The total building mass was 51,600 tonnes, corresponding to a floor mass of 1,290 tonnes. Figures 3a and 3b illustrate the effectiveness of the MTLCD system in controlling the base shear force and top floor acceleration. The response has been normalised against the response obtained when there was no damping system present. The following conclusions may be drawn:

1. Of the seven central tuning ratios investigated (ie from 95% to 101% in 1% increments), 95% was found to be the optimum over virtually all mass ratios and orifice opening ratios.

2. For mass ratios below approximately 1.25%, for both base shear force and top floor acceleration, an orifice opening ratio of 46% was the most effective. For mass ratios higher than this an orifice opening ratio of 25% gave optimum results for both response types. Higher mass ratios gave increasingly better response reductions for a 25% orifice opening. Reductions of 68% for top floor acceleration were achieved for mass ratios around 4%. However, even a mass ratio of 1.25%, which would be considered a practical value, still produced a reduction in top floor acceleration of about 57%.

3. As orifice opening increased, the optimum response reduction decreased. In addition, the optimum mass ratio decreased as the orifice opening ratio increased.

The 50 storey building was then used to investigate the following:
a)The effect of varying the tuning ratio distribution within the MTLCD system.
b)The sensitivity of both the MTLCD system and a single TLCD to being out of tune by up to 20%.
c) The effectiveness of having MTLCD systems tuned about both the first and second natural frequencies of the building.

The total mass of the 50-storey building was 109,500 tonnes. The first three natural frequencies were 1.08, 2.35 and 4.02 radians per second, respectively (or 0.172, 0.374 and 0.640 Hz, respectively).

The responses due to five different tuning ratio distributions about the first natural frequency were compared with the results of the uncontrolled case and the case of only one TLCD tuned to the first natural frequency. With the exception of the single TLCD, seven TLCDs were used in all other cases. Each distribution had a central tuning ratio of 100% of the first natural frequency.The results indicated that:

1. Those distributions which had the tuning ratios of the TLCDs distributed over a wide range below the first natural frequency of the structure were least effective (ie Distribution Nos 2 and 4 in Table 1). Indications are that a distribution covering 10% above and below the first natural frequency of the structure would be likely to yield the best results. There is virtually no difference in effectiveness of the MTLCD and a single TLCD. The response is not very sensitive to the tuning distribution chosen, provided that the central tuning ratio remains constant.

2. The sensitivity to tuning ratio is reduced by using a MTLCD system rather than a single TLCD. The further the central tuning ratio deviates from the first natural frequency of the building (ie 100%) the greater the effectiveness of the MTLCD system over the single TLCD. This is particularly true when the dampers are tuned to values above the first natural frequency of the building.

3. Both first and second mode control can be achieved by tuning a single TLCD or a MTLCD system to each of the first and second natural frequencies of the structure. In addition, response reductions can be further improved by varying the mass distribution between the two modes as shown in Table 2. The following combinations were considered :

(a) 1 TLCD tuned to first natural frequency of the structure and 1 TLCD tuned to second natural frequency.
(b) 7 TLCDs distributed about the first natural frequency and 1 TLCD tuned to second natural frequency.
(c) 7 TLCDs distributed about the first natural frequency and 7 TLCDs distributed about the second natural frequency.

The results presented in Table 2 pertain to combination (b). The idea behind this approach was that instead of increasing the mass ratio at the first natural frequency (ie, a traditional single TLCD), this additional mass could be distributed about the second natural frequency hoping that a greater response reduction could be obtained by controlling both the first and second modes of vibration. It should be noted that this will only be significant for force or acceleration type responses as these are dependent upon higher modes of vibration. It can be seen from Table 2 that the combination of 2% damper mass at the first mode and 1% at the second, has produced the best results in terms of response reduction. This combination can reduce the acceleration response by a further 9%

compared with the case where the entire mass (3%) is associated with the first mode of vibration.

Table 1 : Response due to variation of tuning ratio distribution about the first natural frequency - 50 storey building

TLCD Arrangement	**Standard Deviation of Base Shear Force**		**Top Floor Displacement**		**Top Floor Acceleration**	
	kN	**% red.**	**mm**	**% red.**	**mil.g**	**% red.**
Uncontrolled	13793.0	-	225.23	-	30.32	-
1 TLCD	10181.8	26.18	167.23	25.75	21.50	29.09
Distribution 1	10179.8	26.20	167.05	25.83	21.50	29.09
Distribution 2	10648.9	22.80	170.12	24.47	22.62	25.40
Distribution 3	10273.8	25.51	168.60	25.14	21.59	28.80
Distribution 4	10510.9	23.80	166.88	25.91	22.44	25.99
Distribution 5	10177.1	26.22	165.70	26.43	21.51	29.06

$\xi = 30.1$ (orifice opening = 25%)
Total damper mass = 2%
Single TLCD Tuning ratio = 100% of first natural frequency of building
Distribution 1 - 97%, 98%, 99%, 100%, 101%, 102%, 103%
Distribution 2 - 70%, 80%, 90%, 100%, 110%, 120%, 130%
Distribution 3 - 90%, 93%, 97%, 100%, 110%, 120%, 130%
Distribution 4 - 70%, 80%, 90%, 100%, 103%, 107%, 110%
Distribution 5 - 90%, 93%, 97%, 100%, 103%, 107%, 110%

Table 2. Response due to variation of mass distribution between the first and second mode dampers - 50 storey building

TLCDs Distributed About First Mode		**TLCDs Distributed About Second Mode**		**% of Total Damping Mass Distributed At Second Mode**	**Standard Deviation Of Top Floor Acceleration**	
TLCD No. off	**% building mass**	**TLCD No. off**	**% building mass**		**mil-g**	**% reduction**
-	-	-	-	-	30.32	-
1	3.0	-	-	-	21.87	27.87
7	3.0	-	-	-	22.43	26.02
7	2.25	1	0.75	25	19.21	36.64
7	2.0	1	1.0	33.3	19.14	36.87
7	1.5	1	1.5	50	19.36	36.15
7	1.0	1	2.0	66.6	20.16	33.51

MTLCD distribution at first mode = 97% 98% 99% 100% 101% 102% 103%
$\xi = 5.21$ (46% orifice opening ratio)
Total damper mass = 3% of building mass

3 CONCLUSIONS

It is concluded that MTLCD damper system are effective in suppressing cross-wind induced vibrations of tall buildings. When considering first mode control, the tuning ratio distribution within the MTLCD system can be varied to provide optimum response reductions without the need to increase the mass ratio.

The sensitivity to tuning ratio, encountered when using a single TLCD, is greatly reduced when a MTLCD system is used. This is considered to be a significant advantage of using a MTLCD system rather than a single TLCD. First and second mode control can be achieved through the use of either two single TLCDs or two MTLCD systems (or combinations of the two) tuned about the first and second natural frequencies of the structure. Furthermore, response control can be improved by varying the mass distribution between the damper systems at the first and second natural frequencies of the structure.

4 REFERENCES

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