LIQUID TUNED DAMPERS FOR THE MITIGATION OF WIND INDUCED VIBRATION

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ABSTRACT: *This paper describes the principles of liquid tuned dampers and how they may be introduced into multi-storey building design to reduce building vibrations in wind storms. A case study is described and the effectiveness of the dampers is demonstrated by comparing the building response both with and without the installation of dampers..*

KEYWORDS: Damping, Liquid Tuned Dampers, alteration of structural response, vibration

1 INTRODUCTION

High strength materials have allowed the reduction of member sizes and the increase of spans of structures compared to the norm of thirty years ago. This gain in strength typically results in a decrease in the amount of material used in construction, a reduction in mass, and most likely a reduction in stiffness. Both of these reductions can give rise to modern light weight structures being more dynamically sensitive to ambient loading such as wind and traffic loads. This response is often described in terms of; "lively" floors and bridges and as "wind sensitive" buildings.

In all instances these reflect poorly on the design, yet they are quite difficult to detect in advance as codes and design guides can only give guidance. The issue of unwanted structural vibration is further complicated as it is subject to human perception and expectation. It is a fact that some people are more sensitive to vibrations than others. In addition, expectations can influence outcomes, thus owners of very expensive apartments most probably anticipate less vibration and noise than owners in the cheaper areas of town.

When designing structures that are known to have long spans, are high and/or light weight it is important that the possibility of unwanted vibration is anticipated early in the design process. Then possible steps towards mitigation including; adding more mass, providing more stiffness (or both) and possibly adding additional damping can be contemplated. This paper overviews the situation where the latter approach was undertaken and a multi-storey building was designed to have additional damping through the addition of liquid tuned dampers to mitigate possible wind induced vibration.

2 DAMPING IN BUILDINGS

Damping is a property that while acknowledged as present in buildings, is not specifically included in the design. Engineers are able to specify; weight, mass, stiffness and strength, but are required to accept whatever damping they end up with. This lack of knowledge does not influence most designs, as the mass and stiffness usually ensure by default a satisfactory performance. However in structures that could possibly be vibration sensitive, the amount of damping is often important, but unknown, especially at the time of design. The best a designer can do is to refer to guidance from test results of previously built similar structures. This may not always be satisfactory approach, as the possible range of damping in the structure is most likely to be about equal to, but possibly less than the amount of damping specified as required by a wind consultant to ensure an acceptable dynamic performance.

To guarantee a specific value of damping, the most secure way for the designer, is to provide in the design "additional" damping. This can take the form of an energy absorbing material introduced in positions of relative movement within the structure, or a device that moves to oppose the motion of the building. This concept is described in the following development.

Eq. 1 is the equation of motion for a multi-degree of freedom structure:

$$m\ddot{u} + c\dot{u} + ku = w(t) \tag{1}$$

where m, c, and k are the mass, damping and stiffness matrices respectively for the building and w(t) is a driving force, in this case, the wind on the building. This equation can be simply rearranged to:

$$w(t) - ku - c\dot{u} = m\ddot{u} \tag{2}$$

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which is in the form “F = ma”. This shows that the wind force attempting to push or accelerate the building, while the stiffness forces, ku, and the damping forces, $c\dot{u}$, are trying to resist or reduce it. It is usual in this context to express all damping in the building as “equivalent viscous” damping, that is, as a force that is proportional to the velocity of the system, that is trying to slow the system down. In buildings the damping forces are smeared throughout, and are the result of energy losses due to; material strain and slight movements between members, both structural and non-structural. The form of “c” the damping matrix is unknown but in classical structural dynamics it is assumed that it will take a form that allows the decoupling of the equations when they are expressed in terms of their modal components. Thus if the ith mode displacements of the building are expressed as:

$$u^i = \emptyset^i Z_i \tag{3}$$

where $\emptyset^i$ is the i^{th} mode shape and Z_i is a representative displacement, say for example, a horizontal displacement on the top floor, then by using the orthogonality properties of the mode shapes, Eq. (2) can be expressed as

$$\emptyset^{i\,T} w - k_i^* Z_i - c^* \dot{Z}_i = m^* \ddot{Z}_i \tag{4}$$

giving rise to a single degree of freedom equation of motion in terms of the displacement, Z_i. The coefficients of the displacement, Z_i and its derivatives, velocity and acceleration, are the generalised stiffness, damping and mass terms for the i^{th} mode. The terms; $\emptyset^{i\,T} w \text{ and } c^*$ are unknown, but k_i^* and m_i^* can be calculated, and their ratio

$$\sqrt{k_i^* / m_i^*} = \omega_i \tag{5}$$

provides an expression for the frequency of the i^{th} mode (in radians).

Added damping can be introduced into Eq. (4) simply as:

$$\emptyset^{i\,T} w - k_i^* Z_i - c^* \dot{Z}_i - F_D = m^* \ddot{Z}_i \tag{6}$$

where F_D is the force applied to oppose $\ddot{Z}_i$.

3 LIQUID TUNED DAMPERS

Liquid (or mass) dampers are essentially mechanisms that are placed within the building to represent F_D in Eq. (6) above. In essence they have a mass, m_d connected to their base through a spring, k_d and a damper, c_d. Their base is securely fastened to the building at degree of freedom Z_i. If the displacement of the mass with respect to the base of the mechanism is defined by u_d, then the equation of motion of the mass is described by:

$$m_d \ddot{u}_d + c_d \dot{u}_d + k_d u_d = -m_d \ddot{Z}_i \tag{7}$$

The force applied to the mass of the damper, or reaction of the base of the mechanism to the building is:

$$F_D = c_d \dot{u}_d + k_d u_d \tag{8}$$

As the motion of the top of a building as a result of wind induced loading will be primarily harmonic, Z_i takes the form of:

$$Z_i = \bar{Z} \sin \omega_i t \tag{9}$$

allowing the solution of Eq. (7) to be obtained and substituted into Eq. (8) to give an expression for the damping force in the form:

$$F_D = \bar{F} \sin(\omega_i t - \alpha) \tag{10}$$

The force provided by the damper to the building, F_D is proportional to the product of the damper mass, m and the peak building acceleration, $\omega_i^2 \bar{Z}$. Its magnitude also depends upon the damping of the damper and the frequency ratio, ω_i / ω_d.

Example plots of the non-dimensional damping force versus frequency ratio are plotted in Fig. (1). It can be seen from this plot, that for a modest amount of internal damping, 5% in this example, the damper can provide a restoring force of a value up to approximately ten times the mass of the damper multiplied by the building acceleration. This scale factor is however a function of the frequency ratio. The scale advantage drops off rapidly if the damper cannot be accurately tuned.

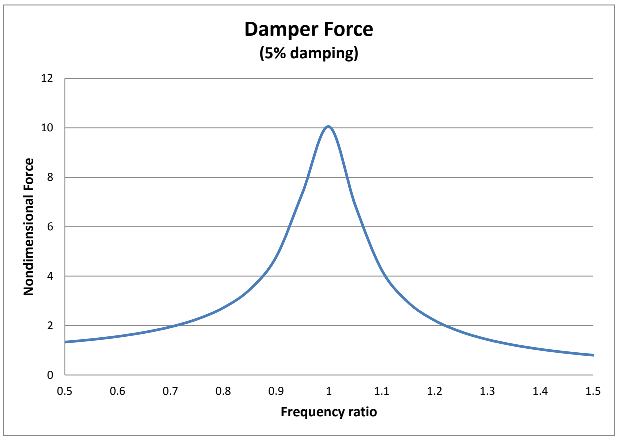

Figure 1: *Damper Force vs Building/Damper Frequency Ratio*

The damper force may also be expressed in term of the displacement of the point of attachment of the building, thus:

$$F_D = c_v \dot{Z}_i + m_v \ddot{Z}_v \tag{11}$$

where c_v and m_v are virtual damping and mass presented to the point of attachment by the damping mechanism. If Eq. (11) is introduced into Eq. (6), a solution can be developed to allow the damper parameters to be adjusted to satisfy the design damping requirements. Figure 2 shows the ratio of damper mass, m_d to modal mass, m_i^* to obtain two values of additional building damping percentages.

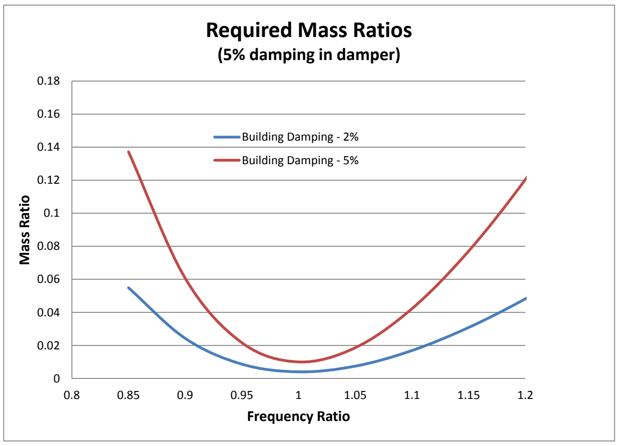

Figure 2: *Required mass of damper to Effective Damping in Building*

The above theory is equally applicable for both added mass and liquid tuned dampers. The latter are essentially a tank or series of tanks of water with the depth adjusted to ensure that the frequency of “sloshing” is adjusted so that the frequency ratio is approximately equal to “1”. Baffles are added to the tanks to provide additional damping to the liquid. The amount of damping provided by the baffles needs to be determined by experiment.

Liquid tuned dampers have a number of advantages over mass tuned dampers. These arise from the design and construction process. While computer models are made of the building during design, differences between the calculated frequency and what may be experimentally determined means that a design based upon computed values will need to allow for later adjustment. In addition, as the frequency of the building will not be known until it is constructed, often there is only a few days between completion and the removal of cranes from the site. Empty tanks can be lifted in place during construction or possibly after the removal of heavy lifting gear. Additional flexibility in this approach is obtained as the mass required can be “poured” into the tanks at a later date. Another advantage arises from the accuracy allowed in providing the required m_d as the density of water is consistent and tanks can be manufactured to a close tolerance.

4 CASE STUDY

Liquid Tuned Dampers (LTDs) were introduced into the design of a 40 storey Auckland building to minimize the possibility of unacceptable wind induced vibrations. Initial wind tunnel studies concluded that an additional damping between 1.5 to 2.5% would be desirable for a suitable performance. The dampers were designed to deliver an additional 2% damping and based upon the dynamic properties of the building obtained from an analysis assuming un-cracked sections. A summary of the properties are presented in Table 1.

Table 1: *Calculated Building Properties*

Mode	Direction	Frequency (Hz)	Mass (tonnes, m^2)
1	Y	0.418	5346
2	X	0.456	4161
3	Rot	0.806	530708

After the completion of major construction including the installation of all glazing and the dampers, wind induced vibrations were recorded to determine the first mode frequencies of vibration and estimates of damping. This was achieved by recording floor accelerations in two orthogonal directions and calculating the Power Spectra, the Cross Power Spectra and the Cross Correlation Functions. The Power Spectra were used to determine the first model frequencies of the building in each of the “X”, “Y” and “θ” directions. The calculation of damping from acceleration records resulting from ambient vibrations is not straight forward and the method used here is described by Farrar [1] and James [2] and discussed by Davidson [3]. It is based upon a theory that assumes that the wind loading can be expressed as “white noise”, this being made, then the Cross Correlation Functions from the records represent decaying sinusoids with frequencies equal to the associated mode and viscous damping terms that represents the “equivalent viscous” damping for that mode. Typical results from the recordings are presented in Figure 3.

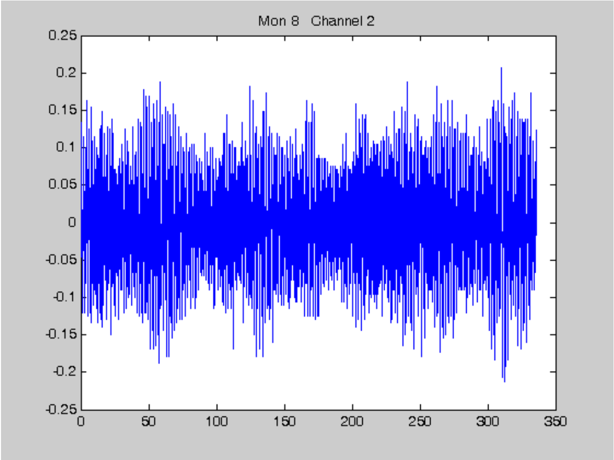

Figure 3a: *Typical Acceleration Time History Recorded*

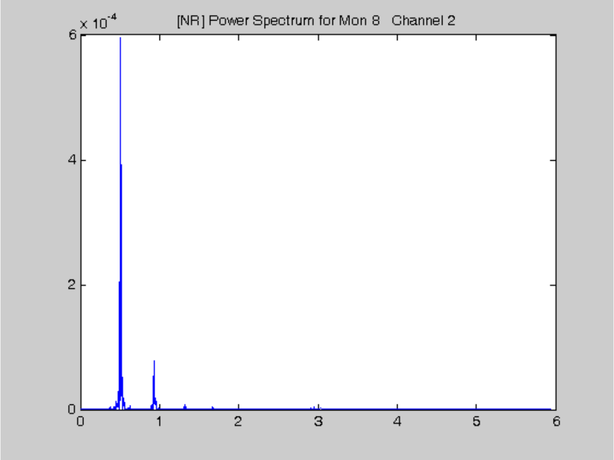

Figure 3b: *Power Spectrum (used to determine natural frequencies)*

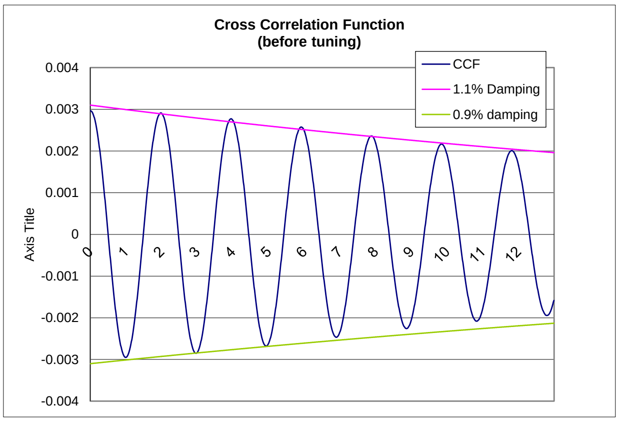

Figure 3c: *Cross Correlation Function – Mode 2 with damping curves*

In Fig. 3(c), the upper (red) and lower (green) curves are the decay terms used to estimate the damping. It is intended that the upper is fitted in an attempt to fit an "upper" bound estimate, the lower a "lower" bound. The chosen properties for tuning are listed in Table 2. While all experimentally determined properties are estimates, it was found that there was little torsional response to the building during the recording period. Consequently, the calculation of damping for the torsional mode had more uncertainty than that for the others.

Table 2: *Experimentally Determined Properties (before tuning of dampers)*

Mode	Direction	Frequency (Hz)	Damping est. (%)
1	X	0.47	0.08
2	Y	0.51	1.0
3	Rot	0.94	0.03 ~ 0.08

The frequencies obtained allowed the dampers to be accurately tuned to obtain the maximum amount of damping. As the experimentally determined frequencies differed from those used in design, water depths were required to differ from design values, which dictated different damper mass and thus the damping provided differed from what was initially intended. However, the objective of providing an addition damping of approximately 2% in the first two translational modes was still able to be satisfied.

The recording of accelerations after tuning allowed the calculation of damping in the building to be determined. Typical results for the Y direction mode are presented in Figure 4.

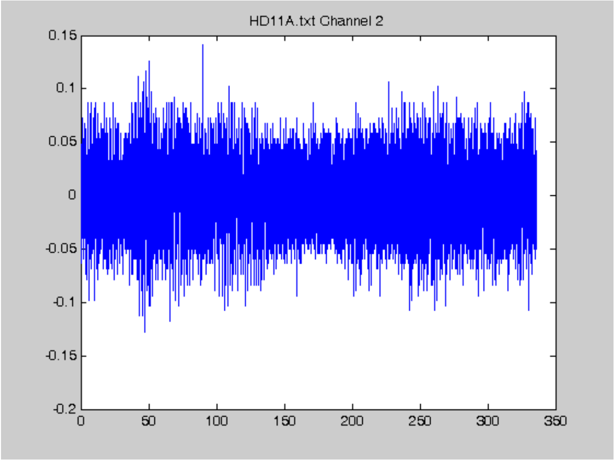

Figure 4a: *Typical Acceleration Time History Recorded*

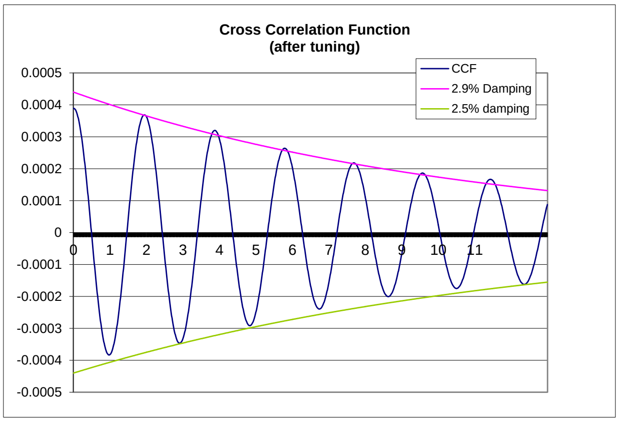

Figure 4c: *Cross Correlation Function – Mode 2 with damping curves*

Table 3: *Experimentally Determined Properties (after tuning of dampers)*

Mode	Direction	Frequency (Hz)	Damping est. (%)
1	X	0.47	2.8
2	Y	0.51	2.9
3	Rot	0.94	~

5 CONCLUSIONS

The performance of the dampers depends upon the accuracy of the tuning. If the dampers are going to be installed prior to the determination of the actual building frequencies, they must be designed to allow for sometimes significant changes in required performance.

While the implementation of LTDs provides a solution that allows for the accurate tuning of the damping system, the time to full them for a significant building can take a number of days.

It is important to demonstrate the performance of the dampers. However, the calculation of damping is not trivial and it is not exact. Damping in buildings is expressed in terms of “equivalent viscous” damping, however the sources of the actual damping mechanisms are unknown and mainly amplitude dependent. Consequently reference can be only be made to estimates of damping.

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