DESIGN AND INSTALLATION OF AN ADJUSTABLE MASS - TUNED MASS DAMPER

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Abstract

A Tuned Mass Damper (TMD) that can be tuned over a wide frequency range by varying auxiliary mass has been designed and installed in a series of slender wind-sensitive cantilever structures making up Melbourne's City Link "Stick" Wall.. A ten-fold increase in damping of the structures was measured in full scale following installation of the TMD units. A state-matrix mathematical model gave good agreement with the measured free-vibration response of the combined Structure/TMD system.

1.0 Background

As part of Melbourne's City Link Project-Western Link, a new 'Stick Wall' has been constructed by Baulderstone Hornibrook Engineering that will present a striking aesthetic effect for motorists using the expressway. The Stick Wall comprises two continuous lines of cantilevered steel boxes standing near vertically at centre to centre intervals of 8 metres. Stick heights vary between 23-27 metres and each Stick has a square cross-sectional area of 1 m^2 resulting in a series of extremely slender wind-sensitive structures.

Baulderstone Hornibrook's Design Consultants, Hyder/CMP Joint Venture, predicted that the cross-wind response of the Sticks would be large due to critical 'lock-in' vortex shedding, interference effects from upstream Sticks and low inherent structural damping. To eliminate potential long-term fatigue problems with the Sticks, Vipac Engineers and Scientists Ltd were commissioned to increase the effective damping of the Stick structures through the implementation of an auxiliary passive damper.

Due to the variability in Stick lengths and foundation types, a reliable design estimate of the first-mode natural frequency of the Sticks was difficult to predict prior to erection. Accordingly, a large Stick natural frequency range of 1.1-2.0 Hz was specified by Hyder/CMP Joint Venture which necessitated a large tuning range for any auxiliary damper. An additional restraint on the design required that any auxiliary dampers should be installed in the Stick structures prior to Stick erection and that they should be easily tuned once in their final position.

2.0 TMD Design

Passive Auxiliary Dampers can be broadly divided into two main categories; namely; Tuned Mass Dampers (TMD) and Liquid Dampers. Liquid Dampers were eliminated at the design stage for two reasons. Firstly, the natural frequency of the liquid inside a Liquid Damper is governed by the geometric configuration of the container and could not be readily tuned over the specified Stick frequency range of 1.1-2.0 Hz. Secondly, a large number of damper units would be required to achieve a high liquid frequency with sufficient effective mass. In addition, access to the damper units following installation was extremely limited and any evaporated liquid (probably water) could not be readily replaced.

A Tuned Mass Damper (TMD) unit was devised that could overcome these constraints and meet the specified design criteria. The final configuration of the TMD in plan view is illustrated in Figure 1 and consists of a cylindrically shaped 'bucket' resting on ball bearing rollers which in turn slide on a flat horizontal steel base plate. The base plate is located approximately 1 metre from the top of each Stick. Four horizontal concentric coil springs of predetermined stiffness connect the bucket to the corners of the Stick structure. In plan view, the whole TMD assembly is encased by the 1 m × 1 m cross-section of the Stick.

A two degree-of-freedom idealisation of the Stick structure and TMD is shown in Figure 2. The circular natural frequency 'ω', stiffness 'k', mass 'm' and damping 'c' of the primary structure (the steel Stick) and auxiliary structure (TMD) are denoted by the subscripts 1 and 2 respectively. The TMD can be tuned to the first mode natural frequency of each Stick structure by varying the mass in the bucket.

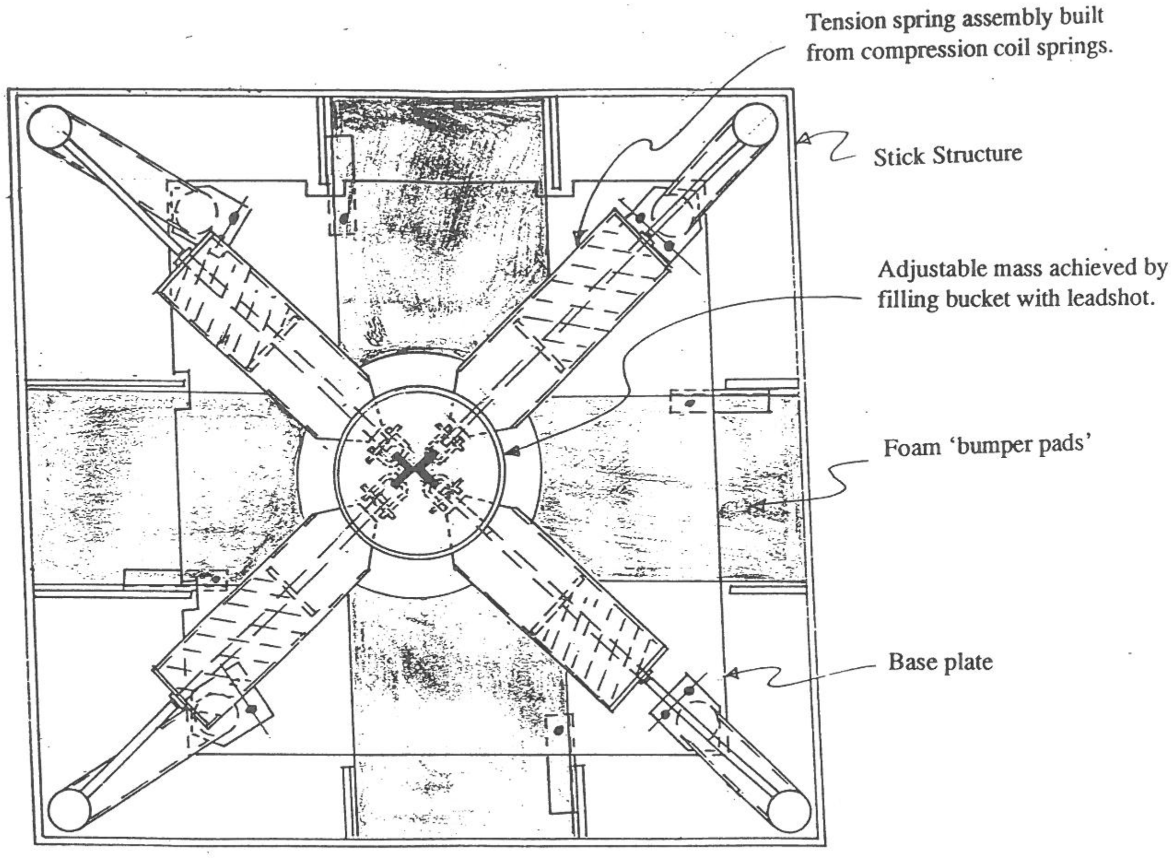

Figure 1 Configuration of the Tuned Mass Damper - Plan View

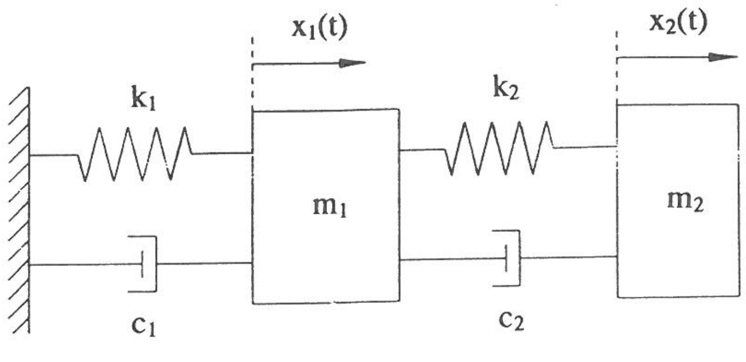

Figure 2 Two Degree-of-Freedom Idealisation of the TMD and Stick Structure

The following TMD properties were considered during design:

Auxiliary Frequency ω_2: The optimal tuning frequency ratio (ω_2/ω_1) of an auxiliary damper to a primary structure is dependant upon the mass ratio m_2/m_1 but typically varies between 95 and 99% (eg, see [1], [2]). A ratio of 99% was adopted in the present design.

Auxiliary Mass m_2: From previous TMD installations (eg see [1], [2]) it has been demonstrated that a mass ratio (m_2/m_1) as low as 1% will provide ample mass for effective TMD performance. Since the first mode generalised mass m_1 of the Sticks was calculated at approximately 3500 kg, a minimum damper mass of 35 kg was needed. As the mass ratio m_2/m_1 is increased, the relative amplitude of the auxiliary mass to primary mass decreases. Hence it was desirable to use the greatest bucket mass possible given the limited geometry of the TMD housing.

TMD tuning was performed by varying the auxiliary mass m_2 which was readily adjusted in small increments by adding or removing 2 mm diameter leadshot balls to and from the bucket.

Auxiliary Stiffness k_2: A fixed spring stiffness was chosen to provide an expected mid-range TMD frequency for a bucket effective mass of 170 kg.

The limited fatigue life of coil springs in tension led to the implementation of compression springs for the current design. By pulling a compression spring closed from opposite ends, a tension spring assembly was formed without the disadvantage of a limited fatigue life. To restrict the compression spring from buckling outwards (when the spring assembly was pulled in tension) the spring was encased in a cylindrical shroud made from PVC pipe of 10 mm wall thickness.

Auxiliary Damping c_2: Energy of the auxiliary mass was dissipated through friction of moving components and the impact of the oscillating mass with the foam 'bumper pads' shown in Figure 1. The bumper pads also serve to prevent the oscillating mass from impacting with the Stick walls at extreme auxiliary mass amplitudes of vibration.

3.0 Measured TMD Performance

A series of full-scale free-vibration tests were performed on the Sticks, before and after the installation of the TMD units, to obtain structural damping decay curves for the first mode of vibration along both principle axes. Two accelerometers were used for the measurements, one mounted on the auxiliary bucket mass and the other on the Stick structure itself. Each Stick was excited by human movement synchronised with the first mode natural frequency of each Stick. Forcing was ceased with the Stick resonating at accelerations of approximately 170 mg, at which time the structure was allowed to vibrate freely to rest. Accelerations were later easily converted into displacement since sinusoidal acceleration and displacement are linearly proportional and in phase.

Prior to TMD installation, the structural damping of the Stick structures were measured to be typically less than 0.5% of critical damping. A ten-fold increase in Stick damping was measured following TMD installation as shown in the typical free vibration decay trace of Figure 3. At displacement amplitudes greater than 25 mm, the effective damping of the coupled Stick/TMD system exceeds 5 % of critical damping.

Below Stick amplitudes of 25 mm the bucket mass was observed to become friction locked and stopped moving relative to the Stick structure. At these low amplitudes, the TMD became ineffective as an auxiliary damping device as can be observed by the lightly damped decay trace in Figure 3 beyond three seconds. Friction lock of the auxiliary bucket mass was considered beneficial to the long term performance of the TMD's since continual rubbing of the components would be minimised.

Also shown in Figure 3 is the simultaneous vibration amplitude of the auxiliary bucket mass during decay. This trace was obtained by subtracting the Stick accelerometer trace from the bucket accelerometer trace. It is seen that bucket amplitudes are approximately twice the magnitude of Stick amplitudes until the bucket becomes friction locked.

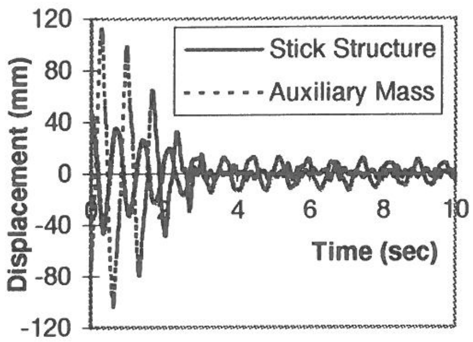

Figure 3 Measured Free-Vibration Decay

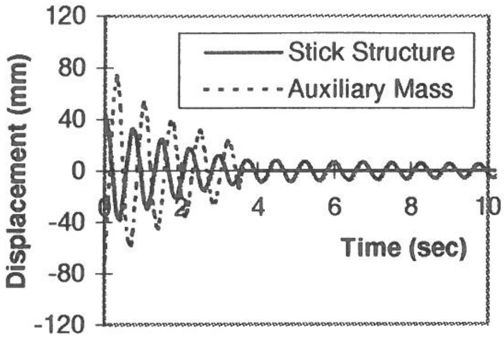

Figure 4 Predicted Free-Vibration Decay

4.0 Predicted TMD Performance

A mathematical model of the Stick/TMD coupled system was created during design to obtain predictions of free-vibration response and effective structural damping. The Stick and TMD were modelled as the two degree of freedom system idealised in Figure 2 using a state-matrix modal analysis. Good agreement is observed between the predicted and measured free vibration decay traces of Figures 3 and 4.

TMD stiffness k_2 and damping c_2 were estimated from a static load-deflection calibration performed on a fully installed TMD unit. The slope of the load-deflection hysteresis loop provided the stiffness of the auxiliary damper while the area enclosed by the loop provided an estimate of the energy dissipation of the damper c_2.

5.0 Conclusions

A series of Tuned Mass Dampers have been designed and installed in the Stick Wall cantilever structures of the Melbourne City Link Project-West Link. Each TMD can be tuned to the natural frequency of a completed Stick structure by varying the TMD's auxiliary mass.

Typically, a ten-fold increase in Stick damping was measured following installation of the TMD units. A state-matrix mathematical model provided a good comparison with the measured free-vibration response of the Stick/TMD system.

References

1) Fujii K., Y. Tamura, T. Sato and T. Wakahara "Wind-Induced Vibration of Tower and Practical Applications of Tuned Sloshing Damper", Journal of Wind Engineering and Industrial Aerodynamics, Vol 33, 1990, pp.263-272.

2) Hitchcock P.A., M.J. Glanville, K.C.S. Kwok, R.D. Watkins and B. Samali, "Damping Properties and Wind Induced Response of a Steel Frame Tower fitted with Liquid Column Vibration Absorbers", Fourth Asia-Pacific Symposium on Wind Engineering, Gold Coast, Australia, 1997.