

## TUNED MASS DAMPERS FOR HIGH RISE BUILDINGS - A CASE STUDY

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### 1. INTRODUCTION

The Chifley Tower in Sydney Australia is a 46 story, 275 meter high steel structure, which is rare in Australia. Being steel it is lighter and more flexible than an all-concrete design. The building is wedge shaped with curved external surfaces and numerous setbacks and transfers. The design wind condition was 155 km per hour. These winds could drive the building in any one of three coupled translation and torsion vibration modes whose natural periods ranged from 4 seconds to 6 seconds.

The predicted horizontal acceleration on the upper floors was  $0.3 \text{ m/second}^2$  and  $0.5 \text{ m/second}^2$  in 5 and 50 year return winds. The horizontal displacement in the 50 year wind was 0.47 meters. The assumed damping of the structure was approximately 1.5%. Calculations indicated a 2% modal mass TMD with 14% of critical internal damping would result in 0.15 and  $0.26 \text{ m/second}^2$  accelerations in 5 and 50 in return winds. The effective damping of the structure would be 4.2%. The function of the TMD is to provide greater comfort for building occupants. It is not required for the structural integrity of the building.

The TMD is required to operate in any direction but since the torsion mode was coupled to the translational modes no twisting motion of the TMD is required.

A passive TMD was chosen because of its inherent simplicity and reliability. The passive TMD requires no external power and its operation is initiated by the wind-induced motion of the building. (See Figure 1).

### 2. DESIGN CONSIDERATIONS

The TMD must be tunable to different frequencies so that it can be matched to the finished building natural frequency and also so that it can be adjusted as the natural frequency changes over the life of the building. For a pendulum type TMD this requires changing the effective length of the cables. As it is difficult to raise or lower a large mass block or to raise or lower the pendulum upper support points, the design features a cable supported pendulum with the upper cable support point fixed, the lower support point attached to the mass block and a moveable tuning frame which fixes the cable laterally, much as a violin string is fixed by the players finger.

The mass, at 395 tones is the largest in the world for a single TMD. The TMD mass is set by the desired damping to be added by the TMD, the building model mass and the maximum permissible mass block amplitude. To provide a compact design the mass block was made 4 x 4 x 3 meters high and consisted of a simple box of 50 mm steel plate filled with 100 mm thick plates. Several layers of plates were welded to the sides of the box resulting in a compact and rigid structure. The mass was required to have an amplitude (swing) of 1.5 meters with a working range of 0.9 meters.

Maximum damping force required was 1150 kilo newtons to be applied over the full 3.0 meter excursion of the mass. This total force was provided by 8 hydraulic cylinders, mounted inclined at  $45^\circ$  which reduced the stroke requirement and increased the stability. For redundancy, 8 hydraulic cylinders were used, 2 on each side of the TMD. Each was required to dissipate 60 kilo watts peak power, 15 kilo watts continuous. To achieve this, each cylinder was provided with an oil-to-air heat exchanger and approximately 200 liters of hydraulic oil for thermal capacity.

Smaller TMD's can be tested with a simple pull-and-release but the loads in this case were too large. Consequently, a powered hydraulic system was designed to allow the damper to be driven at its natural frequency. To reduce the power requirements a system of valving to bypass the energy dissipation cylinders was provided.

### 3. COMPONENTS

The mass block was made as a simple box of 50 mm steel plates open at the bottom and the top except for a small shelf angle on the bottom. The mass was constructed by adding 100 mm plates and welding in the bottom two layers and top two layers so as to make a rigid and virtually solid steel assembly. The welding was done on site as the components had to be kept within the capacity of the construction crane.

The mass block is supported by steel cables which provided a simpler flexible support than the bearings and the gimbals used in other designs. Special radiused housings were used top and bottom to allow the cables to bend without stress concentration. Eight cables were used

instead of four for redundant support - in the four cable design if one fails, two will take the entire load. In the eight cable design, if one fails the load is still shared by seven. The tuning frame was a simple steel beam structure supported by four building columns. It was designed to be raised and lowered at 300 mm steps which corresponded to a change of cable length 300 mm and 0.1 second change in natural period. The tuning frame was designed for loads of 400 kilo newtons laterally and has special fittings for the cable to pass through without binding on the cable or causing stress concentration.

For possible over-travel a snuber system was provided which consisted of a post attached to the bottom of the mass block which was designed to impact a circular snuber assembly. The snuber assembly consisted of 80-30 mm rods such that the rods would plastically deform.

The damping force was provided by hydraulic cylinders forming part of the energy dissipation system. Each cylinder had 4" rod couplers, 6" bore, and was 3.8 meters long with a 1.8 meter stroke. Each end of the cylinder was mounted with a ball joint to allow damper motion in any direction.

#### 4. HYDRAULIC SYSTEM

An integrated hydraulic system was designed to provide several functions. The energy dissipation system is passive and is interlocked to the powered hydraulic test system. The power unit was also used to operate eight jacks for lifting the mass block and also a maintenance test system located in the building. The eight dissipative cylinders are permanently connected between mass block and building floor. Lock-out valves allow this system to be shut down and locked in place so that motion of the mass block is prevented. The hydraulic test system consists of two hydraulic cylinders connected to two perpendicular sides of the mass block and which can be operated either individually or simultaneously by the hydraulic system power unit. This allows driving the mass block in several different directions for testing. While the mass block is being driven, the dissipation system circuitry is bypassed so that minimal energy is dissipated thus reducing the size of the hydraulic power supply. Once the mass block is driven to an appropriate amplitude a switch over occurs in which the dissipation system is brought back into play and the hydraulic test system is bypassed. After the switch over the TMD becomes a passive damped system whose properties can be determined from the decay of the vibration amplitude time history.

The maintenance test system consists of a frame into which one of the dissipation cylinders can be mounted and mechanically driven at various stroke velocities. The rod and cap ends of the dissipation cylinders are connected by a hydraulic circuit containing a flow control valve at each end. By setting the flow control valves to various positions, and then measuring stroke velocity and cylinder pressure, the effective flow (or orifice) coefficient of the hydraulic circuit could be calculated. The relationship between orifice coefficient and TMD equivalent linear damping, at the various control valve settings, provides the over all calibration of the energy dissipation system.

The maintenance test system is a permanent on-site accessory of the TMD. This system proved invaluable during commissioning as it allowed for on-site diagnosis and replacement of out-of-spec components.

#### 5. CONCLUSIONS

The TMD was commissioned in February 1994 and is now fully operational. During commissioning tests the TMD was shown to increase the damping ratio of the building by approximately 2% to 3%. The TMD is functioning as expected and will produce significant reductions in wind-induced building vibration amplitudes.

Figure 1. The TMD as explained to Sydney residents. From the Sydney Morning Herald, 12 Feb 94.

