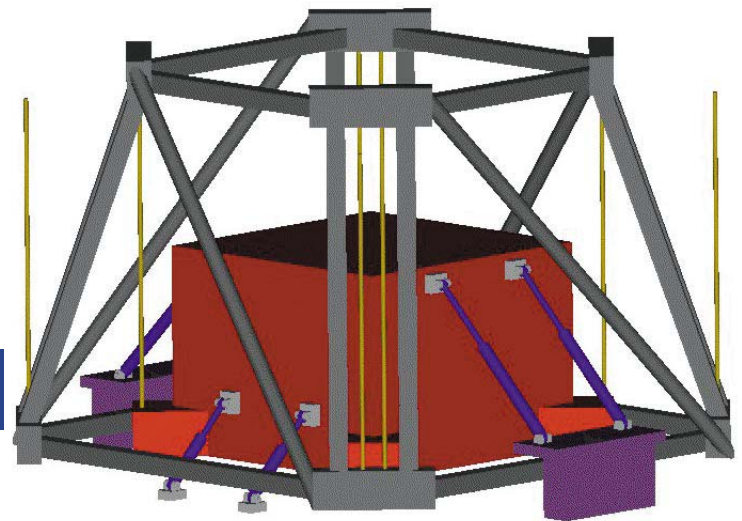


DAMPING SYSTEMS

There has been a recent trend towards utilizing damping systems to reduce building accelerations, motion, or deflections. Traditionally, structural engineers and designers concentrated their design efforts on the more tangible properties of stiffness and mass. The balancing of these properties usually produced an efficient design, capable of allowing the architect the freedom to achieve a desired aesthetic and the structural engineer could limit deflections and stresses for a safe structure.

Figure 1: A 3-D rendering of a compound pendulum type TMD.



Given the desire to build higher buildings, longer bridges and more daring structures, the envelope of what is possible within conventional structural design imposes limitations. Advances in materials, such as high strength steels and efficiencies in structural design through the use of advanced 3-D modelling software, produce designs which may have unexpected deficiencies. Taller, longer, and lighter structures tend to be more sensitive to wind-induced vibrations or vibrations due to pedestrians, traffic, etc. This has led engineers and architects to turn to the damping of a structure as a means of limiting excessive motions/deflections.

Traditionally, there have only been a few methods of increasing the damping of a structure. Visco-elastic materials have been used in some applications, while in others, the Tuned Mass Damper (TMD) has been used successfully. The direct application of viscous dampers in a structural system or between two separate components has been used. Since the deflections involved are usually small it can be a challenge to design these viscous damping systems to work effectively.

Research in vibration suppression has led to a large number of different types of damping systems, each employing different technological advances. Some of the more common systems are briefly described below:

Tuned Mass Damper (TMD): A TMD is a passive damping system which utilizes a secondary mass attached to a vibrating structure. The secondary mass is given dynamic characteristics that relate closely to that of the primary structure. By varying the mass ratio of the secondary mass to the primary body, the frequency ratio between the two masses and the damping ratio of the secondary mass, a certain amount of damping can be produced. Essentially, the TMD can be viewed as an energy sink, where excess energy that is built up in the building or bridge is transferred to a secondary mass. The energy is then dissipated by some form of viscous damping device that is connected between the building and the TMD mass itself.

Figure 1 illustrates a compound pendulum design produced by RWDI for a TMD in a tall tower in New York. A large mass (600 tonnes) hanging on a system of cables acts as the secondary mass, while viscous dampers provide the energy absorption.

Tuned Liquid Column

Damper (TLCD): This passive damping system is a variation of the TMD. Whereas a spring and a viscous damper are combined with a mass block (usually concrete or steel) in the TMD, water or other liquid is used in a TLCD, combining the functions of the mass, spring and viscous damping elements. The geometry of the tank that holds the water is determined by theory to give the desired natural frequency of water motion. A sluice gate (or other similar device) is used to dissipate the energy in the moving water. Figure 2 illustrates scale model tests of a TLCD in RWDI's laboratories.

The benefits of using a TLCD to reduce motions of a building can be threefold. In addition to reducing building accelerations, the water in the tank can also be used for firefighting purposes and in some instances can be used for chilled water storage as well.

Tuned Sloshing Water Damper (TSWD): The TSWD is yet another variation of the TMD. In the case of the TSWD, a rectangular tank is designed with the correct length and water depth to initiate wave motion in the tank. This moving wave then represents a moving mass that behaves similarly to the moving mass of a TMD. Energy is dissipated by using a damping screen or mesh to create turbulence in the water. Other variations of the TSWD include circular containers or a bi-directional tank where the wave moves in two directions. It is also possible to use a different fluid than water, such as oil, in more hybrid types of applications.

A TSWD is an excellent choice of a damping system for retrofit applications. The wide variety of shapes that can be configured as a TSWD help this type of system fit into existing spaces within a structure.

Viscous Damping System: Installing viscous dampers in a structure has long been recognized as an effective means of reducing the effects of wind and earthquakes. The benefits of a viscous damper are well known in the



Figure 2: A scale model experimental set-up that was used to confirm the theoretical predictions for natural frequency and internal damping for a large 600 ton TLCD installation for a Vancouver building.

automobile industry. Recent technological advances in viscous damper technology and ingenious means of amplifying small structural motions make this type of damping system more viable for suppressing wind-induced motions.

Viscoelastic Damping System: In a system similar to a Viscous Damping system, the use of viscoelastic damping material, such as rubber, has been used for some applications. Shearing action of a rubber compound placed between layers of steel dissipates energy. The installation of this system at locations in a structure where relative motion exists has been effectively used in some tall buildings to reduce the effects of wind and earthquakes.

Active Mass Damper (AMD): Another method of reducing vibrations is to try to counter the force that is actually causing the vibration. The Active Mass Damper is a system that attempts to achieve this. Motion in a structure is sensed by instruments, such as an accelerometer, and a computer controlled actuator system moves a large mass to generate a force to counter that which is causing the motion in the first place. The keys to a successful AMD are fast sensing equipment, stable control algorithms and responsive actuator technology. A benefit of an AMD is that for a given amount of mass, a larger amount of "damping" can be provided than a passive TMD. However, a typical AMD is generally more expensive than a passive TMD and has higher maintenance requirements. In some applications where seismic loads govern, this type of damping system can be effective in reducing the impact of the seismic event.

WIND-INDUCED CABLE OSCILLATIONS

By Peter Irwin, Principal

Many engineered structures have cables exposed to wind, rain, and ice. Electrical power lines, guys supporting communication towers, and cables supporting certain types of roofs are examples. This article focuses on cable-stayed bridges. Interaction of wind and precipitation with cables can result in damage to or failure of the cable system. Most problems are caused by cable oscillations rather than the simple lateral force of the wind (although this can be a factor in severe icing conditions). Many instances of cable oscillations have been reported and a variety of solutions have been tried.

One well-known type of vibration is aeolian vibration or vortex shedding. The wind blowing past a cable is broken up into a series of vortices that trail off the downwind side of the cable in a vortex wake. The vortices are shed at a distinct frequency, n , which is given by the formula

$$n = S \frac{U}{D} \quad (1)$$

where S is a constant known as the Strouhal number, U is speed, and D is cable diameter. For most cables, the amplitude of oscillation caused by vortex shedding is small and not a cause of many problems. On bridge stays, it is typically no more than a few millimetres. It is not uncommon to see higher vibration modes excited on a bridge cable. The oscillation amplitude of vortex shedding vibrations varies roughly in inverse proportion to the aerodynamic stability parameter called the Scruton number. It is defined as

$$\text{Scruton number, } S_c = \frac{m\zeta}{\rho D^2} \quad (2)$$

where m = mass of cable per unit length, ζ = damping ratio, ρ = air density, and D = cable outside diameter. Since vortex oscillations become smaller as the Scruton number is increased, the more dense and highly damped the cable, the less it will oscillate.

The vibration that has caused most problems on bridge cables is called rain-wind vibration. This occurs in wind combined with rain and is caused by rivulets of water running down the inclined cables. Two rivulets are formed, one on the top side of the cable to the windward of the highest point, and one on the bottom side. The positions of these rivulets on the cable perimeter affect the aerodynamic force in the across-wind direction, but are influenced by the aerodynamic forces on the rivulets themselves and by accelerations due to cable motions. This gives rise to coupled motions of the rivulets and cable.

Rain-wind oscillations begin in the wind speed range of 7 m/s to 15 m/s and can reach amplitudes higher than a metre. Below this speed, the top rivulet does not form because the wind force is insufficient to prevent it from running downwards around the windward face to the bottom of the cable. Above this range, the wind forces on the rivulets are high enough to blow them right off the cable. Like vortex excitation, a range of vibration modes can be excited by rain-wind oscillations.



Figure 1: RWDI's field monitoring team undertaking measurements on bridge cables.

As with vortex shedding, the Scruton number is an important parameter. The higher the number the better. The latest draft of the Handbook on Cable-Stayed Bridges of the Post-Tensioning Institute proposes that to avoid rain-wind oscillations the Scruton number should be greater than 10, i.e.

$$\frac{m\zeta}{\rho D^2} > 10 \quad (3)$$

This means that methods of augmenting the natural damping of cables need to be found for many bridges. Hydraulic dampers have been added to the cables of several bridges. Another approach is to attach secondary transverse cables or cross ties to the main cables. These add extra damping and eliminate some of the lower modes of vibration that could be excited. Some damping does come from neoprene split-ring washers used at the ends of bridge cables to reduce bending moments at the cable anchorages. However, on long cables the split-ring washers often do not result in a damping ratio any higher than about $\zeta \approx 0.003$ and in most cases ζ needs to be at least 0.006.

Figure 1 illustrates the measurement of the damping of cables on an existing bridge by RWDI's field monitoring team. Accelerometers mounted on the cable enable its damping and natural frequencies to be measured. These damping measurements can be useful in assessing whether the cable's inherent damping will be sufficient to avoid problems or whether special damping systems need to be added. Typically, the longer the cable, the lower its inherent damping. Thus, shorter cable-stayed bridges tend to run into less vibration problems than longer ones.

An alternative approach to avoiding rain-wind oscillations is to shape the outer sleeve of the cable so the rivulets of water are disrupted. For example, both a helical bead wound around the sleeve and dimpled surfaces have been tried. Their effectiveness is still not really confirmed due to limited use in the field and because they have usually been tried at the same time as other measures such as increased damping or cross ties.

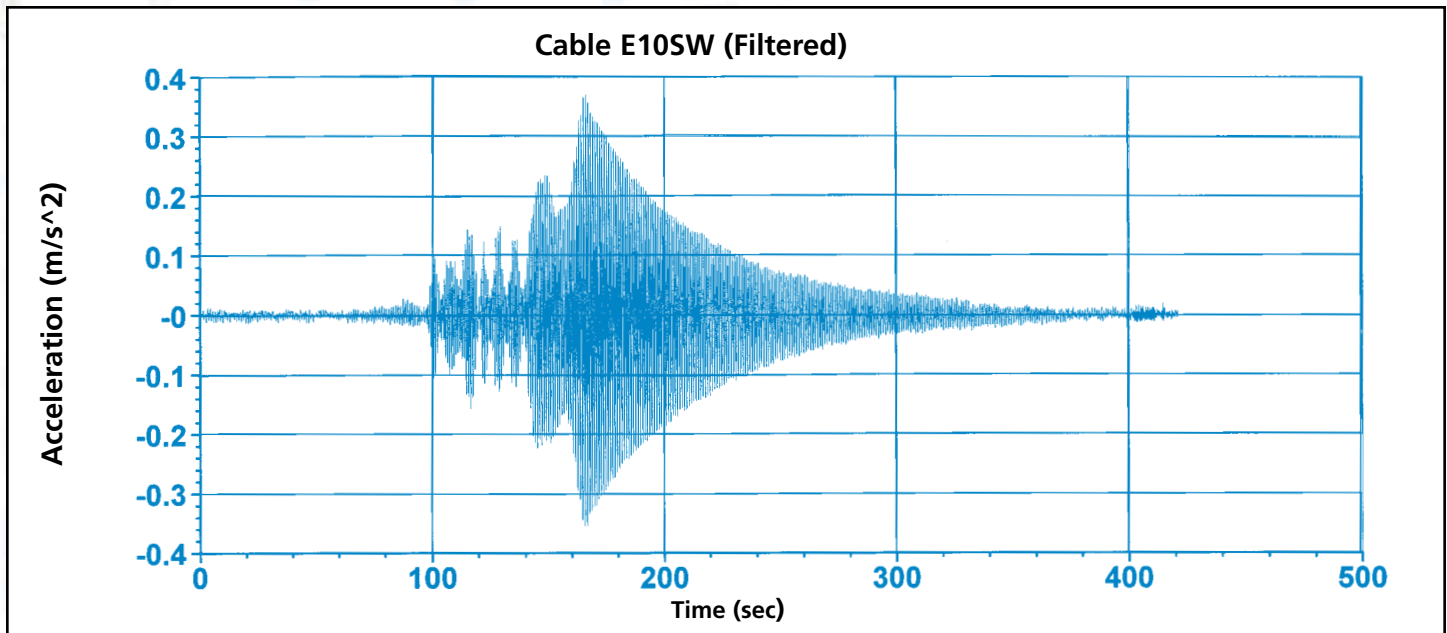


Figure 2: Example of an accelerometer oscillation-decay trace used for determining the damping of a cable.

Besides rain-wind oscillations there are a number of less common types of oscillation. These are in need of further research for bridge cables. Two that are frequently cited are: wind forces acting on the main bridge structure that cause oscillations in a vibration mode primarily consisting of cable motions; and inclined cable "galloping". The latter does not require rain and typically begins at a higher wind speed than rain-wind oscillations. It can reach amplitudes of several metres and tends to involve only the lowest modes of vibration. A tentative criterion giving the onset wind speed U_{CRIT} for galloping is

$$U_{CRIT} = c n D S_C \quad (4)$$

where c = constant. The value of the constant c for this type

of galloping is probably around 40, but needs further investigation.

Increasing the Scruton number S_C , which can be achieved by adding damping to the cables, makes galloping a less likely problem. It increases the wind speed required to initiate galloping and makes it less probable. Equation 4 also shows that increasing the frequency, n , increases the critical velocity. A cost effective way of increasing the frequency is to install secondary, small diameter cables as cross-ties between the main cables. This has been implemented and shown to be effective on a number of bridges as long as the cross-ties are installed with adequate pretension.

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