APPENDIX A1: DATABASE OF REFERENCE MATERIALS

An extensive amount of research was initially performed to form a baseline for the current study. An on-line database of references was created so that all members of the Research Team could add or extract information as necessary. The database includes the article titles, authors, reference information, and abstracts when attainable. There are 198 references in the database, including 89 with abstracts.

Search capability is also provided, with options to search by key word, author, source, and date. The search page is shown in Figure 26, and a search results page is shown in Figure 27. A full listing of the references in this database is included at the end of this appendix.

Figure 26: Reference database search page.
Figure 27: Reference database search results page.
List of References Included in Database

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   Authors: Fang, J.
   Source: Journal of Applied Mechanics
   Month: Sep, Year:1963, Volume: N/A, Issue: N/A, Pages: N/A
   Abstract: N/A

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   Source: Journal of Applied Mechanics
   Month: Sep, Year:1963, Volume: N/A, Issue: N/A, Pages: N/A
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   Source: Journal of Applied Mechanics
   Month: Sep, Year:1965, Volume: N/A, Issue: N/A, Pages: N/A
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   Month: N/A, Year:1974, Volume: N/A, Issue: N/A, Pages: 369-99
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   Month: N/A, Year:1975, Volume: N/A, Issue: N/A, Pages: 1378-82
   Abstract: N/A

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   Source: Van Nostrand Reinhold Company, New York
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    Authors: Szemplinska-Stupnicka, W.
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    Abstract: N/A

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    Authors: Wianecki, J.
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    Month: N/A, Year:1979, Volume: N/A, Issue: N/A, Pages: 1381-93
    Abstract: Available
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Authors: Irvine, H. Max
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Authors: Sergev, S. S.; Iwan, W. D.
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Bridge. Part I: Modal Analysis
Authors: Caetano, E.; Cunha, A.; Taylor, C. A.
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An inventory of cable-stayed bridges in the United States was created to organize and share existing records with the Research Team. This database includes information on bridge geometry, cable properties, cable connections, aerodynamic detailing, site conditions, and observed responses to wind. The inventory is stored in Microsoft Access (Microsoft Office) database format, which allows for easy data entry and retrieval. Forms were designed to perform this task, complete with pull-down menus and control buttons, using the Visual Basic programming language. These forms for data entry include a “switchboard” form and three categories of bridge data forms: General bridge data, cable data and wind data.

Overall, 26 bridges have been added to the database, including several from outside the United States. Copies of contract drawings from which data was taken have been copied and filed for future reference. The following is the full list of bridges included in the inventory:

Table 8: Cable stayed bridge inventory.

<table>
<thead>
<tr>
<th>Bridge</th>
<th>Location</th>
<th>Main Span (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annacis Bridge</td>
<td>British Columbia</td>
<td>1526</td>
</tr>
<tr>
<td>Greenville Bridge (US 82)</td>
<td>Mississippi</td>
<td>1378</td>
</tr>
<tr>
<td>Dames Point Bridge</td>
<td>Florida</td>
<td>1300</td>
</tr>
<tr>
<td>Fred Hartman Bridge</td>
<td>Texas</td>
<td>1250</td>
</tr>
<tr>
<td>Sidney Lanier Bridge</td>
<td>Georgia</td>
<td>1250</td>
</tr>
<tr>
<td>Luling Bridge</td>
<td>Louisiana</td>
<td>1222</td>
</tr>
<tr>
<td>Sunshine Skyway Bridge</td>
<td>Florida</td>
<td>1200</td>
</tr>
<tr>
<td>William Natcher Bridge</td>
<td>Kentucky</td>
<td>1200</td>
</tr>
<tr>
<td>Cape Girardeau Bridge</td>
<td>Missouri</td>
<td>1150</td>
</tr>
<tr>
<td>Talmadge Memorial Bridge</td>
<td>Georgia</td>
<td>1100</td>
</tr>
<tr>
<td>Maysville-Aberdeen Bridge</td>
<td>Kentucky</td>
<td>1050</td>
</tr>
<tr>
<td>Pasco - Kennewick Intercity Bridge</td>
<td>Washington</td>
<td>981</td>
</tr>
<tr>
<td>East Huntington Bridge</td>
<td>West Virginia</td>
<td>900</td>
</tr>
<tr>
<td>FA Route 63 over Mississippi River</td>
<td>Illinois</td>
<td>900</td>
</tr>
<tr>
<td>Weirton - Steubenville Bridge</td>
<td>West Virginia</td>
<td>820</td>
</tr>
<tr>
<td>Cochrane Bridge</td>
<td>Alabama</td>
<td>780</td>
</tr>
<tr>
<td>Clark Bridge</td>
<td>Illinois</td>
<td>756</td>
</tr>
<tr>
<td>Chesapeake and Delaware Canal Bridge</td>
<td>Delaware</td>
<td>750</td>
</tr>
<tr>
<td>Leonard P. Zakim Bunker Hill Bridge</td>
<td>Massachusetts</td>
<td>745</td>
</tr>
<tr>
<td>Sixth Street Bridge</td>
<td>West Virginia</td>
<td>740</td>
</tr>
<tr>
<td>Burlington Bridge</td>
<td>Iowa</td>
<td>660</td>
</tr>
<tr>
<td>Veterans Memorial Bridge</td>
<td>Texas</td>
<td>640</td>
</tr>
<tr>
<td>Varina Enon Bridge</td>
<td>Virginia</td>
<td>630</td>
</tr>
<tr>
<td>PR 148 over La Plata River</td>
<td>Puerto Rico</td>
<td>525</td>
</tr>
<tr>
<td>Sitka Harbor Bridge</td>
<td>Alaska</td>
<td>450</td>
</tr>
<tr>
<td>Foss Waterway Bridge</td>
<td>Washington</td>
<td>350</td>
</tr>
</tbody>
</table>
The inventory forms are described in detail in the following pages:

a) Switchboard

Overall control of data entry and referential integrity between categories is provided by a
switchboard from which the user selects which type of data to enter or retrieve. An example of
the switchboard is shown below. The user may select from the three categories to either add a
new entry or edit an existing entry. The selection will open data entry forms for the category
requested.

![Switchboard Image]

Figure 28: U.S. cable-stayed bridge database - Switchboard.
b) General Bridge Information

General bridge information is divided into two sections. General information includes bridge name, designers, suppliers and bridge location. Structural data includes information on the superstructure, tower, cable, anchorages, and cross-ties.

Figure 29: U.S. cable-stayed bridge database - General bridge information.
c) Cable Data

Cable Data is divided into four sections: cable geometry, cable properties, cable connections and aerodynamic details. Cable Geometry gives the end coordinates and calculates the cable length. Cable Properties includes strand type, size, dead load tension, and the protection system. Cable Connections describes upper and lower anchors and fatigue test information. Aerodynamic Details includes descriptions of dampers and sheathing surface treatment. Information for each cable of the bridge is given individually.

Figure 30: U.S. cable-stayed bridge database - Cable data.
d) Wind Data

Wind Data includes bridge dynamic modes, superstructure mass, design wind speeds, and vibration measurement information. Data has only been entered for the Cape Girardeau Bridge.

Figure 31: U.S. cable-stayed bridge database - Wind data.
B1.1 MECHANICS OF WIND-INDUCED VIBRATIONS

General Background

There are a number of possible types of wind-induced vibrations of cables.

1. Vortex excitation of an isolated cable
2. Vortex excitation of groups of cables
3. Wake galloping for groups of cables
4. Galloping of single cables inclined to the wind
5. Rain/wind induced vibrations of cables
6. Galloping of cables with ice accumulations
7. Galloping of cables in the wakes of other structural components (e.g. arches, towers, truss members etc.)
8. Aerodynamic excitation of overall bridge modes of vibration involving cable motion, e.g. vortex shedding off the deck may excite a vertical mode that involves relatively small deck motions but substantial cable motions
9. Motions due to buffeting by wind turbulence
10. Motion due to Fluctuating Cable Tensions

Some of these are more critical or probable than others, but they are all listed here for completeness. They are discussed in turn in the following sections.
Vortex Excitation of an Isolated Cable and Groups of Cables

Vortex excitation of a single isolated cable is caused by the alternate shedding of vortices from the two sides of the cable when the wind is approximately at right angles to the cable axis. The vortices are shed from one side of the cable at a frequency, \( n \), that is proportional to the wind velocity \( U \) and inversely proportional to the cable diameter \( D \). Thus

\[
n = S \frac{U}{D}
\]

(12)

where \( S \) is a non-dimensional parameter, the Strouhal number, that remains constant over extended ranges of wind velocity. For circular cross-section cables in the Reynolds number range \( 10^4 \) to about \( 3 \times 10^5 \), \( S \) is about 0.2.

Each time a vortex is shed it gives rise to a force at right angles to the wind direction. The alternate shedding thus causes an oscillating across-wind force. If the frequency of the oscillating force matches the frequency \( N_r \) of the \( r^{th} \) natural mode of vibration of the cable, then oscillations of the cable in that mode will be excited. The wind velocity \( U_{VS} \) at which this matching of vortex shedding frequency \( n \) to natural frequency \( N_r \) occurs can be deduced from Equation 12 and is

\[
U_{VS} = N_r \frac{D}{S}
\]

(13)

Thus, as an example of a typical situation for a long stay cable, if the cable natural frequency \( N_r \) were 2 Hz and its diameter were \( D = 5.9 \) in (0.15 m) then, using a Strouhal number \( S = 0.2 \), it can be determined that the vortex shedding excitation of the \( r^{th} \) mode will occur at a wind speed of \( U_{VS} = 3.4 \) mph (1.5 m/s). This is clearly a very low wind speed, showing that vortex shedding can begin in the lower modes at very modest speeds. For higher modes the wind speed will be higher.

The amplitude of the cable oscillations depends on the mass and damping of the cable. An approximate formula for the maximum amplitude \( y_0 \) as a fraction of the diameter is:

\[
\frac{y_0}{D} \approx 0.008 \left( \frac{C_L}{m \zeta / \rho D^2} \right) \left( \frac{U_{VS}}{n D} \right)^2
\]

(14)

\( C_L \) = oscillating lift coefficient,
\( m \) = mass of cable per unit length,
\( \zeta \) = damping ratio,
\( U_{VS} \) = wind velocity at peak of oscillations and
\( \rho \) = air density

The lift coefficient \( C_L \) has some dependence on oscillation amplitude as well as Reynolds number, but a rough value suitable for order of magnitude estimates is \( C_L \approx 0.3 \).
It can be seen from this relationship that increasing the mass and damping of the cables reduces oscillation amplitudes. The parameter \( \frac{m\zeta}{\rho D^2} \) is called the Scruton number. Higher values of Scruton number will tend to suppress vortex excitation and, as will be seen later, other types of wind-induced oscillation also tend to be mitigated by increasing the Scruton number.

It is difficult to give a precise estimate of the damping expected to occur in the cables of cable-stayed bridges, however, cable damping ratios can range anywhere from 0.0005 to 0.01 (0.05\% to 1.0\% of critical). The lower end of this range is typical of very long cable stays prior to cement grouting, while the upper end of this range is more typical of shorter cable-stays with grouting and some end damping.

For a bundled steel cable stay with a damping ratio of \( \zeta = 0.005 \), the Scruton number \( \frac{m\zeta}{\rho D^2} \) has a value in the range of about 7 to 12 depending on the sheathing material, on whether grouting is used, and if so, on how much of the cable system mass consists of grouting. The value of \( \frac{U_{VS}/nD}{\zeta} \approx 5 \), so the above expression leads to \( y_0/D \approx 0.008 \times 0.3 \times (1/7) \times 25 = 0.0084 \) for the lower end of the range of \( \frac{m\zeta}{\rho D^2} \). The lower end of the range of \( \frac{m\zeta}{\rho D^2} \) would correspond to a typical cable on a cable-stayed bridge prior to grouting. The predicted amplitude of oscillation is small, of order one percent of the cable diameter and it would drop to about \( y_0/D \approx 0.0049 \) (i.e. about one half of a percent of the cable diameter) for the higher value of \( \frac{m\zeta}{\rho D^2} = 12 \) that corresponds to a grouted cable with 0.005 damping ratio.

If the damping ratio of the stay cables is extremely low, e.g. 0.001, as has been observed on some cable-stayed bridges prior to grouting being applied, then the amplitude could conceivably increase to about \( y_0/D = 0.044 \), i.e. about 4\% of the cable diameter. Typically, 4\% of the cable diameter would amount to not more than a few millimeters, i.e. still a small amplitude. Over many cycles at this amplitude it may be possible for fatigue problems to arise, but these larger oscillations are expected to be primarily a construction phase phenomenon when low values of \( \frac{m\zeta}{\rho D^2} \) occur on ungrouted and lightly damped cables. Therefore the time period involved is less likely to be long enough for fatigue problems to develop.

From the above discussion it is clear that the classical vortex type of excitation of a single isolated cylindrical shape is unlikely to lead to serious oscillations of typical bridge cables. The predicted amplitudes are small even for lightly damped stay cables prior to grouting.

When one cable is near to other cables, especially when it lies in their wakes, the interactions become very complex especially at close spacings, e.g. 2 - 6 diameters. The vortex shedding behavior is modified, occurring at slightly different wind speeds, and leading to amplitudes that can be several times larger than for the isolated cable. However, even with this further magnification of the vortex response due to interaction effects the amplitudes still do not reach magnitudes sufficient to explain the vibrations observed on some bridges.

Therefore a general conclusion is that vortex shedding from the cables themselves is unlikely to be the root cause of cable vibration problems on bridges. There are other more serious forms of wind-induced oscillations, as explained below, that are more likely candidates for causing fatigue problems. Almost any small amount of damping that is added to the cables will be sufficient to effectively suppress vortex excitation.
Wake Galloping for Groups of Cables

When a cable lies in the wake of another cable the wind forces on it depend on its position in the wake. When the cable is near the center of the wake the wind velocity is low and it can move upwind against a lower drag force. If it is in the outer part of the wake it experiences a stronger drag force and will tend to be blown downwind. Also, because of the shear flow in the wake of the upwind cable, the downwind cable will experience an across-wind force tending to pull it away from the wake center, the magnitude of this across wind force being a function of the distance from the wake center. These variations in drag and across wind forces can lead to the cable undergoing oscillations which involve both along wind and across wind components, i.e. the cable moves around an elliptical orbit. Over each complete orbit it can be shown that there is a net transfer of energy from the wind into the cable motion. For smaller spacings of the cables, say 2 - 6 diameters, the downwind cable moves around a roughly circular orbit. For larger spacings the orbit becomes more elongated into an ellipse with its major axis roughly aligned with the wind direction.

This type of instability is called wake galloping. The wind speeds involved are typically substantially higher than those for the onset of vortex excitation. It can cause oscillations much larger in amplitude than those seen in vortex excitation. For example oscillation amplitudes of order 20 cable diameters have been observed on bundled power conductors for cable spacings in the 10 - 20 diameter range. In some cases adjacent cables clashed with each other. This type of wake galloping could potentially occur on the cable arrays on cable stayed bridges or for grouped hangers. Less severe forms of galloping, but still problematic, can occur at smaller spacings in the 2 - 6 diameter range.

As for vortex excitation of the isolated cable, the Scruton number \( \left( \frac{m \zeta}{\rho D^2} \right) \) is an important guide as to the likelihood of there being a problem due to wake galloping effects. Cooper (1985) has proposed an approximate global stability criterion, based on earlier work by Connors (1970). This criterion gives the wind velocity \( U_{CRIT} \) above which instability can be expected due to wake galloping effects. It is given in terms of \( \left( \frac{m \zeta}{\rho D^2} \right) \) as follows:

\[
U_{CRIT} = c N_r D \sqrt{\frac{m \zeta}{\rho D^2}}
\]

where \( c \) is a constant. For close cable spacings (e.g. 2 - 6 diameters) the value of the constant \( c \) appears to be about 25 but for spacings in the 10 to 20 diameter range it goes up to about 80. This relationship shows that increasing the Scruton number \( \left( \frac{m \zeta}{\rho D^2} \right) \) or natural frequency \( N_r \) will make the cable array stable up to a higher wind velocity.

Thus, if for example \( \left( \frac{m \zeta}{\rho D^2} \right) = 10 \), \( D = 6 \) inches, and \( N_r = 1 \) Hz then for the spacing in the range 2 - 6 diameters we find \( U_{CRIT} = 27 \) mph. This is quite low and is a common enough speed to have the potential to cause fatigue problems. However, \( N_r \) may be increased by installing cross-ties to the cables to shorten the effective length of cable for the vibration mode of concern. If cross-ties were used at two locations along this cable, dividing it into three equal
lengths, the frequency $N_r$ would be tripled resulting in $U_{\text{CRIT}} = 80$ mph which is high enough to have a much smaller probability of occurring. Added to the stiffening effect of the spacers is the additional damping that they most likely cause. For a cable significant damping occurs at the points where it is clamped such as at its ends or at spacers placed along its length.

It should be noted that the values of $c$ in Equation 15 quoted above were for wind normal to the axis of the cable. For cable-stayed bridges, wind normal to the axis of the cable typically is not possible, at least for wind directions where wake interference can occur. The angle is typically in the range 25° to 60° rather than 90°. Therefore, it is probable that for stay-cable arrays the values of $c$ would be higher than those quoted above. Most cables on cable-stayed bridges are separated by more than six diameters. Therefore, it is probably conservative to assume a $c$ value of 80 when estimating the critical velocity for wake galloping. More research is needed in this area to better define wake galloping stability boundaries for inclined cables.

The oscillations caused by wake galloping are known to have caused fatigue of the outer strands of bridge hangers at end clamps on suspension and arch bridges. Fatigue problems of this type have yet to be encountered on cable-stayed bridges, but could potentially occur on cross-cables. Therefore, it is good practice to avoid sharp corners where the cross-cables enter the clamps linking them to the main cables or the deck. Bushings of rubber or other visco-elastic materials at the clamps can help reduce fatigue and can be a source of extra damping.

**Galloping of Dry Single Cables**

Single cables of circular cross-section do not gallop when they are aligned normal to the wind. However, when the wind velocity has a component along the span it is no longer normal to the cable axis and for cables inclined to the wind an instability with the same characteristics as galloping has been observed. In Figure 32 the data of Saito et al. (1994) are shown plotted in the form of $U_{\text{CRIT}}/(fD)$ versus $S_c$. The data came from a series of wind tunnel experiments on a section of bridge cable mounted on a spring suspension system. Also plotted are curves calculated from Equation 15 for several values of $c$ in the range 25 to 55. It can be seen that all the data points except one lie above the curve for $c=40$ and that this value could be used to predict the onset of single inclined cable galloping.

Another possible mechanism of single inclined cable galloping which has not received a lot of attention in the literature is the notion that the wind “sees” an elliptical cross-section of cable, for the typical wind directions where single cable galloping has been seen. Elliptical sections with ellipticity of about 2.5 or greater have a lift coefficient with a region of negative slope at angles of attack between 10° to 20°. An ellipticity of 2.5 would correspond to an angle of inclination of the cable of approximately 25°, which can occur in the outer-most cables of long-span bridges. (Ellipticity is defined as the maximum width divided by the minimum width - e.g., a circle has an ellipticity of 1.0.) The negative slope of the lift coefficient may result in galloping instability if the level of structural damping in the cables is very low. The ellipticity range and angle range where galloping occurs is likely to be sensitive to surface roughness and Reynolds number.
There is a need for further experimental studies to confirm the results of Saito et al. (1994) and to extend the range of conditions studied. Saito’s results were nearly all at very low damping. There is a particular need to investigate if galloping of an inclined cable is indeed possible at damping ratios of 0.005 and higher.

The conclusion of recent testing (see Appendix B2) was that instability occurs at very low damping levels, however if enough damping is added these instabilities disappear. It is expected that if enough cable system damping is supplied to mitigate rain/wind vibrations, these vibrations should also be suppressed.

Rain/Wind Induced Vibrations

It has been observed on several bridges that the combination of rain and wind will cause cable vibrations. Hikami and Shiraishi (1987) described this phenomenon as it was observed on the Meikonishi cable stayed bridge on cables of about 5.5-in diameter. This well documented case is a good illustration of the phenomenon. Oscillation single amplitudes of more than 10-in developed. In other cases, amplitudes in excess of 3-ft have been observed. The cables, consisting of parallel wires inside a polyethylene pipe, had masses of 25 lb/ft and 35 lb/ft before and after cement grouting respectively. The damping ratio was reported to be in the range 0.0011 to 0.0046 depending on cable length, vibration mode and construction situation. It is probable that the lower values of damping corresponded to the ungrouted case. With this assumption the Scruton number for the ungrouted cables was as low as $(m\zeta/\rho D^2) = 1.7$. The cable lengths were in the range 210-ft to 650-ft.
The oscillations were seen in the wind speed range of 18 to 30 mph and the modes of vibration affected by oscillations all had frequencies in the 1 to 3 Hz range and were any one of the first four modes. Based on wind tunnel tests that reproduced the oscillations it was established that rivulets of water running down the upper and lower surfaces of the cable in rainy weather were the essential component of this aeroelastic instability. The water rivulets changed the effective shape of the cable. Furthermore they moved as the cable oscillated causing cyclical changes in the aerodynamic forces which led, in a not fully understood way, to the wind feeding energy into oscillations. The wind directions causing the excitation were at about 45 degrees to the plane of the cables with the affected cables being those sloping downwards in the direction of the wind. The particular range of wind velocities that caused the oscillations appears to be that which maintained the upper rivulet within a critical zone on the upper surface of the cable. A lower velocity simply allowed the water rivulet to drain down to the bottom surface and a higher velocity pushed it too far up onto the upper surface for it to be in the critical zone.

As with vortex excitation and galloping, any increase in the Scruton number \( \frac{m\zeta}{\rho D^2} \) is beneficial in reducing the cable's susceptibility to rain/wind vibrations. It is noteworthy that many of the rain/wind vibrations that have been observed on cable-stayed bridges have occurred during construction when both the damping and mass of the cable system are likely to have been lower than in the completed state, resulting in a low Scruton number. The grouting of the completed cables adds both mass and probably damping, and often sleeves of visco-elastic material are added to the cable end connections which further raises the damping. The available circumstantial evidence indicates that the rain/wind type of vibration primarily arises as a result of some cables with exceptionally low damping, down in the \( \zeta = 0.001 \) range.

Since many bridges have been built without experiencing problems from rain/wind vibration of cables it appears probable that in many cases the level of damping naturally present is sufficient to avoid the problem. The rig test data of Saito et al. (1994), obtained using realistic cable mass and damping values, are useful in helping to define the boundary of instability for rain/wind oscillations. Based on their results it appears that rain/wind oscillations can be avoided provided that the Scruton number is greater than 10,

\[
\frac{m\zeta}{\rho D^2} > 10
\]

This criterion can be used to assess how much damping a cable needs to avoid rain wind oscillation problems. Recent full-scale data have generally supported this criterion (Jones and Main, 2002).

Since the rain/wind oscillations are due to the formation of rivulets on the cable surface it is probable that the instability is sensitive to the surface roughness, or to small protrusions on the surface and to the type of sheathing material. One approach to solving the rain/wind problem is to have small protrusions running parallel to the cable axis or coiled around its surface. For example, Matsumoto et al. (1989) indicate that they found axially aligned protrusions of about 3/16-in height and 7/16-in width at 30 degree intervals around the perimeter of 6-in diameter cables were successful in suppressing oscillations. This method has been used on the Higashi-Kobe Bridge, and has proven effective. However, for longer main spans, the additional drag
force on the cables introduced by the protrusions can become a substantial part of the overall wind loads.

Flamand (1994) has used helical fillets 1/16-in high and 3/32-in wide with a pitch length of 2 ft on the cables of the Normandie Bridge. This technique has proven successful, with a minimal increase in drag coefficient. Work by Miyata and Yamada (1995) has shown that lumped surface roughness elements, typically of order 1% of cable diameter, can be used to introduce aerodynamic stability in rain/wind conditions with no appreciable increase in drag force.

Examples of these techniques are illustrated in Figure 33.

![Aerodynamic devices](image)

**Figure 33: Aerodynamic devices.**

**Galloping of Cables with Ice Accumulations**

The accumulation of ice on a cable in an ice or freezing rain storm can lead to an effective change in shape of the cable to one that is aerodynamically unstable. This has caused large amplitude oscillations of long power conductor cables and could potentially occur on bridge cables. However, we are not aware of this being a common problem on bridges. In the power industry special dampers such as the Stockbridge damper have been employed to mitigate this problem. For bridges the general measure of ensuring that cables do not have excessively low damping will probably be sufficient to avoid most problems from this source.

**Galloping of Cables in the Wakes of Other Structural Components**

The wakes of bridge components such as towers or arches have velocity gradients and turbulence in them, and if a cable becomes impacted by these disturbed flows they can in principle experience galloping oscillations. It might be difficult to distinguish oscillations caused by this
mechanism from those due to other causes such as buffeting, galloping in the wakes of other cables, or rain/wind oscillations. There do not appear to be any reports of cases where galloping in the wake of another structural component such as a bridge tower has been specifically identified. As with other types of instability, ensuring the cable has as high a damping as possible would be a good general preventive measure against this type of galloping.

**Cable Oscillations due to Aerodynamic Excitation of Other Bridge Components**

The natural modes of vibration of a long span bridge and its cables, treated as a single system, are numerous. Many of these modes involve substantial cable motions accompanying relatively small motions of other major components such as the deck. It is conceivable therefore that the deck could be excited, by vortex shedding for example, into very small oscillations which are of little significance for the deck but which involve concomitant motions of one or more of the cables at much larger amplitude. To the observer this type of response to wind could well appear like pure cable oscillations if the deck motions were too small to notice, and yet the source of the excitation would in this case be wind action on the deck.

Pinto da Costa et al. (1996) have shown analytically that small amplitudes of anchorage oscillation can lead to large cable responses if the exciting frequency is near the natural frequency of the lower modes of the cables. Anchorage displacement amplitudes as low as 1½-in are shown to cause steady-state cable displacements of over 6 ft for a 1450 ft stay cable with a critical damping ratio below 0.1%, typical of bridge stay cables during erection. Anchorage motions with frequencies equal to or double the first natural frequency of vibration of the cables are most likely to excite the cables. This type of excitation appears not to have been specifically identified in full scale observations of bridges. On the other hand it is a subtle effect that could easily be confused with other forms of cable excitation. It is a subject requiring further research.

**Motions due to Buffeting by Wind Turbulence**

Flexible structures such as long bridges and their cable systems undergo substantial motions in strong winds simply due to the random buffeting action of wind turbulence. Very long cables will have their lower modes of vibration excited by this effect but it is not an aeroelastic instability. Even very aerodynamically stable structures will be seen to move in strong winds if they are flexible. Buffeting motions are not typically a problem for bridge cables. However, they may be mistakenly identified as the beginnings of an aeroelastic instability. The buffeting motions increase gradually with wind speed, rather than in the sudden fashion associated with an instability.
Motion due to Fluctuating Cable Tensions

Fluctuating forces due to turbulence produces fluctuating tension in the stays, which induce fluctuating forces at the anchorage points (lifting on the deck and pulling on the tower). Davenport (1995) has noted that the fluctuating axial tension in cable stays produced by drag is an additional excitation mechanism for the cables. Denoting the change in drag per unit length of the cable by $\Delta F_D$, the magnitude of the fluctuating tension as a fraction of the fluctuating lateral load on the stays is:

$$\frac{\Delta T}{\Delta F_D L} = \frac{k_e \cdot \frac{T}{(mL)}}{k_g \cdot 1 + (k_e/k_g) - (\omega/\omega_0)^2}$$

where:
- $L$ = cable length
- $k_e$ = elastic stiffness of the cables, $AE/L$
- $k_g$ = gravitational stiffness, $[m \pi^2/8][T/(mL)]^3$
- $\omega_0$ = natural frequency of the cable
- $\omega$ = exciting frequency

A strong multiplier effect is indicated in Equation 17 through the term $[T/(mL)]$, and the term $[1 + (k_e/k_g) - (\omega/\omega_0)^2]$ which has resonance characteristics at $\omega = \omega_0$.

It is important to note the relationship between anchorage displacements and cable tension. A combination of fluctuating tension in the stay cables and oscillation of the anchorage points will likely have the effect of feeding energy into the cables, amplifying the motion. Ensuring adequate damping levels for the stay cables will reduce cable motion considerably.
B1.2 MITIGATING MEASURES

From the above discussion it is clear that there are a number of causes of aerodynamic excitation of cables, so there are several possible approaches to developing mitigating measures. Some of these are not always practical for implementation but they are all listed below for completeness.

(i) **Modify Shape**: Increasing the surface roughness with lumped regions of roughness elements or helical fillets has the benefit of stabilizing the cables during rain/wind conditions without an increase in drag. Well-defined protrusions on the cable surface with a view to modifying the behavior of the water rivulets in rain/wind vibration (as discussed earlier, Figure 33) have been used in Japan. These methods are most effective for the rain/wind instability problem. It is unclear how effective these techniques are for solving the wake galloping problem. The use of helical fillets as cable surface treatment is becoming popular for new cable-stayed bridges, including Leonard P. Zakim Bunker Hill Bridge (MA), U.S. Grant Bridge (OH), Greenville Bridge (MS), Maysville-Aberdeen Bridge (KY), William Natcher Bridge (KY), and Cape Girardeau Bridge (MO).

(ii) **Modify Cable Arrangement**: The wake interaction effects of cables can be mitigated by moving the cables further apart. Clearly, the implications of this must be weighed against other design constraints such as aesthetics and structural design requirements.

(iii) **Raise Natural Frequencies**: By raising the natural frequencies of the cables the wind velocity at which aerodynamic instability starts is increased. The natural frequency depends on the cable mass, the tension and on the length. Often the tension and mass are not quantities that are readily adjusted without impacting other design constraints, but the effective cable length can be changed, at least in arrays of cables, by connecting the cables transversely with secondary cable cross-ties (Figure 34). The lowest natural frequency susceptible to aerodynamic excitation can be easily be raised several fold by this means. An example was given earlier in the section on wake galloping. Bridges where cross-ties are being provided include Dames Point Bridge (FL), Greenville Bridge (MS), Cape Girardeau Bridge (MO), Leonard P. Zakim Bunker Hill Bridge (MA), Maysville-Aberdeen Bridge (KY), and U.S. Grant Bridge (OH).

(iv) **Raise Mass Density**: By increasing the mass density of the cable one may increase the Scruton number and, as discussed in the earlier sections, this is universally beneficial in reducing susceptibility to aerodynamic instability. However, in practice the cable mass density can only be varied within a very limited range.

(v) **Raise Damping**: Increasing the damping is one of the most effective ways of suppressing aerodynamic instability, or postponing it to higher wind velocity and thus making it rare enough not to be of concern. Since the damping of long cables tends to be naturally very low, the addition of relatively small amounts of damping at or near the cable ends can provide dramatic improvements in stability. Several techniques have been successfully used on existing structures, including viscous (oil) dampers (Figure 35), neoprene bushings at the cable anchorages, petroleum wax in-fill in the guide-pipes, and visco-elastic dampers in the cable anchorage pipe (Figure 36). It should be noted that the
addition of cross-cables to the primary stay cables can also introduce additional damping to the system, on the order of 10 to 50 percent (Yamaguchi & Nagahawatta, 1995). Experimental studies (Saito et al. 1994) of the cables of the Higashi-Kobe Bridge in Japan have indicated that cable vibrations are not a problem at damping ratios above 0.3% of critical. Full-scale damping measurements on the long-lay cables of the Annacis Bridge in Vancouver, which include neoprene dampers at both ends of the cable, indicate damping ratios of 0.3% to 0.5% (Steimer & Taylor, 1988). This bridge has apparently had no reported difficulties with cable vibrations. Thus a damping ratio of about 0.5% appears to be a minimum threshold to meet to minimize potential cable instability problems.

A number of bridges that have reported cable vibration problems are listed in Table 9. Also listed in Table 9 are remedies used to solve the cable vibration problem. All of the remedies listed in the table use some of the measures discussed above, and have apparently been effective in mitigating the cable vibration problem. These methods are illustrated in Figures 33-36.

Figure 34: Cable cross-ties.
Figure 35: Viscous damping.

Figure 36: Material damping.
Table 9: Bridges reporting cable vibration and mitigating measures.

<table>
<thead>
<tr>
<th>Name</th>
<th>Location</th>
<th>Length of main span (ft)</th>
<th>Observations</th>
<th>Double Amplitude of Vibration (ft)</th>
<th>Remedy*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normandy</td>
<td>Le Havre, France</td>
<td>2800</td>
<td>cable vibrations during steady 1-2m/s winds</td>
<td>5</td>
<td>viscous dampers installed</td>
</tr>
<tr>
<td>Second Severn</td>
<td>Bristol, United Kingdom</td>
<td>1500</td>
<td>cable vibrations with and without rain</td>
<td>1.5-5</td>
<td>cross-cables installed</td>
</tr>
<tr>
<td>Helgeland</td>
<td>Sandnessjoen, Norway</td>
<td>1400</td>
<td>large cable vibrations; depending on deck motion</td>
<td>2</td>
<td>cross-cables installed</td>
</tr>
<tr>
<td>Meiko Nishi</td>
<td>Aichi, Japan</td>
<td>1325</td>
<td>vibration during light rain / low wind speeds</td>
<td>1.8</td>
<td>cross-cables installed</td>
</tr>
<tr>
<td>Tjorn Bridge</td>
<td>Gothenburg, Sweden</td>
<td>1180</td>
<td>vibration during light rain</td>
<td>-</td>
<td>viscous dampers installed</td>
</tr>
<tr>
<td>Tenpozan</td>
<td>Osaka, Japan</td>
<td>1150</td>
<td>vibration during rain and 10m/s winds</td>
<td>6.5</td>
<td>-</td>
</tr>
<tr>
<td>Kohlbrandt</td>
<td>Hamburg, Germany</td>
<td>1070</td>
<td>-</td>
<td>3.3</td>
<td>viscous dampers installed</td>
</tr>
<tr>
<td>Brotonne</td>
<td>Rouen, France</td>
<td>1050</td>
<td>vibrating in 15m/s winds</td>
<td>2</td>
<td>viscous dampers installed</td>
</tr>
<tr>
<td>Weirton-Steubenville</td>
<td>W. Virginia, USA</td>
<td>820</td>
<td>vibrations noted when winds are parallel to deck</td>
<td>2</td>
<td>visco-elastic dampers to be installed in the guide pipe at deck level</td>
</tr>
<tr>
<td>Yobuko</td>
<td>Saga, Japan</td>
<td>820</td>
<td>vibration during light rain</td>
<td>0.5</td>
<td>manila ropes attached to cables</td>
</tr>
<tr>
<td>Aratsu</td>
<td>Kyushu Is., Japan</td>
<td>610</td>
<td>vibration during light rain</td>
<td>2</td>
<td>viscous dampers installed</td>
</tr>
<tr>
<td>Wandre</td>
<td>Wandre, Belgium</td>
<td>550</td>
<td>vibration during light rain and 10m/s winds</td>
<td>1.6</td>
<td>petroleum wax fill in the guide pipe</td>
</tr>
<tr>
<td>Ben-Ahin</td>
<td>Huy, Belgium</td>
<td>550</td>
<td>vibration noted during light drizzle and 10m/s winds</td>
<td>3.3</td>
<td>petroleum wax grout added in the guide pipe and cross-cables also added</td>
</tr>
<tr>
<td>Alzette</td>
<td>Luxembourg</td>
<td>425</td>
<td>vibration during drizzle and light winds</td>
<td>-</td>
<td>neoprene guides inside the guide pipe at deck and petroleum wax fill in the guide pipe</td>
</tr>
</tbody>
</table>

*see Figure 33-36 for illustrations of mitigating measures
APPENDIX B2: WIND-TUNNEL TESTING OF STAY CABLES

EXECUTIVE SUMMARY

In order to clarify the dry cable galloping phenomenon and verify the instability data by Saito et al. (1994), a series of wind tunnel tests of a 2D sectional model of an inclined cable was conducted. The wind tunnel tests were performed in the “Propulsion” wind tunnel at the Montreal Road campus of the Institute of Aerospace Research, National Research Council Canada (IAR/NRCC). The main findings of the current study can be summarized as follows:

1) Limited-amplitude high-speed vortex shedding excitations have been observed under a variety of conditions.
2) Motions that reached the limits of the test rig were observed at low damping for one case, i.e., 2C: it is possible that this was a divergent galloping instability.
3) The limited-amplitude vibration was observed only in the limited wind speed range at different wind speed levels corresponding to the critical Reynolds number. The maximum amplitude of the response depends on the orientation angle of the cable.
4) The limited-amplitude high-speed vortex excitation was easily suppressed by increasing structural damping.
5) If wind blows along the cable, for cables with a vertical inclination angle $\theta \leq 45^\circ$, the increase of surface roughness makes the unstable range shift to lower wind speeds.
6) Since elastic bands were used to change the frequencies of the cable motion in the X-and Y-directions, which at the same time affects the system damping, no clear frequency ratio effect was identified from the test results. However, this parameter could be important for the aerodynamic behavior of the inclined dry cable, and thus is worthy of further investigation.
7) The instability data for inclined cable vibration defined by Saito et al. (1994) is found to be more conservative than the results obtained from the current study. The instability defined by the current findings has a much steeper slope than that given by Saito.
8) The Reynolds number effect, which results from the model surface condition and the orientation angle, needs to be further explored.
B2.1 INTRODUCTION

The focus of the test program was to examine the response of a dry cable (i.e. no rain-wind interaction) inclined at various angles to the wind. As discussed in the main text, various methods for suppressing rain-wind oscillations have been developed and appear to be effective, even though not all aspects of the excitation mechanism are fully understood. Therefore, tests on rain-wind excitation were concluded to be not at the top of the priority list. However, the question of oscillations of dry cables is still the subject of much debate. Some believe the only dry cable oscillations that occur are due to parametric excitation, in which the fluctuating aerodynamic forces acting on the deck and towers cause some oscillations of those components, which then feed energy into the cables causing them to develop much larger oscillations. Others believe wind action on the cables themselves, either involving Den Hartog type galloping or a high speed form of vortex excitation, is the source of oscillations. The aim of the test program was to investigate the direct action of wind on dry inclined cables with a view toward helping to resolve the debate. In particular, the tests would duplicate some of the conditions tested by Saito et al. (1994), and attempt to confirm or modify the criteria suggested in that paper for dry cable galloping.

Since the wind speeds where oscillations have been observed and the typical stay cable diameters result in the cables being in a critical range of Reynolds number (where the aerodynamic parameters such as drag coefficient and Strouhal number undergo rapid transformations), it was important to undertake the testing in the same Reynolds number range as experienced in the field. The “model” scale was therefore selected to be approximately 1:1. A segment of cable with overall diameter 6.3 in (160 mm) was selected (the outer PE sheath, without a spiral bead, being the same as used for the Maysville bridge). The test cable mass was selected to facilitate achieving realistic Scruton numbers. Also it was important to use a wind tunnel with a speed range similar to the range of wind speeds seen on bridges. The Propulsion wind tunnel at the National Research Council of Canada (NRCC) in Ottawa was selected for this purpose, having a speed range of 0 - 87 mph (0 - 39 m/s), and having working section dimensions of 20 ft in the vertical direction and 10 ft in the horizontal direction. The local assistance of Prof. Hiroshi Tanaka and his graduate student S.H. Cheng at the University of Ottawa was also obtained for the running of the tests, data analysis, and assistance in report preparation. The testing also benefited from the advice and experience of NRCC staff, including Dr. Guy Larose who had undertaken tests previously in Europe on cable vibration problems.
The dynamic test rig supporting the test cable was designed and constructed by Rowan Williams Davies & Irwin, Inc. (RWDI) and shipped to Ottawa after initial shake down tests in Guelph. RWDI staff also directed the test program. In designing the rig, use was made of the fact that, in the context of cable vibrations, wind does not know the difference between the vertical and horizontal directions. The only angle that matters as far as its interaction with a cable is concerned is the angle between the wind vector and the cable axis. This simplified the wind tunnel tests because it implied that the test cable could be maintained in a vertical plane aligned with the central axis of the wind tunnel. The only angle adjustment needed to cover the range of relative angles between wind and cable seen on a real bridge was the angle of the test cable to the horizontal. However, a cable on a bridge does have slightly different frequencies in the vertical plane and in lateral direction. Therefore, to the extent that this frequency ratio matters, it was felt that there should be the ability to alter the cable frequencies in two orthogonal directions on the model. This was made possible by having adjustable sets of orthogonal springs at each end of the test cable. The orientation of the test rig springs could be rotated to any angle about the test cable axis. This, combined with the adjustable angle between test cable and the horizontal axis of the wind tunnel, allowed various combinations of wind direction relative to the bridge axis and full scale cable angle relative to the horizontal to be simulated, covering most of the range of interest.

Other parameters of importance to cable vibrations, besides those already discussed, are the damping ratio, frequency ratio of vertical and horizontal cable frequencies and the surface roughness. Therefore the test program included an examination of the influence of these parameters.
B2.2 MODEL DESIGN

Cable Model

A 6.7 m long full-scale cable model is used for the purpose of the current project. It is supplied by RWDI. The cable, consisting of an inner steel pipe and outer smooth polyethylene (PE) tube, has an outside diameter of 160mm. A 3/8-16 machine screw was put on at one end only during the initial setup stage to prevent the inner steel pipe sliding out of the PE tube. The weight of the cable itself is 356.4kg (785 lb.), i.e. 53.2kg/m. The model is supported on a rig designed and manufactured by RWDI. When the cable vibrates, the effective cable mass should include that of the steel shaft at the pipe ends, and 1/3 of the spring mass on the supporting rig. Thus, the total active dynamic mass of the cable is 407.4kg, and the effective mass per cable length is 60.8 kg/m.

Angle relationships between the cable and mean wind direction

As shown in Figure 37, the orientation of the cable with respect to the mean wind direction can be represented by two angles. If the wind blows with a horizontal angle of $\beta$ to the bridge axis, the projection of the cable on the horizontal plane makes a horizontal yaw angle $\beta$ with the wind vector. Also, if the cable is assumed to be in a vertical plane parallel to the bridge axis, it has a vertical inclination angle $\theta$.

![Figure 37: Angle relationships between stay cables and natural wind (after Irwin, P. A.).](image)

The relative angle $\Phi$ between the wind direction and cable axis has the relationship with $\theta$ and $\beta$ as follows

$$\cos \Phi = \cos \beta \cos \theta$$  \hfill (18)
The direction of cable motion is normal to both the wind direction and the cable axis, and can be represented by the vector OB’ given in Figure 37. OB’ has an angle $\alpha$ with respect to its horizontal projection OB. This angle $\alpha$ also has a relationship with the orientation angles $\theta$ and $\beta$, given by

$$\tan \alpha = \tan \beta / \sin \theta$$  \hfill (19)

**Supporting Rig**

The cable supporting rig was designed and built for the current project by RWDI. For the purpose of the test, there are a number of requirements for the design of the rig as follows:

a) To allow the vibration of a 6.7m long, 356.4kg full-scale cable model at the natural frequency of 1-2Hz;
b) To allow the convenient change of cable orientation angles for exploring more different setup cases;
c) This setup of the cable model allowed for approximately 6.0 m of the 6.7 m cable in the wind flow and maintained the upwind support out of the wind flow.
d) To keep the inherent structural damping of the whole system as low as possible, so that the level of damping for controlling dynamic behavior can be examined by supplying additional damping;
e) To be able to simulate a slight difference between the horizontal and vertical frequencies as it is expected of in the case of real stay cables.

The designed test rig meets all these requirements. It consists of the upper and bottom parts to support both ends of the cable model, as shown in Figure 38. There are two pairs of springs set in two perpendicular directions on each part of the rig. Both springs are in the plane perpendicular to the cable axis. The adjustment of the spring stiffness controls the change in cable frequencies in the spring direction. The total mass of the springs is 60 kg. The vertical spring constant is 4.99kN/m, and the horizontal one is 4.78kN/m, when one of them is placed horizontally.

![Figure 38: Cable supporting rig.](image)
Because of the size of the cable model and the limitation in the dimension of the wind tunnel facility, the simulation of real cable orientation angles, $\theta$ and $\beta$, for the range of interest is difficult to reproduce. Thus, the simulation of the corresponding wind-cable relative angle $\Phi$ and cable motion direction angle $\alpha$ are considered instead.

The cable model is set up in the wind tunnel with its upper wind end protruding through the tunnel ceiling and supported by the upper part of the rig. One panel of the wind tunnel ceiling was cut out to allow the cable to go through. The down wind end of the model is supported by the bottom part of the rig, which is supported on a horizontal H-shaped frame. Two sides of the frame are fixed on the wind tunnel wall. The distance from the tunnel floor to the plane of the frame can be adjusted by fixing the two sides of the frame at different heights on the tunnel wall. By doing so, different wind-cable relative angle $\Phi$ can be modeled. The cable model is in a similar orientation as the tests performed by Saito et al. (1994) by this setup.

In the present study, an aerodynamic instability is explored that is not a function of the gravitational force but of the inertial mass in the direction of motion. The two parts of the test rig can support the gravitational force of the cable model. Further, an axial cable is attached from the building frame to the upper end of the model to provide more support. The two pairs of springs at both ends can be rotated about the central axis of the cable model. Consequently, the horizontal and vertical vibration planes of the cable are rotated, and the ground plane is effectively being rotated. By rotating the ground plane, the direction of cable motion is changed, thus different cable motion direction angle $\alpha$ can be achieved. According to Equations 18 and 19, by choosing appropriate combinations of $\Phi$ and $\alpha$, the desired orientation angles $\theta$ and $\beta$ of stay cables in real cable-stayed bridges can be modeled in the wind tunnel tests.

For the initial setup, one pair of springs at each end was set along the horizontal direction, while another pair was set perpendicular to it (spring rotation angle $\Phi = 0^\circ$). In this report, the direction coinciding with the initial horizontal spring is defined as X-direction, while that coinciding with the initial vertical spring is defined as Y-direction. The definition of X and Y directions is kept consistent in this report even in the cases where the spring rotation angle was other than $0^\circ$.
B2.3 WIND TUNNEL TESTS

Wind Tunnel Facilities

The Propulsion wind tunnel at the Montreal Road Campus of IAR/NRCC is used to carry out a series of tests for the project. It is an open circuit wind tunnel of the blowing type with fan at the entry. The flow enters the test section through a contraction cone, which accelerates the flow and improves the uniformity of the flow velocity. Figures 39 and 40 show the longitudinal section and cross-section of the tunnel respectively. There is a removable cap of 3.7m (12ft) long at the tunnel roof. An overhead travelling crane with a 15 ton capacity is available to lift the roof cap and install the model. The floor of the working section can be raised up to 0.46m to facilitate work on model installations, to simulate varying ground effects, or to modify floor boundary layer characteristics. The wind tunnel working section is 12m long, 3m wide and 6m high.

By using the electric drive in the tunnel, the maximum wind speed can reach 39 m/s. The non-uniformities of the working section velocity are generally less than 0.5% of mean wind velocity, and flow direction is within 1° of tunnel axis over most of the working section. Because the tunnel is of an open circuit type, the quality of the working section flow depends somewhat on the external wind conditions.

Figure 39: Longitudinal section of the “Propulsion” wind tunnel.
Figure 40: Cross-section of the working section of “Propulsion” wind tunnel.
Data acquisition system

The tests were conducted within the Labview environment. Seven channels were recorded simultaneously to collect the response data. The sampling frequency was 100Hz. The setup of the data acquisition system is shown in Figure 41.

![Data acquisition system](image)

Figure 41: Data acquisition system.

At each end of the model, two non-contact type laser displacement sensors (Model ANR 1226) and controllers (Model ANR 5141) were installed to measure the displacements along the X and Y directions. They were placed within the spring/damper housings and are protected from any influence of the flow. The range of the sensors is ±150mm with the linear error of less than 0.4%.

Two Pitot tubes were mounted separately on the two sides of the tunnel walls. They were placed upwind at the 2/3 points of the model to give a representative mean pressure over the full length of the cable, i.e. at 2.07m from the inlet and 3.61m above the tunnel floor. The pressure was read by a sensitive high differential pressure transducer Druck LPM 9381. The average pressure obtained from these two Pitot tubes was used for the calculation of wind tunnel speed.

The description of the input channels are given as follows:
Channel 1: Downwind end X direction displacement
Channel 2: Downwind end Y direction displacement
Channel 3: Upwind end X direction displacement
Channel 4: Upwind end Y direction displacement
Channel 5: Pitot tube #1
Channel 6: Pitot tube #2
Channel 7: Temperature
The real-time viewer of the collected response data contains three plots:
Plot 1: X-direction displacements vs. time at each end from laser sensors 1 and 3 (2 lines)
Plot 2: Y-direction displacements vs. time at each end from laser sensors 2 and 4 (2 lines)
Plot 3: Mean X- and Y-direction displacements vs. time, i.e. (Laser 1 + Laser 3)/2 and (Laser 2 + Laser 4)/2 (2 lines)

The measured real-time wind pressure in the tunnel given by Pitot tubes #1 and #2, the corresponding mean wind speed calculated based on the readings from these two Pitot tubes, and the instantaneous tunnel temperature were also displayed.

For each testing case, the collected data from those seven channels were saved in two files. The first file was a time history file. It contained the X- and Y-direction displacements at the two ends of the model recorded by the four laser sensors. The second file contained the summary statistics of the data collected from the seven channels, as well as the mean X-displacement ((Laser1 + Laser3)/2), mean Y-displacement ((Laser2 + Laser4)/2), mean angle
\[
(Arc \tan \frac{Laser1 + Laser3}{Laser2 + Laser4})
\]
in terms of mean, RMS, maximum, and minimum, respectively.

The convention of the filenames allowed the identification of each individual testing case. It contains the following parameters:
Pipe finish (surface roughness): — “A”: Smooth surface
— “B”: Rough surface
Vertical inclination angle of the model: 2-digit descriptor in degrees
Spring rotation angle: 2-digit descriptor in degrees
Wind speed: 2-digit descriptor in m/s
Damping: 3-digits descriptor as fraction of critical
Excitation method: “h” for hard or manual excitation, “s” for soft excitation, i.e. without manual excitation
Multiple runs of the same case: 2-digit flag to identify the running sequence

As an example, for the testing case of a smooth pipe, with model inclination angle 45°, spring rotation angle 0°, wind speed 18m/s, structural damping 0.6% of critical, soft excitation, third trial of the same case, the file names would be
A_450018006_s03.tms for the time history file, and
A_450018006_s03.sta for the statistical summary file.

A monitor, which was linked to a video camera installed outside the window of the wind tunnel, was set up in the control room, the cable motion under different wind velocity levels during the tests could be monitored. Once the instability behavior of the cable motion was observed, it would be recorded on videotape.
Control of the damping level: airpot damper

The effect of damping level on the inclined dry cable vibration was examined. The airpot damper, as shown in Figure 42, was initially suggested to be used for supplying additional damping to the cable system at each end of the cable support; two airpot dampers installed along the directions of the two perpendicular springs. A cross-sectional view of the airpot damper is given in Figure 43.

Figure 42: Airpot damper.

Figure 43: Cross-section of airpot damper.
The airpot damper uses the ambient air as the damping medium. The force to be damped is transmitted through the airpot piston rod, which moves the piston within the cylinder. The orifice setting and the diametric clearance between the piston and cylinder control the rate of air transfer. As the piston moves in response to the force exerted, there will be a change in volume and pressure in the airpot, causing ambient air to enter or leave the cylinder. The rate of airflow can be controlled to provide the exact degree of damping required by a simple adjustment of the orifice.

However, during the preparation of the tests, it was found that the frictional damping between the piston and the cylinder wall inside the airpot damper had a significant impact on the small-amplitude motion, which suppressed the hand-excited cable vibration in just a few cycles. Finally, the airpot damper was only used in the cases of very high level damping with the order of 1% of critical, while for the intermediate and high level damping cases, elastic bands were used along the spring coils to increase the system damping (Figure 44). By adjusting the number and locations of the elastic bands to be installed on the spring coils, the desired structural damping levels were achieved.

![Elastic bands on the spring coils.](image)

**Figure 44:** Elastic bands on the spring coils.

**Surface Treatment**

In order to explore the surface roughness effect on the cable oscillation, a kind of liquid glue was sprayed on the windward side of the model surface to simulate the accumulation of dirt and salt on the real cable.

**Frequency Ratio**

One distinguishing response characteristic of cable galloping is that the motion follows an elliptical trajectory. In the current model setup, the stiffness of the two pairs of perpendicular springs will affect the amplitude of motion in these two directions, and thus the resultant
oscillation path of the cable. By properly adjusting the spring stiffness of these two directions, the associated in-plane and out-of-plane vibration frequencies are changed. If the frequencies are close enough, the motions in these two directions would become resonant, which forms an elliptical shape of the motion path. Thus, the impact of the frequency ratio between the two perpendicular directions on the cable behavior of interest is worth studying.

**Outline of Test Cases**

The aerodynamic behavior of the inclined cable model has been investigated in this wind tunnel testing by different combinations of model setup, damping level and surface roughness as described in the following tables:

### Table 10: Model setup.

<table>
<thead>
<tr>
<th>Model Setup</th>
<th>Full scale cable angles (deg.)</th>
<th>Model cable angles (deg.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>θ</td>
<td>β</td>
</tr>
<tr>
<td>1B #</td>
<td>45</td>
<td>0</td>
</tr>
<tr>
<td>1C</td>
<td>30</td>
<td>35.3</td>
</tr>
<tr>
<td>2A</td>
<td>60</td>
<td>0</td>
</tr>
<tr>
<td>2C *</td>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td>3A</td>
<td>35</td>
<td>0</td>
</tr>
<tr>
<td>3B</td>
<td>20</td>
<td>29.4</td>
</tr>
</tbody>
</table>

# Setup 1A (θ = 0°, β = 45°) and 1B are identical in reality, except that the sway and vertical frequencies are switched.

* Setup 2C is the same case in which Miyata et al. (1994) have found the divergent motion of the inclined dry cable.

### Table 11: Different damping levels of the model.

<table>
<thead>
<tr>
<th>Damping Description</th>
<th>Dampers Used</th>
<th>Approximate Damping Range (% of critical)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low damping</td>
<td>No damper added</td>
<td>0.03 to 0.09</td>
</tr>
<tr>
<td>Intermediate damping</td>
<td>16 elastic bands per sway spring</td>
<td>0.05 to 0.10</td>
</tr>
<tr>
<td>High damping</td>
<td>28 elastic bands per sway spring</td>
<td>0.15 to 0.25</td>
</tr>
<tr>
<td>Very high damping</td>
<td>Airpot damper with 1 ¼ dial turns</td>
<td>0.30 to 1.00</td>
</tr>
</tbody>
</table>

### Table 12: Surface condition.

<table>
<thead>
<tr>
<th>Surface Condition</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smooth surface</td>
<td>Polyethylene (PE) Pipe with clean surface</td>
</tr>
<tr>
<td>Rough surface</td>
<td>Polyethylene (PE) Pipe with glue sprayed on the windward side of the cable</td>
</tr>
</tbody>
</table>

Figures 45-47 show the model set-ups of the investigated cases in the wind tunnel tests, and Figure 48 shows a picture of the inclined cable set up in the wind tunnel.
Figure 45: Side view of Setups 1B and 1C.
Figure 46: Side view of Setups 2A and 2C.
Figure 47: Side view of Setups 3A and 3C.
Figure 48: Cable set up in wind tunnel for testing.
B2.4 RESULTS AND DISCUSSION

General Procedures for a Given Test Setup

For a given case with its specific setup, the general procedures of the wind tunnel test are as follows:

i) In still air, take tare case of the model;

ii) Measure the system structural damping in X- and Y-directions by hand exciting the model along these two directions respectively. Once reached the desired amplitude level, stop the hand excitation and let the model undergo free vibration. The structural damping of the system and the vibration frequency can thus be identified;

iii) Start at the low wind speed (for the setup that is tested for the first time, take 7m/s, while for other cases, the starting value can be determined based on previous trials), increase in 2m/s increments. When the wind speed approaches the expected unstable range, increase the speed by 1m/s until unstable vibrations occur;

iv) In reality, some external effects such as wind turbulence and motions of the deck may help to initiate cable vibrations. Thus, during the tests, if no unstable vibration occurs within the expected wind speed range, hand excitation will be used to help initiate the unstable motion of the model and see if the motion decays or grows;

v) If the unstable behavior is observed, add additional damping to the system. Repeat the above procedure for different damping levels until the unstable motion is eliminated;

vi) For the low damping level (no additional damping added), change the surface roughness and repeat the same procedure.

Characteristics of Cable Motion

Both the divergent type of cable vibration and the limited-amplitude cable motion at a certain wind speed range have been observed in the current study.

Divergent type of motion

Motions of the cable that resembled divergence were observed only in Setup 2C. For this setup, the model has a vertical angle of \( \Phi = 60^\circ \), and the spring rotation angle of \( \alpha = 54.7^\circ \). This is equivalent to the full-scale cable orientation of the vertical inclination angle \( \theta = 45^\circ \) and horizontal yaw angle \( \beta = 45^\circ \).

The relationships between the system structural damping and response amplitude were obtained by hand exciting the model in X- and Y-directions, respectively. The maximum amplitude of the hand excitation was about 35mm. The free vibration immediately following the hand excitation was recorded for 15 minutes. The amplitude-dependent structural damping as a percentage of critical values in X- and Y-directions are given in Figure 49. The vibration frequency in X-direction is 1.400Hz, and that in Y-direction is 1.415Hz.
The wind-induced response of Setup 2C is given in Figure 50. The test started at a low wind speed of 10m/s. When wind speed reached 32m/s, the motion became more organized and the amplitude in the Y-direction was built up steadily from ±20mm to ±80mm within 3 minutes. As shown by Figures 51 and 52, which are the time histories in the X- and Y-motion at both ends of the model and the motion trajectory, the predominant motion occurs in the Y-direction. The motion had the tendency of growing further, but it had to be manually suppressed because of the clearance for the model setup at the wind tunnel ceiling. The recorded peak-to-peak amplitude was about 1D, where D is the cable diameter.

**Limited-amplitude motion**

The limited-amplitude unstable motion of the inclined cable model has been observed at certain wind speed levels under Setups 2A, 1B, 1C and 3A. The full-scale cable orientation angles, the model setup angles, and the unstable wind speed ranges corresponding to each individual case are given in Table 13.

<table>
<thead>
<tr>
<th>Model Setup</th>
<th>Full scale cable angles</th>
<th>Model cable angles</th>
<th>Unstable range</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>θ</td>
<td>β</td>
<td>Φ</td>
</tr>
<tr>
<td>2A</td>
<td>60</td>
<td>0</td>
<td>60</td>
</tr>
<tr>
<td>1B</td>
<td>45</td>
<td>0</td>
<td>45</td>
</tr>
<tr>
<td>1C</td>
<td>30</td>
<td>35.3</td>
<td>45</td>
</tr>
<tr>
<td>3A</td>
<td>35</td>
<td>0</td>
<td>35</td>
</tr>
</tbody>
</table>

* $U_r$ = Reduced wind speed

Figures 53 ~ 62 show the time histories at both ends of the model as well as the trajectory of the motion for those four different setups when unstable behavior of the cable was observed.

Three sets of time histories are given in Figures 53 ~ 55 for Setup 2A. The first and second set describe the time history and trajectory of the cable motion at wind speed of 18m/s during the first and second 5 minutes, whereas the third set describes the time history and trajectory of the motion when wind speed increased to 19m/s. It can be clearly seen from these three sets that the vibration amplitude in the X-direction increases from about ±20 mm to about ±50 mm within the first 5 minutes of $U = 18$ m/s, then increases a little bit to ±60 mm and stays steadily at that level during the second 5 minutes of $U = 18$ m/s. Once the wind speed increases to 19 m/s the vibration amplitude in the X-direction starts reducing slowly.
The relationship between the wind speed and response of these four setups are given in Figures 63 ~ 66. The unstable ranges are clearly indicated by the peaks in the response curves.

Based on observations, this limited-amplitude cable motion looks more like vortex shedding excitation rather than galloping. The characteristics of the motion are summarized as follows:

a) The amplitude of the motion is limited. As given in Table 13, the largest amplitude observed is in Setup 2A. When wind speed is 19m/s, the amplitude of the cable motion reaches 67mm;

b) The vibration was observed only in the limited wind speed range at different wind speed levels. The reduced wind velocities corresponding to these ranges are approximately the multiples of 20;

c) The maximum magnitude of the vibration depends on the orientation angle of the cable. It is larger with a greater vertical inclination angle, as given in Table 13. In Setup 3B, which represents the full-scale cable with a very shallow inclination angle of 20° and yaw angle of 29.4°, no unstable motion was observed within the wind speed range of 8m/s -34m/s. Figure 67 gives the response of the cable with respect to wind speed in Setup 3B. It can be seen that the amplitude of the motion stayed at less than 5mm.

d) At the wind speed range where the cable motion was observed, there are two types of response: one is an organized harmonic motion, another is with a regular beating, which is similar to what Matsumoto (1998) described as the case of 3D Karman vortex shedding excitation. He explains that this regular beating is caused by the aerodynamic interaction between the axial vortices along the inclined cable surface and the ordinary Karman vortices in the wake of the cable. The Karman vortex shedding is amplified intermittently by the axially produced vortices and induces the beating type motion of the inclined cable.

e) In some of the setups when the spring rotation angle is not 0°, which is equivalent to the wind horizontally oblique to the cable, an elliptical motion of the cable was observed, which correlates well with the field observation (Matsumoto et al., 1990)

f) The critical Reynolds number at which the sudden decrease in the drag coefficient occurs is influenced both by surface roughness and flow turbulence. The critical Reynolds number range for a smooth circular cylinder under uniform flow is 2 ~ 4x10⁵, as shown in Figure 68 (Scruton, 1981). From the Reynolds numbers listed in Table 13, it is interesting to observe that for the current study, all of these instabilities occurred more or less at wind speeds corresponding to this critical Reynolds number range.

**Damping Effect**

Four different levels of damping, i.e. low, intermediate, high, and very high damping have been used in the tests to investigate the impact of structural damping on the aerodynamic behavior of the inclined cable.

A comprehensive set of damping tests was carried out with the model setup 1B, which represents the cable vertical inclination angle of 45° and horizontal yaw angle of 0° in full-scale bridge cables. No additional damper was applied for the low damping case. For the intermediate and high damping cases, the elastic bands were used to bind the spring coils together to increase the system damping, as shown previously in Figure 44. The achieved damping level depends on the
number and locations of the elastic bands. To obtain the intermediate level of damping, 16 elastic bands were used on each sway spring in the X-direction; while for the high damping level, 28 elastic bands were used on each spring in both X- and Y-directions. The very high damping level was achieved by installing the airpot dampers at both ends of the model with 1 ¼ dial turn.

The relationship between the critical damping ratio and the sway amplitude corresponding to these four levels of damping are given in Figure 69. Figure 70 gives the wind-induced response of the cable model with Setup 1B under those four levels of damping. As clearly shown in the figure, when the damping is increased, the response is significantly reduced, but the position of the unstable wind speed range does not change. This set of results indicates that this limited-amplitude unstable motion can be suppressed by increasing the damping of the cable.

**Surface Roughness Effect**

The cable model has been tested under both smooth and rough surface conditions. For the rough surface case, a kind of liquid glue was sprayed on the windward side of the model to simulate the accumulation of dirt and salt on the real cable.

Figures 71 ~ 73 describe the response of the model cable with Setups 3A, 1B and 2A under both smooth and rough surface conditions. These three cases are equivalent to wind blowing along the cable in full-scale situation. The vertical inclination angles θ are 35°, 45°, and 60°, respectively.

It can be seen from these three figures that for Setups 3A and 1B, of which the inclination angle θ ≤ 45°, the increase of cable surface roughness makes the unstable response range shift to lower wind speed. For Setup 2A, there are two peaks in the sway response curve of the smooth surface case: one is around 19m/s, and another is at about 34m/s. However, in the rough surface case, only one peak is identified, which is in the range of 31-32m/s. No clear peak shift phenomenon can be found for this setup. Since the inclination angles of these three setups are different, the difference in the responses given by those three figures not only include the surface roughness effect, but the influence of the orientation of the cable as well. Therefore, although the increase of cable surface roughness makes the unstable response range shift to lower wind speed for the cases of θ ≤ 45°, the conclusion regarding the surface roughness effect is still inconclusive from the present study alone.

The difference between the surface roughness would affect the flow separation point of the cable model, which changes the critical Reynolds number. This is likely to alter the lift and drag forces acting on the inclined cable, and thus changes its aerodynamic behavior. Further, recent study (Larose & Zan, 2001) shows that the change of orientation angle of the smooth cylinder will also affect the Reynolds number. In order to better understand the mechanism of the unstable motion of the inclined cable and develop methods to eliminate or mitigate the instability, it is very important to further explore this Reynolds number effect.
**Frequency Ratio Effect**

In real cable-stayed bridges, the horizontal and vertical frequencies of the stay cables are slightly different. The design of the cable model and supporting rig in the current project faithfully reproduced this characteristic. Results obtained from the tested cases show that for the vibration of the cable model, the predominant motion was always in the direction of higher frequency. In order to investigate the impact of frequency ratio on the aerodynamic behavior of inclined dry cable, efforts were made to change the frequency ratio between the horizontal and vertical motions. Tests were conducted for three different frequency ratios with Setup 2A:

i) \( f_s = 1.477 \text{ Hz}, \ f_v = 1.452 \text{ Hz}, \ f_s / f_v = 1.017; \)

ii) \( f_s = 1.460 \text{ Hz}, \ f_v = 1.448 \text{ Hz}, \ f_s / f_v = 1.008; \)

iii) \( f_s = 1.428 \text{ Hz}, \ f_v = 1.432 \text{ Hz}, \ f_s / f_v = 0.997; \)

where \( f_s \) is the sway frequency in the X-direction, and \( f_v \) is the vertical frequency in the Y-direction. All three cases were done with the smooth surface condition. For both case (i) and (ii), 28 elastics bands were applied on each spring. In case (i), the elastic bands were placed such that they not only bound the spring coils into several groups, but touched the steel rods inside the spring coils as well. In case (ii), only half number of the elastic bands touched the rods. In order to get higher frequency in the Y-direction in case (iii), the elastic bands on the sway springs were removed, and those kept on the vertical springs did not touch the steel rod.

Given in Figures 74 and 75 are the damping records and responses corresponding to these three cases. In Figure 74a, which is the damping of the motion in the X-direction, case (iii) has a much lower damping ratio within the same amplitude range as compared to case (i) and (ii). This is because in case (iii), the elastic bands on the sway springs were removed, which reduced the system damping in the X-direction. The larger sway response of case (iii) shown in Figure 75a correlates well with this fact.

From the response curves shown in Figure 75, no clear effect of the frequency ratio can be identified. This could be that the differences between the frequencies of those three cases are too small. Also, by using elastic bands to change the frequencies, the system damping was also affected. In order to further explore this frequency ratio effect, it will be a better approach to get different frequencies by adjusting the stiffness of the springs. Therefore, other effects, such as the change in the system damping, can be kept as small as possible.

**Comparison with Other Studies**

A limited number of experimental studies on inclined cables have been carried out particularly in Japan. Saito et al. (1994) defined an instability criterion for the inclined cable motion based on three different model setups. Two of them are exactly the same as Setup 1B and 2A in the current study. Miyata et al. (1994) investigated the inclined dry cable motion with one model setup, which corresponds to Setup 2C in the present series of tests. In order to make comparison, these two sets of results, as well as the results obtained from the current study are shown together in Figure 76. Among the results from current findings, only the one corresponding to Setup 2C exhibited signs of divergent galloping motion, whereas the others are all high speed vortex
shedding excitation. The Scruton number is defined as $Sc = \frac{m\zeta}{\rho D^2}$, where $m$ is cable mass per unit length, $\zeta$ is the logarithmic decrement, $\rho$ is the air density, and $D$ is the cable diameter. As can be seen from the figure, the boundary for instability defined by Saito is much more conservative when compared with the results given by Miyata and the current study. In addition, the similar instability criterion that could be defined by current findings would have much steeper slope than that given by Saito, which implies that with the increase of the cable structural damping, the instability range of the inclined cable motion will be shifted to even higher wind speed level, or the motion would be effectively eliminated.
Figure 49: Amplitude-dependent damping with Setup 2C (smooth surface, low damping).
Figure 50: Divergent Response of Inclined Dry Cable (Setup 2C, smooth surface, low damping).

Figure 51a: Lower end X-motion, time history of Setup 2C at U=32 m/s.
Figure 51b: Top end X-motion, time history of Setup 2C at U=32 m/s.

Figure 51c: Lower end Y-motion, time history of Setup 2C at U=32 m/s.
Figure 51d: Top end Y-motion, time history of Setup 2C at U=32 m/s. (File: A_605532006_S02.tms, smooth surface, low damping)

Figure 52: Trajectory of Setup 2C at U=32 m/s. (File: A_605532006_S02.tms, smooth surface, low damping)
Figure 53a: Lower end X-motion, time history of Setup 2A at $U=18$ m/s in the first 5 minutes.

Figure 53b: Top end X-motion, time history of Setup 2A at $U=18$ m/s in the first 5 minutes.
Figure 53c: Lower end Y-motion, time history of Setup 2A at U=18 m/s in the first 5 minutes.

Figure 53d: Top end Y-motion, time history of Setup 2A at U=18 m/s in the first 5 minutes.
(File: A_600018006_S01.tms, smooth surface, low damping)
Figure 54a: Lower end X-motion, time history of Setup 2A at U=18 m/s in second 5 minutes.

Figure 54b: Top end X-motion, time history of Setup 2A at U=18 m/s in second 5 minutes.
Figure 54c: Lower end Y-motion, time history of Setup 2A at U=18 m/s in second 5 minutes.

Figure 54d: Top end Y-motion, time history of Setup 2A at U=18 m/s in second 5 minutes.
(File: A_600018006_S02.tms, smooth surface, low damping)
Figure 55a: Lower end X-motion, time history of Setup 2A at U=19 m/s.

Figure 55b: Top end X-motion, time history of Setup 2A at U=19 m/s.
Figure 55c: Lower end Y-motion, time history of Setup 2A at $U=19$ m/s.

Figure 55d: Top end Y-motion, time history of Setup 2A at $U=19$ m/s.
(File: A_6000019006_S01.tms, smooth surface, low damping)
Figure 56a: Lower end X-motion, time history of Setup 1B at U=24 m/s.

Figure 56b: Top end X-motion, time history of Setup 1B at U=24 m/s.
Figure 56c: Lower end Y-motion, time history of Setup 1B at U=24 m/s.

Figure 56d: Top end Y-motion, time history of Setup 1B at U=24 m/s.
(File: A_450024006_S05.tms, smooth surface, low damping)
Figure 57a: Lower end X-motion, time history of Setup 1C at U=36 m/s.

Figure 57b: Top end X-motion, time history of Setup 1C at U=36 m/s.
Figure 57c: Lower end Y-motion, time history of Setup 1C at U=36 m/s.

Figure 57d: Top end Y-motion, time history of Setup 1C at U=36 m/s.
(File: A_455536006_S02.tms, smooth surface, low damping)
Figure 58a: Lower end X-motion, time history of Setup 3A at U=22 m/s.

Figure 58b: Top end X-motion, time history of Setup 3A at U=22 m/s.
Figure 58c: Lower end Y-motion, time history of Setup 3A at $U=22$ m/s.

Figure 58d: Top end Y-motion, time history of Setup 3A at $U=22$ m/s.

(File: A_35022006_S03.tms, smooth surface, low damping)
Figure 59a: Trajectory of Setup 2A at U=18 m/s, first 5 minutes.
(File: A_600018006_S01.tms)

Figure 59b: Trajectory of Setup 2A at U=18 m/s, second 5 minutes.
(File: A_600018006_S02.tms)
Figure 59c: Trajectory of Setup 2A at U=19 m/s.
(File: A_600019006_S01.tms, smooth surface, low damping)
Figure 60: Trajectory of Setup 1B at \( U = 24 \) m/s.
(File: A_450024006_S05.tms, smooth surface, low damping)

Figure 61: Trajectory of Setup 1C at \( U = 36 \) m/s.
(File: A_455536006_S02.tms, smooth surface, low damping)
Figure 62: Trajectory of Setup 3A at U=22 m/s.
(File: A_350022006_S03.tms, smooth surface, low damping)
Figure 63: Wind-induced response of inclined dry cable. (Set-up 2A, smooth surface, low damping)

Figure 64: Wind-induced response of inclined dry cable. (Set-up 1B, smooth surface, low damping)
Figure 65: Wind-induced response of inclined dry cable. (Set-up 1C, smooth surface, low damping)

Figure 66: Wind-induced response of inclined dry cable. (Set-up 3A, smooth surface, low damping)
Figure 67: Wind-induced response of inclined dry cable. (Set-up 3B, smooth surface, low damping)

Figure 68: Critical Reynolds number of circular cylinder (from Scruton, 1981).
Figure 69: Damping trace of four different levels of damping.  
(Set-up 1B, smooth surface)

Figure 70: Effect of structural damping on the wind response of inclined cable.  
(Set-up 1B, smooth surface)
Figure 71: Surface roughness effect on wind-induced response of dry inclined cable.  
(Set-up 3A, low damping)

Figure 72: Surface roughness effect on wind-induced response of dry inclined cable.  
(Set-up 1B, low damping)
Figure 73: Surface roughness effect on wind-induced response of dry inclined cable.
(Set-up 2A, low damping)
Figure 74a: Amplitude-dependent damping in the X-direction with Set-up 2A. (Frequency ratio effect)

Figure 74b: Amplitude-dependent damping in the Y-direction with Set-up 2A. (Frequency ratio effect)
Figure 75a: Wind-induced response of inclined cable in the X-direction with Set-up 2A. (Frequency ratio effect)

Figure 75b: Wind-induced response of inclined cable in the Y-direction with Set-up 2A. (Frequency ratio effect)
Figure 76: Comparison of wind velocity-damping relation of inclined dry cable.

\[ S_c = \frac{m \delta}{(\rho D^2)} \]