An Introductory Discussion on Aeolian Vibration of Single Conductors

PREPARED BY THE
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Overhead Lines Subcommittee
Working Group on Overhead Conductors and Accessories
Aeolian Vibration Task Force
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Finally, on a personal note as the Chair as this document went to print, I wish to acknowledge the contributions of co-workers Sarah Mazzotta for commenting on various drafts.

Bruce Freimark
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1 Introduction

Overhead conductors are constantly moving in response to weather conditions. These weather related movements vary in visibility and intensity from low-frequency, high-amplitude movement, often referred to as Galloping; to higher-frequency, lower-amplitude movement, known as aeolian vibration; to induced movement such as wake-induced oscillation, which can occur within phases using bundled conductors.

This document addresses only aeolian vibration on single conductors, and is to be treated as an introductory guide.

1.1 Purpose and Objective

This guide is intended to provide a baseline understanding of aeolian vibration of single conductors and should be considered an introductory synopsis of the topic for engineers new to the industry.

An introductory overview of aeolian vibration and the associated damages resulting from this conductor motion is presented. Considerations for safe line design tension to minimize potential damage from aeolian vibration and the use of dampers to limit wind induced vibration to non-damaging levels is also discussed.

1.2 Scope

This guide reviews basic principles of aeolian vibration of single conductors made with round-wire strands and having either a steel- or aluminum-core, and is not intended to provide an exhaustive discussion of aeolian vibration. The guide specifically excludes aeolian vibration on bundled conductors. References are provided at the end of the document if the reader wishes to review additional information.

2 What is Aeolian Vibration?

Note: Definitions are listed in Appendix B.

Steady or laminar (i.e. non turbulent) winds of low to moderate speeds passing over a long cylindrical shape produce trailing vortices. A bare (i.e., no ice attached), single conductor on a transmission line is therefore the ideal candidate for creating these vortices. Small forces at right angles to the wind direction are generated by these vortices and the frequency of these vortices is close to one of the natural frequencies of the span, a resonant buildup of forces cause the conductor motion known as “aeolian vibration”. All tensioned aerial cables such as conductors, shield wires, guy wires, Optical Ground Wire (OPGW) and All-Dielectric Self-Supporting (ADSS) cables are subject to aeolian vibration, which is characterized by relatively high frequency (ranging from 3 to 150 Hz) and low peak-to-peak amplitude (ranging from 0.01 to 1 times the conductor diameter) conductor motion.

If the bending caused by aeolian vibration movements is large enough and left unchecked, aeolian vibration can lead to the catastrophic failure of overhead lines due to fatigue breaks of either the conductor strands and/or the support systems at suspension clamps or other attachments. Uncontrolled vibration has also been identified as the cause of damage of insulator strings at supporting hardware connection points, and to the loosening of tower bolts.

2.1 Basics of Aeolian Vibration

As wind passes over a bare, tensioned conductor or cable, vortices are shed. These vortices are shed alternately from the top and bottom surfaces of the conductor, refer to Figure 1. The shedding of the vortices cause cyclic, vertical forces on the conductor which, in turn, cause the
The frequency at which the vortices are cyclically shed from the top and bottom surfaces can be closely approximated by Equation 1, which is based on a Strouhal Number [13]:

**Equation 1:** \( f = \frac{S_0 V}{d} \), where:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>SI Unit</th>
<th>Imperial Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f )</td>
<td>vortex shedding frequency</td>
<td>Hz</td>
<td>Hz</td>
</tr>
<tr>
<td>( S_0 )</td>
<td>Strouhal number, an empirical aerodynamic constant</td>
<td>0.185</td>
<td>3.26</td>
</tr>
<tr>
<td>( V )</td>
<td>wind velocity component normal to the conductor</td>
<td>m/sec</td>
<td>mph</td>
</tr>
<tr>
<td>( d )</td>
<td>conductor diameter</td>
<td>m</td>
<td>inch</td>
</tr>
</tbody>
</table>

As the equation indicates, the frequency of vortex shedding that causes aeolian vibration is inversely proportional to the conductor diameter. This being the case, smaller diameter conductors and overhead shield wires will vibrate at higher frequencies than larger diameter conductors for the same wind velocity.

Aeolian vibration will normally occur at wind speeds between approximately 1 to 7 m/s (2 to 15 mph). Vibration will not occur if wind speeds are too low because vortices do not form; or if wind speeds are too high because winds are too turbulent and do not create the cyclic vertical forces required to cause conductor movement.

Aeolian vibration will be most severe in laminar winds with a uniform wind front across the entire span. Open, flat terrain, as opposed to treed or rough terrain, is most conducive to severe vibration.

Tensioned conductors and cables have many natural frequencies dependent on i) tension, ii) weight/unit length, and iii) span length. This relationship can be approximated by Equation 2 [1].

**Equation 2:** \( f_n = \frac{nV_t}{2S} \), where
When the vortex shedding frequency (Equation 1) is approximately equal to one of the natural frequencies of the conductor (Equation 2), a phenomenon known as “lock-in” occurs and the conductor will start to vibrate in a resonant mode. When the conductor is “locked-in” the oscillation of the conductor begins to control the vortex shedding frequency, and the wind speed can vary ±10% from the initial value and vibration will still be maintained. The locking-in effect does not invalidate the Strouhal relationship (Equation 1), which is often used in design calculation for damper placement.

Once the conductor has “locked-in” and started to vibrate, standing wave vibration “loops” are established as shown in Figure 2. For typical spans multiple vibration loops can be present at any time. The following is a simplification of the vibration mode as several frequencies can occur simultaneously. This simplification has generally served as an acceptable model for damper selection and vibration control.

![Standing Wave Vibration Loops](image)

**Figure 2: Standing Wave Vibration Loops**

The loop length can be calculated as shown in Equation 3.

\[
I = \frac{1}{2f} \sqrt{\frac{Tg}{w}}
\]
If laminar winds persist, peak-to-peak (i.e., anti-node) amplitude will increase until an “energy balance” is established. An energy balance occurs when the wind energy input is balanced by the energy dissipated by (i) the conductor’s self-damping, (ii) dampers attached to the conductor in the span, and (iii) energy absorbed at suspension clamps, insulators and other attached hardware. Please refer to Section 4 for a more detailed discussion of the energy balance principle (EBP).

In extreme cases, un-damped peak-to-peak amplitudes in the span can approach the diameter of the conductor. In most instances, amplitudes will not exceed one-half of the conductor’s diameter.

3 What is Conductor Fatigue?

The negative effect of aeolian vibration is the possibility of conductor fatigue. If the conductor vibration is severe enough, fatigue of individual conductor strands can result. Aluminum strands are particularly vulnerable to fatigue especially when fretting\(^1\) is present. The dynamic bending stresses at support points caused by the aeolian vibration are added to the static stresses that are already present in the conductor. The static stresses include axial stress from line tension, bending stress from the total clamp angle (vector sum of any line angle plus angles due to the weight of spans in the forespan and backspan) plus compressive stresses from the clamp itself.

If the combined stresses are high enough, fatigue cracking can initiate in the conductor strands at locations where the bending stresses are the highest after a finite number of vibration cycles. This is normally where the conductor exits suspension clamps, dead-end clamps, damper clamps, in-line splices, etc. With continued vibration activity, the cracks will propagate across the strands and the strands will break.

Photographs of fatigue damage and failures caused by aeolian vibration are shown in Figure 3, Figure 4, Figure 5, Figure 6, and Figure 7.

---

\(^1\) Fretting is a mechanical wearing of contacting surfaces that are under load and subjected to repeated relative surface motion.
Relating the measurable vibrations of an overhead conductor span to the likelihood of the fatigue failure of its strands is a complicated matter. The complications arise primarily from two facts.

- Firstly, the stresses that cause the failures are complex and not related in a simple way to the gross motions of the conductor involved.
- Secondly, the failures originate at locations where there is surface contact between layers and fretting between components. A realistic analysis relating all of these stresses, including contact stresses and microslip, for a specific conductor-clamp system to the vibrations of the conductor has yet to be published.

Fretting is a mechanical wearing of contacting surfaces that are under load and subjected to repeated relative surface motion. The contact movement causes mechanical wear and material transfer at the mating surfaces, followed by oxidation of both the metallic debris...
and the freshly-exposed metallic surfaces. The black aluminum oxide debris is much harder than the surface from which it came, thus acting as an abrasive that further increases the rate of fretting and mechanical wear.

The combined stresses and fretting activity within conductors secured by bolted suspension clamps is so complex that strand failures can occur in the second layer of strands before the outer layer, as shown in Figure 3.

Armor rods used in conjunction with bolted suspension clamps share the dynamic stresses from the vibration activity, and reduce the stresses on the conductor strands but provide negligible damping. There are situations where the conductor strands fail under the armor rods before the armor rods crack or break.

Suspension clamps that employ elastomer elements, installed with or without armor rods, generally are designed to reduce the compressive stress on the conductor and also redistribute the location of the point of maximum bending stress due to displacement of the elastomer material. The damping provided by these suspension clamps is also negligible.

4 What is the Energy Balance Principle?
The “Energy Balance Principle” (EBP), which is based on the First Law of Thermodynamics\(^2\), is used to understand and analyze aeolian vibration.

Simply stated,

\[
\text{Power Input from Wind} = \text{Energy that needs to be absorbed without resulting damage}
\]

or, the amount of energy entering a conductor system must be equivalent to the amount of energy leaving the conductor system. Energy entering the system consists of wind energy. Energy leaving the system consists of heat energy from conductor self-damping, excitation of vibration dampers, as well as energy that is absorbed by the conductor hardware at the structure attachments.

The arrangement considered in the EBP is that of a “normal” round strand conductor rigidly supported in a metal clamp. Other common conductor types, such as trapezoidal stranded conductors, and conductors with materials other than electrical grade aluminum or aluminum alloy, are not adequately modeled by the EBP. Similarly, support arrangements, such as suspension clamps with armor rods, flexible suspension clamps, and dead ends, are also not represented by the theoretical modeling inherent in the EBP. This is because the EBP assumes that the clamp is rigid and the conductor flexes without restraint within a short length beyond the clamp contact region.

4.1 Wind Power Input
There are many factors which influence how much wind-based energy is actually input to the conductor system. The more significant factors include:

\[
\begin{align*}
i) & \quad \text{conductor diameter} \\
ii) & \quad \text{vibration amplitude and frequency of the conductor} \\
iii) & \quad \text{length of the span} \\
iv) & \quad \text{wind speed} \\
v) & \quad \text{wind direction} \\
vi) & \quad \text{turbulence from the surrounding terrain}
\end{align*}
\]

\(^2\) The First Law of Thermodynamics states that heat is a form of energy, and the total amount of energy of all kinds in an isolated system is constant; it is an application of the principle of conservation of energy.
The major factors influencing wind power input are: conductor diameter, vibration amplitude and frequency, and span length. This relationship is defined in Equation 4. [13]

**Equation 4:**  
\[ P_w = S \times d^4 \times f^3 \times F_n \left( \frac{Y}{d} \right), \]

where:

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<th>Description</th>
<th>SI Unit</th>
<th>Imperial Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_w )</td>
<td>wind power input</td>
<td>Watts</td>
<td>ft-lbf/s</td>
</tr>
<tr>
<td>( S )</td>
<td>span length</td>
<td>m</td>
<td>Ft</td>
</tr>
<tr>
<td>( d )</td>
<td>conductor diameter</td>
<td>m</td>
<td>Inch</td>
</tr>
<tr>
<td>( f )</td>
<td>vibration frequency</td>
<td>Hz</td>
<td>Hz</td>
</tr>
<tr>
<td>( F_n )</td>
<td>function derived from experimentation</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>( Y )</td>
<td>peak-to-peak vibration amplitude at the anti-node</td>
<td>m</td>
<td>inch</td>
</tr>
</tbody>
</table>

The \( F_n \) relationship described in Equation 4 assumes the worst case of completely laminar wind flow, and is based on a number of independent wind tunnel studies [14]. The graph in Figure 8 contains plots of the wind power required to generate aeolian vibration with a peak-to-peak amplitude equal to one half (½) of the conductor diameter, based on \( F_n \).

The practical application of having this experimentally derived wind energy equation is that it can be used as an acceptance criterion for testing the power absorption of Stockbridge type dampers in the laboratory, as described in Section 6.2.

![Conductor Diameter vs. Aeolian Vibration Frequency and Excitation Power in a 61 m (200 ft) Subspan for Displacement = ½ the Conductor Diameter](image)

**Figure 8: Conductor Diameter vs. Aeolian Vibration Frequency and Excitation Power in a 61 m (200 ft) Subspan for Displacement = ½ the Conductor Diameter**

For example, Figure 9 shows the results of laboratory power absorption or "damper effectiveness test" according the IEC Standard 61897 testing on a 795 kcmil 26/7 ACSR (Drake) conductor using a specific vibration damper placed at 1 m (39 in) from the rigid clamp. This testing was performed in accordance with IEC 61897; see Section 6.2.

The lower curve in Figure 9 is the curve generated from the wind energy equation, above, for a specific conductor and tension, and a 275 m (900 ft) span. The upper curve is the measured damper efficiency values (in Watts) for the same range of frequencies.
The laboratory determination of damper power absorption is described in more detail in Section 6.2.

![Figure 9: Laboratory Damper Power Absorption Test Results](image)

### 4.2 Conductor self-damping

Conductor self-damping is the ability of a conductor to dissipate some portion of the mechanical energy imparted from the wind. It is known that a conductor’s ability to absorb energy is greatly affected by conductor tension. To a greater or lesser degree, all conductors have self-damping ability. The major mechanism for stranded conductors to dissipate mechanical energy is inter-strand motion between the strands as they flex with the sinusoidal wave of the vibration. Relative motion between conductor strands causes friction which induces energy losses through the resultant heat. This heat loss is the mechanism that dissipates the energy imparted to the conductor by the wind. Due to the greater number of interstrand contacts, large conductors have more self-damping ability than small ones.

Spans with no dampers must rely on the self-damping capability of the conductor to limit vibration to safe levels. Therefore, only a conductor installed at low tensions is relatively safe from fatigue without dampers being installed. While most conductor properties can be determined with a high degree of confidence, it requires a significant amount of laboratory testing [16] over a wide range of conductor tensions, vibration amplitudes and frequencies to determine a conductor’s self-damping characteristics, which is not often practical.

It should be noted that some conductor designs such as self-damping conductors (SDC) which include an air gap between layers to promote impacts between the layers during vibration that act to break up any large motions and Aluminum Conductor Steel-Supported (ACSS), which has fully annealed aluminum strands, have higher levels of self-damping than conventional ACSR conductors. However, since test data may not be available for a specific conductor size and type, care must be taken when deciding how much self-damping is available. With conductors like ACSS, the self-damping increases only after the conductor has experienced creep over time and has approached the final sag condition. Therefore, unless these conductors are “pre-stressed” to a high tension (about 50% RBS) prior to or during installation, the self-damping should not be considered when an analysis...
is made regarding the need for vibration dampers. In general, the amount of damping available from the conductor is considerably less than that provided by any added Stockbridge-type or other vibration damper.

The latest recommendations for safe design tensions for single conductors without dampers are discussed more fully in Section 5.

4.3 Power Dissipated in the Damper ($P_d$)

Even though analytical models and computer programs exist to determine the power dissipated by a vibration damper at a specific placement in a span of conductor, further work may be required before these methods can be utilized effectively by line designers.

The vibration damper most commonly used for conductors is the Stockbridge type damper. The original design has evolved over the years, but the basic principle remains: weights are suspended from the ends of a length of specially designed and manufactured steel strands, or messenger wire, which is then secured to the conductor with a clamp, Figure 10.

![Figure 10: Stockbridge Type Damper](image)

When the damper is attached to a vibrating conductor, the vertical movement of the damper weights causes bending of the steel messenger strands. The bending of the steel strand causes the individual wires of the strand to rub together, thus dissipating energy. The size and shape of the weights; the stiffness and energy losses of the steel messenger cable supporting the weights, and the overall geometry of the damper influence the amount of energy that will be dissipated for specific vibration frequencies. Some damper designs also twist the messenger wire in response to the vertical vibration of the conductor. Modern Stockbridge dampers are designed to match conductor sizes and typically have four resonant frequencies in the range of aeolian vibration.

For smaller diameter conductors, 19 mm (0.75 inches) diameter or less, an “impact” type damper (Figure 11) has been effectively used over the past 35 years. These dampers are made of rugged non-metallic material that have a tight helix on one end that grips the conductor. The remaining helixes have an inner diameter that is larger than the conductor such that these helixes strike (impact) the conductor during aeolian vibration activity. Rather than dissipating the energy directly, the impacts create pulses which travel back into the span and disrupt and negate the vortex forces produced by the wind.

Impact dampers are made long enough so that a sufficient portion of the standing wave loop is captured under the loose helixes, making specific placement in the span unnecessary to assure performance. The impact damper enhances the conductors self-damping due to the strands rubbing as the impact pulses travel down the span. Due limitations on the stability of some materials, some impact dampers should only be installed on lower voltage lines.

Other types of vibration dampers that are also used around the world and include the Festoon and Bretelle Dampers. Bretelle dampers consist of a length of conductor similar to the main
conductor in the span slung under a suspension string of insulators and attached by a type of parallel groove clamp to each adjacent span approximately 1-3 m (3-10 ft) depending on conductor size out into the span (Figure 12). Festoon dampers, which are commonly used on exceptionally long spans such as fjord crossings, are typically made from a piece of cable of a gauge lighter than that of the main conductor, clamped with deep sag to the main conductor (Figure 13).

Figure 11: Impact Type Damper

Figure 12: Festoon Type Damper

Figure 13: Bretelle Type Damper

As stated earlier, even though there are some computer based methods for determining the effectiveness of dampers in actual field spans, these programs are currently not readily available or widely used.

The most common damper power dissipation data used today are the laboratory damper tests that are performed according to IEEE Standard 664 “Guide for Laboratory Measurement of the Power Dissipation Characteristics of Aeolian Vibration Dampers for Single Conductors”[17], or IEC 61897 “Overhead lines - Requirements and tests for Stockbridge type aeolian vibration dampers”[14] at laboratories operated by damper suppliers or at independent laboratories. The energy absorption of impact dampers can only be measured in tests on laboratory or field spans.

These standards outline different methods to measure the power dissipated by the damper:
   i) Inverse Standing Wave Ratio (ISWR)
   ii) Power Method
   iii) Decay Method
   iv) Forced Response (does not require use of conductor test span)

These laboratory tests are time consuming but necessary to ensure reliable and long term in-service integrity of the conductor and dampers. The test is somewhat specific to a conductor size and damper placement, but as was shown in Figure 9, give a clear comparison between the power absorbed by the damper and the expected wind energy input for the appropriate frequency range. If the conductor self-damping can be determined for the same range of frequencies, the bottom curve can be adjusted (lowered) to account for this.
Ideally, for a given span length the power dissipated by the damper (upper curve of Figure 9) should fall at or above the power input from the wind minus any known self-damping effects. This type of laboratory analysis allows us to determine the maximum span length that can be protected by a single damper. Refer to Section 6 for discussion on field and laboratory testing, and damper placement.

In laboratory settings, the power dissipated by the damper when mounted directly on a shaker can be calculated by the following equation [17]:

\[ P_D = \frac{1}{2} (FV_s) \cos \theta_V \]

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>SI Units</th>
<th>Imperial Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_D )</td>
<td>power dissipated by the damper</td>
<td>Watts</td>
<td>ft-lbf/s</td>
</tr>
<tr>
<td>( F )</td>
<td>force measured at the vibration shaker</td>
<td>N</td>
<td>lbf</td>
</tr>
<tr>
<td>( V_s )</td>
<td>velocity measured at the vibration shaker</td>
<td>m/s</td>
<td>ft/s</td>
</tr>
<tr>
<td>( \theta_V )</td>
<td>phase angle difference between measured force and velocity signals</td>
<td>degree</td>
<td>degree</td>
</tr>
</tbody>
</table>

The dampers also should withstand failure due to vibration for the service life time of the line without failure (see Figure 6). The procedure for a fatigue test of the damper is described in IEC specification 61897 [14].

5 Considerations for Designing a Safe Transmission Line for Vibration

There are several factors to consider in choosing a safe design tension for a transmission line. These factors include:

i) Span length
ii) Horizontal tension/unit weight ratio (H/w)
iii) Terrain
iv) Local climate (expected temperatures and associated tensions)
v) Conductor material
vi) Aeolian vibration entrapment by in-span masses

5.1 Span Length
Since the self-damping within a span is affected by the end supports (suspension or deadend), insulators and hardware used, shorter spans are less susceptible to damage from aeolian vibration than longer spans. Additionally, the shorter spans have less wind energy to be input into the system. Shorter spans are therefore more able to dissipate this lesser amount of wind energy through conductor self-damping. In general, shorter spans require fewer dampers than longer ones.

5.2 Horizontal Tension/Unit Weight Ratio
Conductor tension is a major influence on a line’s susceptibility to aeolian vibration. Higher conductor tensions reduce conductor self-damping and result in more severe vibration and a greater likelihood of fatigue.

The design of a transmission line typically involves the consideration of three (3) conductor tensions:

i) Minimum tension resulting from the conductor maximum operating temperature, which
causes the maximum sag (i.e. the minimum clearances to underlying objects). Long
spans, significant ice loads, and a low modulus of elasticity for certain conductor types
Can have greater sag than the maximum operating temperature.

II) Maximum tension resulting from the most severe climatic loads; i.e. highest wind,
heaviest ice and coldest temperature to avoid tensile failure

III) The cold weather conductor tension.

The cold weather conductor tension is of particular interest when determining a safe line tension
with respect to aeolian vibration. It is typically defined as the initial, unloaded tension at the
average temperature during the coldest month at the location of the line. Experience has shown
that this condition closely correlates to the worst vibration condition.

Beginning in the early 1960s, and based on available field experience at that time, the industry
adopted a “rule of thumb” for safe design tensions with respect to aeolian vibration [1,15]. It
was suggested that the everyday stress (EDS) of ACSR conductors be limited to 18% of the
conductor rated breaking strength (RBS) to assure safe operation with regard to aeolian
vibration. However, more recent surveys of the performance of actual lines [19] that had been in
service for 10 to 20 years revealed that up to 45% of lines installed using an EDS <18% final did
experience fatigue failures. The work that led to the publishing of CIGRE Technical Brochure
#273, “Overhead Conductor Safe Design Tension With Respect To Aeolian Vibrations” in June,
2005 [19], which was based on the ratio of the horizontal conductor tension, \( H \), and the conductor
weight per unit length, \( w \). \( H/w \) is sometimes referred to as the catenary constant. Safe tension values
were determined for round strand ACSR and aluminum alloy conductors for four classes of terrain.

5.3 Terrain

The effects of terrain on the turbulence intensity of the wind were also studied and included as
part of the overall recommendations. Wind turbulence is a function of the type of terrain over
which the line traverses. Since laminar wind flow produces the most severe aeolian vibration,
lines located in terrain that is more likely to promote turbulence are less likely to see aeolian
vibration.

By applying the \( H/w \) ratio and the newly created terrain categories to all available field
experience data, the CIGRE Task Force published the recommendations shown in Table 1 for
single un-damped, conductors without armor rods. It should be noted that the
recommendations in Table 1 are applicable to conventional aluminum based conductors such as
AAC, ACSR, ACAR and AAAC. The Task Force also published the warning that the
recommendations “should be suitable most of the time” but that “special situations require
specific attention”. “Extra-long spans, spans covered with ice, rime\(^3\) or hoarfrost\(^4\), spans
equipped with conductor mounted aircraft warning devices [markers or balls], and spans using
non-conventional conductors” were examples cited of special situations.

CIGRE Report #273 also provides recommendations for safe design tensions for bundled (twin,
tri and quad) conductors.

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\(^3\) Rime Ice: white, opaque, granular deposit of ice crystals formed on objects that are at a temperature below the
freezing point. Rime ice occurs when super-cooled water droplets (at a temperature lower than 0° C [32° F]) in fog
come in contact with a surface that is also at a temperature below freezing; the droplets are so small that they freeze
almost immediately upon contact with the object

\(^4\) Hoarfrost: deposits of ice crystals on objects exposed to the free air, such as grass blades, tree branches, or leaves. It
is formed by direct condensation of water vapor to ice at temperatures below freezing and occurs when air is brought
to its frost point by cooling.
The work published in CIGRE Technical Brochure #273 represents a valuable contribution; however in using the recommendations it is clear that trying to design a line that would not employ dampers may not be practical. For example, a line with 795 kcmil 26/7 ASCR conductor in Terrain Category 2 would have to have the initial tension at the average temperature of the coldest month limited to 4,038 lb. (12.8% of the RBS). This would mean that the final unloaded tension at 60º F could be as low as 3,100 lb., which would be too low, except for short span construction.

5.4 Local Climate
Regions of very cold temperatures can lead to very high tensions and high aeolian vibration levels. Persistent prevailing winds can also cause a large numbers of cycles of vibration and lead to fatigue. Locations where ice or wet snow accumulations occur can produce aeolian vibration at lower frequencies than those on bare conductors for which the dampers were not designed. Dampers are often not able to survive significant numbers and amplitudes of galloping motions.

5.5 Conductor Material
Conductor fatigue endurance depends strongly on the material of the outer layers. Materials commonly used are, in order of decreasing fatigue endurance, steel, copper, aluminum alloys, electrical grade aluminum and annealed aluminum.

5.6 Aeolian Vibration Entrapment by In-span Masses
Occasionally, it is necessary to install one or more concentrated loads in a span: The dynamic stresses in conductors at these in-span masses can be reduced by installing the masses over armor rods.

5.6.1 Aerial Marker Balls or Flags
These devices may be installed to satisfy government (e.g., FAA) requests to mark one or more spans on a line; see Figure 14. The clamps used in mounting these (and other) devices can restrict the relative movement of the wire’s strands when exposed to aeolian vibration and cause fretting to occur. It is a good practice to consider the installation of one or more dampers in each subspan at the appropriate distance from the mounting clamp on the marker ball.

However, typical stockbridge-type dampers, with weights mounted to a messenger, are subject to significant damage when installed away from the structures in areas where the cable may gallop. Some damper manufacturers have alternate damper designs available that do not use a metal messenger and might better survive a galloping conductor situation.
5.6.2 Distributed Series Reactors

In recent years series reactors, Figure 15, have been developed and deployed on higher voltage transmission lines. These DSR units are typically installed directly on the phase conductors, close to the structures.

Since these units are installed close to the structure, the likelihood of aeolian vibration between the DSR and the structure’s insulator and suspension clamp is minimal but the installation of dampers should be considered between the DSR and the next structure using the span-end of the DSR as the reference point for installing the damper(s) instead of using the tower’s suspension clamp as the reference.

5.6.3 Surge Arresters

Surge arresters are specially designed insulator strings comparable in length and mass to the suspension insulators supporting the conductors. These are sometimes suspended directly from conductors. The installation of vibration dampers should be considered on the span side of the surge arrester, at the same distance as they are normally installed from suspension clamps.

6 Testing

6.1 Field Testing

Field testing can be conducted to confirm that vibration dampers installed on a transmission line are doing their job and controlling or mitigating the negative effects of aeolian vibration.

6.1.1 IEEE 1368 Guide for Aeolian Vibration Field Measurement of Overhead Conductors

The general intent of IEEE 1368 [20] is to recommend testing procedures, general data gathering formats, and general data reduction formats for field monitoring of overhead conductor aeolian vibration. IEEE 1368 also provides background information on technical aspects of vibration field measurements for overhead conductors, techniques for evaluating the severity of conductor vibration including amplitude and frequency, and the effects on conductor
performance and life.

The recommendations outlined in IEEE 1368 are intended to standardize data gathering and reduction efforts so the user can evaluate long-term effects of conductor vibration and develop mitigation schemes. Standardizing the data gathering and reduction procedure allows comparison among vibration field monitoring programs. The guide is not intended to be a comprehensive treatment of conductor motion theory, or of the evaluation and prediction of vibration effects, or mitigation techniques. Such technical treatments are beyond the scope of this guide and the reader is referred to Chapter 2 of Reference [13].

Typically, field vibration measurements gathered for overhead transmission lines are useful for the following reasons:

i) Determining the cause of visible conductor fatigue damage
ii) Identifying existing vibration levels
iii) Assessing the likelihood of future conductor fatigue damage
iv) Evaluating the damping performance of conductors and any attached vibration damping systems

Each application requires that field vibration data be gathered and compiled in a standard form that lends itself to accepted analysis procedures and/or comparison with other data.

6.1.2 Bending Amplitude Model

IEEE 1368 uses the measurement of bending amplitude to determine the severity vibration at a clamp. The bending amplitude is a measure of the differential displacement of the conductor, \( Y_b \), at 89 mm (3.5 inches) from the last point of contact (LPC) of the conductor with the clamp (Figure 16, Figure 17). The advantages of the bending amplitude method are its simplicity and the relative ease with which the measured values can be related to useful parameters for the evaluation of the severity of the aeolian vibrations. This method allows for the designing of reliable and practical vibration recorders\(^5\).

The bending strain is determined from the bending amplitude measured by the vibration recorder in the field using a relationship developed by Poffenberger & Swart [18].

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\(^5\) The Bending Amplitude Model possesses a long history; it was first introduced by Tebo in 1941, pursued by Edwards and Boyd in 1961 [21]. It has been recommended in 1966 by the IEEE Task Force on the Standardization of Conductor Vibration Measurements [22] and retained in the revision of that guide (IEEE P1368 2006). CIGRE SC22 WG04 also supported its use in 1979 [23]. It has been also the principal recommendation for aeolian vibration measurements of the CIGRE SC22 WG11 TF2 in 1995 [24].
relationship is dependent on the properties of the conductor, and was developed from extensive laboratory studies.

Field vibration recorders (Figure 18) are typically designed to capture a one second period of the vibration activity, once every 15 minutes. It is assumed that the vibration activity that is captured in each one second trace is representative of the vibration during the entire 15-minute period. The data captured (either continuously by a stylus or digitally) by the recorder includes the amplitude of the differential displacement and the frequency. Using the frequency for a period of 15 minutes gives the number of cycles for that recording (for example 15 minutes at a frequency of 20 Hertz is 0.018 mega-cycles). All the traces during the study period at each differential displacement level are then added together to get the total number of cycles.

6.1.3 Field Data Reporting

IEEE 1368 also outlines a standard method on how the results of field vibration studies should be reported; see Figure 21. As an alternative, the results are presented in a graph which shows micro-strain of bending (inches/inch) on the horizontal axis and megacycles per day exceeding strain shown on the vertical axis, as shown in Figure 19.

It is not unusual, as shown in Figure 19 to measure the vibration levels of phases with and without dampers in the same span during the study period. This provides details of the vibration levels without the dampers, and also an indication of the reduction in the bending strain at the support as a result of the dampers absorbing energy.

As a rule of thumb, for aluminum based conductors bending at the suspension points should be limited to 150 micro-strain to completely avoid broken wires; or 300 micro-strain for only a few broken wires. As can be seen in Figure 18, there is activity measured during the study period on the un-damped phases that exceeds 150 micro-strain. However, with the phase having the dampers, the strains are well below that level.

6.2 Laboratory Testing

As it is not practical to test the performance of all vibration dampers in the field, a variety of laboratory tests may be conducted to ensure the performance of the vibration dampers.

6.2.1 Span Tests

IEEE 664, [17], describes the method used to measure the performance of vibration dampers on a laboratory test span, with typical installation shown in Figure 19. In this test, dampers are installed on a span and the power dissipated by the damper may be measured using a number of methods.
Using the test methods outlined in IEEE Std 664, the performance of the dampers may be compared with other dampers or compared with the calculated wind power input to determine the suitability of the dampers for use on a transmission line, as shown in Figure 9.

6.2.2 Other Tests
In addition to IEEE 664, IEC Standard 61897, [14], is available, which describes a number of tests used to qualify vibration dampers. In the most common of these tests, the damper is mounted directly on a shaker and the damper’s power absorption is determined by measuring power required to oscillate it in a range of amplitudes and frequencies.

In addition to span tests, both IEEE 664 and IEC 61897 describe measurement of the mechanical impedance of the dampers. This is analogous to the measurement of passive electronic components and gives a measure of the “signature” of the dampers. This allows a simple and inexpensive method to compare the performance of dampers taken from a production batch to be compared with dampers that were tested on laboratory spans or tested in the field.
IEC 61897 also prescribes a variety of tests on dampers including tests on the bolts, clamps and other components as well as fatigue tests that should be performed to ensure that dampers and all of their components will withstand vibration on a real transmission line without being damaged.

7 Example: How to Determine Damper Location

To be effective against all aeolian vibration, the first damper is located near to the suspension clamp within the shortest loop length, which is at the highest aeolian wind (7 m/s or 15 mph). Perhaps the best way to describe the placement of stockbridge type dampers is by example.

For this example, the conductor is 795 kcmil 26/7 ACSR DRAKE, tensioned at 6,200 lb. (19.7% of RBS) at 60° F, Final. The span length is 800 ft, and the conductor weight is 1.094 lb. per foot.

By using Equation 1 and Equation 2, and assuming the vortex shedding frequencies and the span’s natural frequencies “lock in” to create aeolian vibration, the resulting frequencies and loop lengths for a range of wind velocities are shown in Table 2.

Table 2: Example of Damper Placement

<table>
<thead>
<tr>
<th>Wind m/s (MPH)</th>
<th>Frequency (Hz)</th>
<th>Loop Length m (Feet)</th>
<th>Distance to First Anti-Node m (Inches)</th>
<th>Damper Position from Anti-Node m (Inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9 (2)</td>
<td>5.9</td>
<td>11.0 (36.2)</td>
<td>5.51 (217)</td>
<td>-4.62 (-182)</td>
</tr>
<tr>
<td>2.2 (5)</td>
<td>14.7</td>
<td>4.4 (14.5)</td>
<td>2.21 (87)</td>
<td>-1.32 (-52)</td>
</tr>
<tr>
<td>3.6 (8)</td>
<td>23.5</td>
<td>2.8 (9.1)</td>
<td>1.40 (55)</td>
<td>-0.51 (-20)</td>
</tr>
<tr>
<td>4.5 (10)</td>
<td>29.4</td>
<td>2.2 (7.3)</td>
<td>1.12 (44)</td>
<td>-0.23 (-9)</td>
</tr>
<tr>
<td>5.4 (12)</td>
<td>35.3</td>
<td>1.9 (6.1)</td>
<td>0.91 (36)</td>
<td>0.03 (-1)</td>
</tr>
<tr>
<td>6.7 (15)</td>
<td>44.1</td>
<td>1.5 (4.8)</td>
<td>0.74 (29)</td>
<td>0.15 (6)</td>
</tr>
</tbody>
</table>

The damper position in Table 2 is based on placing the damper at 35 inches from the suspension clamp. This position is based on a percentage of the loop length for the 15 MPH wind, and may vary slightly from one damper supplier to the other. In this case 60% of the loop length at the highest aeolian wind speed was used; e.g., 0.60 x 1.5 m = 0.9 m (0.60 x 4.8 feet x 12 inch/ft = 35 inch).

It was stated earlier that for a stockbridge type damper to work, it has to be positioned where the vibration is causing vertical motion. The maximum vertical motion occurs at the anti-nodes, and that would be the optimal position, but as shown in Table 2, the anti-node location for this example varies from 29 in to 217 in depending on the wind velocity.

There are two other factors that are considered in the damper placement: i) field vibration data and ii) geometry of the loop.

The first is based on field vibration data that has been collected by damper suppliers, researchers and utilities over the past 40 years. When the data from these field studies are presented in a histogram form as shown in Figure 21, it is common for the data to appear as a bell shaped curve, centered around a frequency which would relate to a wind velocity between 3.6 m/s (8 mph) and 5.4 m/s (12 mph). The example data in Figure 21 is from a 2-week study in Southern Texas in an area that has very flat and open terrain and subject to smooth (laminar) winds. The conductor is 795 kcmil 26/7 ACSR, and the phase being studied had no dampers applied.

The numbers shown on Figure 21 are the number of occurrences for specific frequencies and
differential displacements for the study period, with a sampling rate of one second every 15 minutes. The procedures for field vibration measurements and the associated reporting of results are detailed in IEEE 1368 “Guide for Aeolian Vibration Field Measurements of Overhead Conductors”, [20]. The differential displacements are the measured vertical movement of the conductor relative to the suspension clamp, at a distance of 3.5 inches from the last point of contact of the suspension clamp, and are covered in more detail in Section 6.1.2.

In this example, the highest recorded vibration amplitudes occurred around 24 Hz, which occurs at a wind speed of about 9 MPH for this conductor size (795 kcmil 26/7 ACSR).

Therefore, looking back at Table 2, the damper placement recommended in this case is still very close to the anti-node for the 3.6 m/s to 4.5 m/s (8 to 10 mph) winds.

The second factor for damper placement is related to the geometry of the vibration loop itself. For higher frequencies the loop length is shorter, which means the vertical movement relative to the anti-node falls off faster than with the longer loop lengths associated with the lower frequencies.

As the span length increases, the energy imparted by the wind also increases. The placement of additional dampers may be needed depending on the energy absorption capabilities of the specific damper design and the self-damping of the conductor. (Note: Dampers from different vendors for a specific conductor will likely have different damping capabilities. Refer to Section 8.)

Depending on span length, two or more dampers per span may be required. Very long spans, i.e. greater than 1 km (3280 feet), may require placing additional dampers in the center of the span to provide proper vibration control.
8 Considerations when Evaluating Mitigation Techniques and The Real World

Listed below are a few thoughts regarding the installation of dampers designed to protect conductors from damage due to aeolian vibration.

8.1 Damper Recommendations
There are many sources of uncertainty when determining how much damping is required for a particular span on a particular line, and reputable suppliers will generally provide relatively conservative recommendations.

Each manufacturer will provide a recommendation on the number and placement of THEIR dampers that should be installed. While you may be tempted to take the recommendation that calls for the fewest installed dampers and install the lowest priced unit (from another vendor). DO NOT DO THIS. Vendor A’s recommendation is based on using Vendor A’s dampers, not on using Vendor B’s products. No manufacturer will provide a warranty if someone else’s recommendations are used, and the utility is on their own in the event of a problem with the installation.

8.2 Specifying Dampers
The manufacturer should be required to demonstrate that the recommendation is based on a valid engineering method, such as the energy balance principle discussed in this document and that current data is available on the damping performance of the dampers they are proposing to support their recommendation. Section 6 describes test methods that may be used to measure the performance of vibration dampers, including whether the current production units match the performance of the earlier design due to “minor” changes in materials, mounting of components, etc.

Another approach is to use an independent analysis to determine if dampers are needed, and, if needed, how many and where to place them. The advantage of doing the design in-house is that the line designer avoids putting a damper manufacture in charge of the decisions affecting the long-term reliability of the line. Computer design programs require response data for the damper, and data may be obtained from reputable manufacturers. If there are any concerns over the manufacturer’s data, an independent testing laboratory can provide the response curves for dampers being considered for the line. There can be considerable inconsistencies between nominally identical dampers and the measured energy absorption properties must be downgraded to obtain realistic results from an analytical prediction.

Design programs are probably going to specify more dampers or more energy absorbent dampers than the manufacturer would recommend. However, there is no harm in over-damping a line other than cost. On the positive side, the dampers work less and will therefore last longer. Another positive effect of the in-house design is that the manufacturers compete on damper quality.

The lowest price per damper model is a very poor approach. All dampers are not created equal, and it is cheaper to build dampers that do not work particularly well.

8.3 When to be Wary of a Vendor’s Recommendation
A transmission line designer has many challenges, only one of which is to design to protect the conductor, structures, and fittings from wind-induced damage. Relatively few line designers are vibration experts, and even experienced transmission engineers delegate the details of damping systems to experts in that field, usually damper manufacturers. However, manufacturers recommendations should be carefully checked if there is a competitive bid situation, as there is a
possibility that less reputable suppliers might offer lower performance dampers or fewer dampers than engineering best practice would require. If the low-bid process is the organization’s only way to procure dampers, at least be sure to reject any bid from a supplier who cannot supply test data.

8.4 When Dampers Should Be Installed During Line Construction
IEEE Std 524-2003, “Guide to the Installation of Overhead Transmission Line Conductors”, [25], states in Section 10.8: Dampers, if required, are normally placed on the conductors immediately following clipping-in of the conductor and/or groundwire to prevent any possible wind vibration damage. Damage can occur in a matter of a few hours at initial tensions.

The installation of most dampers takes only a few moments; there is no valid reason to NOT install the units at the time that the conductors are “clipped-in” (placed in their suspension clamps) or the dead-end units are installed.

8.5 Skip Structure Installation of Dampers
For installations where the vendor recommendation calls for installing a single damper in each suspension span, (fairly common when the spans are nearly equal in length) vendors may promote the concept of installing the units in the fore- and back-spans of every other structure instead of in the fore-span (or back-span) of every structure. Consider the following:

There will not be any cost benefit to “skipping” a structure with installed dampers if the dampers are installed at the time the conductor is clipped in. If the lineman gets confused, two structures (or no structures) could be skipped, either leaving unprotected spans or the installation of extra dampers (no harm but extra cost).

The only situation where skip structure theory could be of monetary benefit would be a retro fit on an existing line (after initial line construction was completed)

8.6 Do Dampers Provide Additional Protection?
The primary intent of dampers is to protect the conductor from damage. However, there may be secondary benefits that are not readily apparent.

As an example, one utility’s past policy on dampers was to install armor rods but NOT to install conductor dampers on lines built using wood poles, both single pole and H-frames. This policy was based on the consideration that the spans were relatively short and the wood pole would absorb the vibration. The policy worked quite well for wood structures. However, when steel davit arms were installed on pre-stressed concrete poles (which were considered to be wood equivalents), resonance occurred on the arms and eventually caused fatigue failures of the davit arms.

It was determined that installing a conductor damper at each crossarm location also benefits the crossarm, adding protection from fatigue failure. This is another reason for not installing the dampers on a Skip-Structure basis.
9 Bibliography and References and Works Cited


APPENDIX A – TYPES OF CONDUCTORS

A.1 Types of Conventional Conductors
There are several types of aluminum-stranded conductors in fairly widespread use in the utility industry. Refer to Table 3 for a summary of conventional conductors. The strands of these conventional conductors are typically round and have a concentric lay. These conventional conductors have long, proven track records of performance under specified conditions and certain types of applications.

In addition to the aluminum stranded conductors, many miles of bare copper stranded conductors are also in wide-spread use in transmission and distribution systems world-wide.

Table A1 – Types of Conventional Conductors

<table>
<thead>
<tr>
<th>Conductor</th>
<th>Materials / Construction</th>
<th>Application / In Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAC All Aluminum Conductor</td>
<td>• A1 1350-H19 Al strands&lt;br&gt;• conductivity of 61.2% IACS or more.</td>
<td>• Highest conductivity for applications and moderate strength.&lt;br&gt;• Highest conductivity-to-weight ratio of all the overhead conductors.&lt;br&gt;• Good corrosion resistance.</td>
</tr>
<tr>
<td>ACSR Aluminum Conductor</td>
<td>Conductor consisting of 1350-H19 Aluminum strands reinforced with a galvanized steel core.</td>
<td>• Mechanical strength-to-weight ratio and good current-carrying capacity make ACSR well suited for long spans.&lt;br&gt;• ACSR has a higher thermal rating than equivalent aluminum area AAC, due to steel core conductivity.</td>
</tr>
<tr>
<td>AAAC All Aluminum Alloy Conductor</td>
<td>• Homogeneous conductor of 5005-H19 or 6201-T81 Aluminum Alloy&lt;br&gt;• Conductivity of 53.5% or 52.5%, respectively</td>
<td>• Similar to AAC but with greater mechanical strength&lt;br&gt;• Typically installed at a higher H/w ratio than AAC, and therefore more susceptible to vibration</td>
</tr>
<tr>
<td>ACAR Aluminum Conductor</td>
<td>• Composite conductor consisting of 1350-H19 Aluminum strands reinforced with either 5005-H19 or 6201-T81 Aluminum alloy strands.</td>
<td>• Offers a superior strength to weight ratio, better sag characteristics and a higher resistance to corrosion than the equivalent ACSR conductor.&lt;br&gt;• As with AAAC, the superior strength-to-weight ratio means this conductor is often installed at tensions which make it more susceptible to vibration.</td>
</tr>
<tr>
<td>ACSS Aluminum Conductor</td>
<td>• Composite conductor consisting of fully annealed (0 temper) 1350 Aluminum strands supported by a steel core that is coated for corrosion protection.</td>
<td>• Soon after installation, Aluminum strands creep and their tensile load decreases.&lt;br&gt;• Under typical operating conditions nearly all the mechanical load is carried by the steel core.&lt;br&gt;• Very high self-damping characteristics due to inter-strand motion and impact damping mechanisms.&lt;br&gt;• Dampers are not typically used on ACSS installation.</td>
</tr>
<tr>
<td>Copper Conductors</td>
<td>• Typically either hard-drawn (ASTM B-1) or medium-hard drawn (ASTM B-2).</td>
<td>• Rarely used in new construction; fairly common in older lines.&lt;br&gt;• Because of lower H/w ratios, often considered to be relatively unsusceptible to vibration fatigue.&lt;br&gt;• Frequently installed without dampers.</td>
</tr>
</tbody>
</table>

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6 These aluminum alloys are also more susceptible to annealing and high temperature creep if exposed to high operating temperatures.

7 See Section 4.2, unless these conductors are “pre-stressed” to a high tension (about 50% RBS) prior to or during installation, the self-damping should not be considered when an analysis is made for the need for vibration dampers.
The steel content of ACSR conductor, which can allow a significant increase to the tension, may have little impact on the fatigue endurance of the conductor but it may have a very large impact on the vibration activity and thus the probability of fatigue failure of the conductor if the H/w ratio is allowed to get too high.

The “Type Number” of an ACSR conductor is equal to the ratio of steel to aluminum area expressed as a percentage. Thus a 30/7 ACSR conductor, which has steel and aluminum strands of the same diameter, has a type number of 100 * $\frac{7}{30} = 23$.

The Type Number of ACSR influences vibration in two ways. If ACSR conductors are initially installed to the same percentage of their respective rated breaking strengths (RBS), then the conductor with the lower amount of steel will have a lower mechanical phase velocity (see Equation 2) and a lower level of vibration at the same sag (lower H/w). In addition, at low temperatures the stress in the aluminum portion of the ACSR conductor, which largely determines the self-damping of the conductor, is a function of the steel content.
A.2 Types of Specialty Conductors

Today several conductors on the market boast superior self-damping characteristics as compared to conventional conductors. Refer to Table 4 for a summary of Non-standard conductors. One of the major advantages of self-damping conductors is that their use suggests allowing an increase of unloaded tension levels, resulting in reduced sag and possibly reduced structure costs.

Table A2 – Types of Specialty Conductors

<table>
<thead>
<tr>
<th>Conductor</th>
<th>Materials / Construction</th>
<th>Application / In Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>TW</td>
<td>Trapezoidal Aluminum strands</td>
<td>Smaller diameter means less wind energy may be imparted to the conductor.</td>
</tr>
<tr>
<td></td>
<td>Smaller diameter than a round strand conductor of equivalent Aluminum cross-sectional area.</td>
<td>TW strands may exhibit less inter-strand motion, less self-damping, and higher fatigue resistance than a conductor with round strands having the same cross-sectional area.</td>
</tr>
<tr>
<td>SDC</td>
<td>An ACSR construction designed to limit aeolian vibration by internal damping of the strands.</td>
<td>Exhibits high self-damping because of impact damping between the steel core and the trapezoidal aluminum strand layers.</td>
</tr>
<tr>
<td></td>
<td>Layers of Aluminum consist of trapezoidal strands whose dimensions and lay lengths deliberately leave gaps between the two inner most layers of Aluminum and the inner-most layer of Aluminum and the steel core.</td>
<td>Onset of motion due to aeolian vibration causes impact between the separated layers, imparting the self-damping characteristics of the conductor.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Impact damping allows elimination of tension limit requirements on the conductor for the purpose of controlling aeolian vibration.</td>
</tr>
</tbody>
</table>
|           | | Dampers are not typically used on SDC installation.  

Twisted Pair Conductor (Figure A-3)

- Consist of two conventional conductors twisted about one another with a lay length of about 3 meters.
- Two sub-conductors selected based on thermal and mechanical strength requirements of the line.
- Sub-conductors may be any of the conventional conductors (AAC, AAAC, ACAR, or ACSR) or even the ACSR/TW and AAC/TW conductors.
- The Figure-8 wind profile of the conductor is intended to reduce the wind energy input by causing vortex shedding at multiple frequencies.
- Can be installed to higher tension levels without the need for additional dampers.
- Conductor cross-section forms a rotating “figure-8” as shown in Figure A-3
- Amplitude and frequency of galloping due to ice-shedding and high winds are reduced or eliminated because of the continuously rotating non-round cross-section.
- Self-damping characteristics are the same as those of the component conductors and are designed for use in overhead lines normally subject to aeolian vibration and galloping.

Figure A-2: Self Damping Conductor

Figure A-3: Twisted Pair Conductor

8 SDC may dramatically fail after 25+ years of exposure to vibrations; it is very difficult to inspect for internal damage.
**APPENDIX B – DEFINITIONS**

**Aeolian Vibration**: A high frequency, low amplitude movement caused by a mainly smooth, non-turbulent fluid (wind) flowing over a surface.

**Anti-Node**: The point along a standing wave where the maximum amplitude occurs.

**Bending Stress**: Surface stress in the strands of a conductor due to bending, such as over a suspension clamp, plus any additional movement such as from aeolian vibration.

**CIGRE** (Conseil International des Grands Réseaux Électriques): An international non-profit Association for promoting collaboration with experts from all around the world by sharing knowledge and joining forces to improve electric power systems of today and tomorrow. Founded in 1921.

**Clipped-In**: A term used to describe the process following the installation and sagging of a cable when it is moved from the stringing blocks to the suspension clamps.

**Cold Weather Conductor Tension**: The initial, unloaded tension at the average temperature during the coldest month at the location of the line.

**Conductor Lock-In**: A phenomenon where the conductor begins to vibrate in a resonant mode and the oscillation of the conductor begins to control the vortex shedding frequency.

**Composite Conductor**: Non-homogeneous conductor consisting of strands of two or more materials; for example ACSR which is comprised of strands of 1350-H19 Aluminum and strands of steel and ACAR which is comprised of strands of 1350-H19 Aluminum and strands of 6201 Aluminum alloy.

**Energy Balance Principle**: The amount of energy entering a system must be equivalent to the amount of energy leaving the system.

**Everyday Stress (EDS)**: The maximum tensile load to which a conductor may be subjected at the temperature occurring for the longest period without any risk of damage due to Aeolian Vibration, typically at the average ambient temperature, often taken to be 10° to 20° C (50° to 70° F).

**Fretting**: Mechanical wearing of contacting surfaces that are under load and subjected to repeated relative surface motion.

**H/w**: Horizontal Tension / unit weight ratio. This ratio is used to assist in the determination of “safe” design tensions of a wire to minimize damage due to aeolian vibration. It is a ratio of the horizontal wire tension applied to the unit weight of the wire. H/w ratio is also the “catenary constant”, defining the shape of the sag.

**Homogeneous conductor**: Conductor consisting of strands of a single material; for example AAC consists of strands of 1350-H19 Aluminum and AAAC consists of strands of 6201 Aluminum alloy.

**Inverse Standing Wave Ratio**: A method for measuring the self-damping of cables that is based on the measurement of nodal and antinodal amplitudes along the test span (Orange Book, [13]).

**Kcmil, KCM or MCM**: A circular mil is a unit of area, equal to the area of a circle with a diameter of one mil (one thousandth of an inch). It is a convenient unit for referring to the area of a wire with a circular cross section, because the area in circular mils can be calculated without reference to $\pi$ ($\pi$). The area in circular mils, $A$, of a circle with a diameter of $d$ mils, is given by the
formula: \( A = d^2 \) 1000 circular mils = 1 kcmil = 0.506708 sq. mm = 0.000785399 sq. in.

**Laminar Wind**: Smooth, non-turbulent wind flow.

**Natural Frequency**: A frequency at which a body will naturally vibrate once set into motion. Also referred to as the fundamental frequency.

**Rated Breaking Strength**: A calculated value of composite tensile strength, which indicates the minimum test value for stranded bare conductor. Similar terms include Ultimate Tensile Strength and Calculated Breaking Load.

**Standing Wave**: Occurs when two opposing waves combine to create a wave that remains in a stationary position.

**Strouhal Number**: A dimensionless number describing oscillating flow mechanisms. (See Equation 1)

**Twisted Pair Conductor**: A pair of stranded conductors that has been twisted into a helical pattern. This pattern behaves as a form of motion control for the conductor.

**Vortex Shedding**: A phenomena caused by a fluid flowing over a stationary cylindrical body, where vortices form in the wake of the body.
APPENDIX C – LIST OF ACRONYMS

AAC: All-Aluminum Conductor
AAAC: All-Aluminum Alloy Conductor
ACAR: Aluminum Conductor Alloy Reinforced
ACCC: Aluminum Conductor Composite Core
ACCR: Aluminum Conductor Composite Reinforced
ACSR: Aluminum Conductor, Steel Reinforced
ACSS: Aluminum Conductor, Steel-Supported
ADSS: All-Dielectric Self-Supporting fiber optic cable
CBL: Calculated Breaking Load
DSR: Distributed Series Reactor
EBP: Energy Balance Principle
EDS: Everyday Stress
IEEE: Institute of Electrical and Electronic Engineers
ISWR: Inverse Standing Wave Ratio
LPC: Last Point of Contact
OPGW: Overhead Ground Wire containing optical fibers used for the transmission of data
RBS: Rated Breaking Strength
SDC: Self Damping Conductor
TW: Trapezoidal Wire
UTS: Ultimate Tensile Strength
APPENDIX D – ELEMENTS OF A DAMPER PROCUREMENT SPECIFICATION

Regardless of the engineering approach used for line design, the manufacturers should bid on a well-considered specification. Consider the following elements for a damper procurement specification:

Vendor Technical Qualification:
- Qualifications and experience of the vendor's technical staff.
- What engineering approach or software tools are used to design the damper?
- What engineering approach or software tools are used to support damping recommendations?
- What laboratory support is available to the design organization? How often is it used?
- What laboratory support is available to the manufacturing organization? How often is that used?
- Technical support at short notice

Line Design General Information:
- Conductor(s) used on the line
- Line tension
- Span chart
- Operating voltages (address corona/RIV issue).
- Terrain in the region
- Weather conditions (www.NOAA.gov has statistical weather for regions of the US).
- Environmental conditions (sea coast and industrial sites may need special materials or enhanced corrosion protection).

Damper Quality/Workmanship
- Surface finishes
- Color and appearance
- Castings free of slag, dross, porosity, and excessive sags
- Rounded edges and corners, and free of burrs that could potentially cause skin cuts or damage insulating gloves.
- Packaging
- Markings
  - Manufacturer
  - Catalog number
  - Clamp diameter range
  - Date code or lot code
  - Other markings "agreed upon" between buyer and supplier.

Damping Effectiveness
- Design test: damping (power absorption) versus frequency for the conductor (measured on a laboratory span). The damper used for the design test should also have its mechanical impedance measured on a shaker (see b below) to provide a benchmark for production dampers.
- Production test: damper impedance versus frequency (measured on an instrumented shaker table). The properties of the production lot should not differ significantly from the properties of the design test samples.

Note: The damping (power absorption) test is expensive, and need not be required for production samples. The impedance test on a shaker is low cost, and should be used to prove that production samples have similar dynamic response as dampers qualified in the design test.
c. Protectable span length: what is the basis for the vendor’s recommendations?

d. Damper location: what is the basis for the recommended installation location?

e. Service life:
   • What is the expected service life?
   • What inspections are needed to ensure dampers are still working?
   • Was the damper tested for fatigue endurance?

Corrosion Protection:
   a. Damper weight and clamp corrosion is an esthetics issue.
   b. Messenger cable corrosion will shorten the working life of the damper and should be addressed separately.

Damper Fatigue and Wear: Dampers are a moving part and subject to wear. IEC 61897 specifies a fatigue test to demonstrate resistance to early fatigue or wear.

Clamp performance: Clamp slip forces, and design to prevent conductor damage from the clamp should be specified.

Installation: Ensure your company’s tools and training are compatible with the clamping system. Some manufacturers require a special tool, and several have clamps that are difficult to install. Does the clamp bolt require a backing wrench? Do you want break-away bolts? Does the clamp design support live-line installation or live-line replacement?

Radio Interference and Corona: Dampers should be tested for RIV and corona inception using procedures in IEC Publication 61284, 1997 [26].