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Aeolian Vibration Basics

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Preformed Line Products

Aeolian Vibration Basics

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ABSTRACT

Wind induced (aeolian) vibrations of conductors and overhead shield wires (OHSW) on transmission and distribution lines can produce damage that will negatively impact the reliability or serviceability of these lines. Lines damaged by vibration may have to be de-rated or even taken out of service until repairs can be made. This could have an impact on an entire network.

Understanding aeolian vibration and how it can be managed or controlled is the key to minimizing its possible effect on a line or network.

This report will present an executive summary of the research and findings of industry experts all over the world who have contributed to the understanding of aeolian vibration and its control. The references cited will provide a more detailed explanation of individual principles, findings and recommendations.

MECHANISM OF AEOLIAN VIBRATION

When a “smooth” stream of air passes across a cylindrical shape, such as a conductor or OHSW, vortices (eddies) are formed on the leeward side (back side). These vortices alternate from the top and bottom surfaces, and create alternating pressures that tend to produce movement at right angles to the direction of the air flow. This is the mechanism that causes aeolian vibration [1].

The term “smooth” was used in the above description because unsmooth air (i.e., air with turbulence) will not generate the vortices and associated pressures. The degree of turbulence in the wind is affected both by the terrain over which it passes and the wind velocity itself. It is for these reasons that aeolian vibration is generally produced by wind velocities below 15 miles per hour (MPH). Winds higher than 15 MPH usually contain a considerable amount of turbulence, except for special cases such as open bodies of water or canyons where the effect of the terrain is minimal.

The frequency at which the vortices alternate from the top to bottom surfaces of conductors and shield wires can be closely approximated by the following relationship that is based on the Strouhal Number [2].

Vortex Frequency (Hertz) = $3.26V / d$

where: V is the wind velocity component normal to the conductor or OHSW in miles per hour

d is the conductor or OHSW diameter in inches

3.26 is an empirical aerodynamic constant

One thing that is clear from the above equation is that the frequency at which the vortices alternate is inversely proportional to the diameter of the conductor or OHSW.

For example, the vortex frequency for a 795 kcmil 26/7 ACSR (“Drake”) conductor under the influence of an 8 MPH wind is 23.5 Hertz. A 3/8” OHSW under the same 8 MPH wind will have vortices alternating at 72.4 Hertz. The fact that the vortex frequency for an OHSW is much higher than that for a conductor will be important to remember when the effects of vibration are discussed later in this report.

To further illustrate the difference in vibration frequencies between conductor and OHSW, Figures 1 & 2 show actual vibration recordings made on a line in the western part of the U.S. The recordings were taken with an Ontario Hydro Recorder on a 1400’ span. The conductor is 1272 kcmil 45/7 ACSR (“Bittern”) and the OHSW is 3/8” EHS. Plugging the recorded frequencies and diameters into the above equation yields the same apparent wind velocity (4.5MPH) for both the conductor and OHSW.

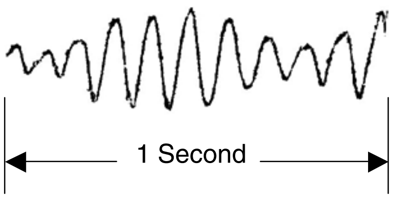

Figure 1 – Vibration Recorded on 1272 kcmil 45/7 ACSR (11 Hertz)

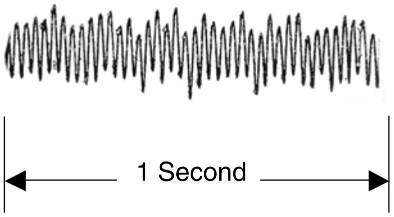

Figure 2 – Vibration Recorded on 3/8” OHSW (41 HERTZ)

Sustained aeolian vibration activity occurs when the vortex frequency closely corresponds to one of the natural vibration frequencies of the span of conductor or OHSW. This sustained vibration activity takes the form of discrete standing waves with forced nodes at the support structures and intermediate nodes spaced along the span at intervals that depend on the particular natural frequency (Figure 3).

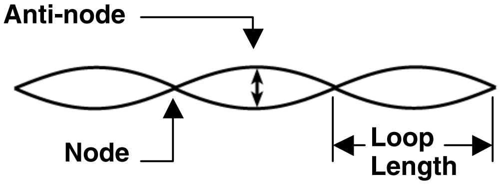

Figure 3 – Standing Wave Vibration

The natural frequencies at which a conductor or OHSW under tension will vibrate in a series of standing waves are approximated by:

$$F = (Tg/w)^{1/2} \times N/2S$$

where:
F is the natural frequency in hertz
T is the tension in pounds
g is the gravitational constant of 32.2 ft/sec^2
w is the conductor or OHSW weight per foot
N is the number of standing wave loops
S is the span length in feet

For example, the natural frequencies for an 800’ span of 795 kcmil 26/7 ACSR (“Drake”) conductor at a tension of 4,725# are given by:

$$F = 0.233 \times N$$

It was stated earlier that sustained vibration will occur when the vortex shedding frequency of the wind is equal to one of the natural frequencies of the span. Therefore, for this example, using 800’ of Drake conductor at a tension of 4,725#:

$$2.9422 \times V = 0.233\ N$$

or

$$12.6275 \times V = N$$

For a wind velocity of about 8 MPH, the span in this example would have 100 standing waves (N=100), each about 8’ in length (loop length). At a higher wind speed near 12 MPH the loop length will decrease to 5.3’ (N=150). The importance of loop lengths will be discussed in a later section dealing with the placement of dampers.

The amplitude at which a span will vibrate (peak-to-peak movement at the anti-node in Figure 3) depends on a number of factors which include the energy that is transferred to the span by the wind and the amount of damping in the span from the conductor or OHSW itself (self damping) or from additional dampers installed in the span.

In most cases the maximum peak-to-peak amplitude of a vibrating conductor or OHSW will not exceed its diameter.

Extensive research utilizing wind tunnel studies has been used to determine the energy imparted by the wind to a vibrating conductor [3], [4], [5], [6], [7], [8], [9]. Collectively this research has shown that wind energy may be expressed in the general (non-linear) form:

$$P = L \times d^4 \times f^3 \times \mathrm{fnc}(Y/d)$$

where:
P is the wind energy in watts
L is the span length
d is the conductor diameter
f is the vibration frequency in hertz
Y is the anti-node vibration (peak-to-peak)
fnc(Y/d) is a function derived from experimentation

The above expression assumes completely laminar wind flow, free of turbulence. The effects of turbulence will be discussed later in this report.

The self damping characteristics of a conductor or OHSW are basically related to the freedom of movement or “looseness” between the individual strands or layers of the overall construction. In standard conductors the freedom of movement (self damping) will be reduced as the tension is increased. It is for this reason that vibration activity is most severe in the coldest months of the year when the tensions are the highest.

Some conductors designed with higher self damping performance use trapezoidal shaped outer strands that "lock" together to create gaps between layers. Other conductors, such as ACSS (formerly SSAC), utilize fully annealed aluminum strands that become inherently looser when the conductor progresses from initial to final operating tension.

Procedures have been established for measuring self damping performance of conductors and OHSW in the laboratory [10].

The energy absorbed by damping devices added to a span of conductor or OHSW is the subject of a later section of this report.

EFFECTS OF AEOLIAN VIBRATION

It should be understood that the existence of aeolian vibration on a transmission or distribution line doesn't necessarily constitute a problem. However, if the magnitude of the vibration is high enough, damage in the form of abrasion or fatigue failures will generally occur over a period of time.

Abrasion is the wearing away of the surface of a conductor or OHSW and is generally associated with loose connections between the conductor or OHSW and attachment hardware or other conductor fittings. The looseness that allows the abrasion to occur is often the result of excessive aeolian vibration.

Abrasion damage can occur within the span itself at spacers (Figure 4), spacer dampers and marker spheres, or at supporting structures (Figure 5).

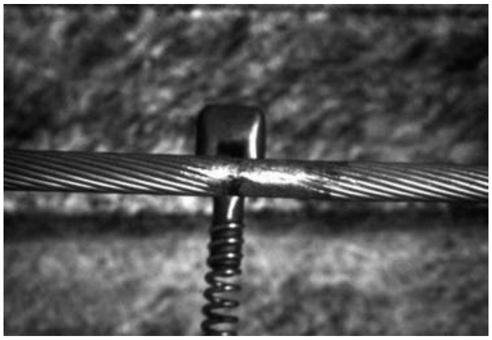

Figure 4 – Abrasion Damage at Spacer

Figure 5 – Abrasion Damage at Loose Hand Tie

Fatigue failures are the direct result of bending a material back and forth a sufficient amount over a sufficient number of cycles. Removing the pull tab from a can of soda is a good example.

All materials have a certain "endurance limit" related to fatigue. The endurance limit is the value of bending stress above which a fatigue failure will occur after a certain number of bending cycles, and below which fatigue failures will not occur, regardless of the number of bending cycles.

In the case of a conductor or OHSW being subjected to aeolian vibration, the maximum bending stresses occur at locations where the conductor or OHSW is being restrained from movement. Such restraint can occur in the span at the edge of clamps of spacers, spacer dampers and stockbridge type dampers. However, the level of restraint, and therefore the level of bending stresses, is generally highest at the supporting structures.

When the bending stresses in a conductor or OHSW due to aeolian vibration exceed the endurance limit, fatigue failures will occur (Figure 6). The time to failure will depend on the magnitude of the bending stresses and the number of bending cycles accumulated [11], [12], [13].

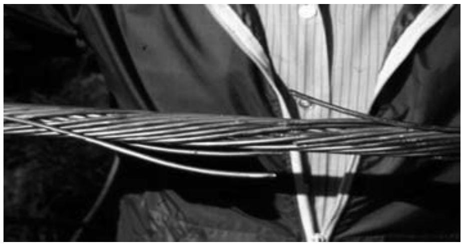

Figure 6 – Fatigue of Conductor Strands

In a circular cross-section, such as a conductor or OHSW, the bending stress is zero at the center and increases to the maximum at the top and bottom surfaces (assuming the bending is about the horizontal axis). This means that the strands in the outer layer will be subjected to the highest level of bending stress and will logically be the first to fail in fatigue.

The same principle applies to the addition of Armor Rods to the conductor or OHSW at support locations. A portion of the bending stress is applied to the Armor Rods, which reduces the bending stress on the conductor or OHSW. Since the Armor Rods are located the furthest from the center line of the conductor, they will be subjected to the highest level of bending stress, and would be expected to fatigue before the conductor strands. However, with the use of bolted suspension clamps this is not the usual mode of failure (Figure 7).

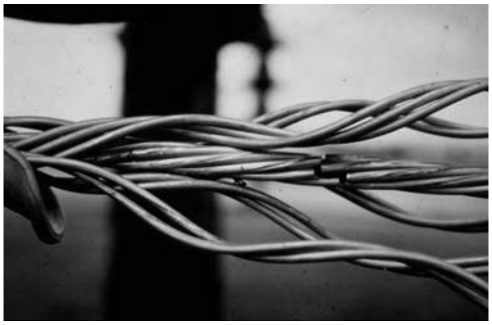

Figure 7 – Fatigue Failure of Conductor Under Armor Rods

The reason that a conductor will fail under Armor Rods is that the bolted suspension clamp produces a substantial amount of compression load when it is installed. The compression between the keeper and the clamp body somewhat "crushes" the conductor (Figure 8).

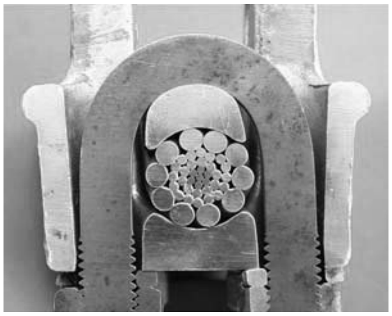

Figure 8 – Cut-Away of Suspension Clamp

The compression force produces notches in the aluminum strands of conductors as they pass over each other (the strands in each layer are produced in the opposite lay direction). The resulting notches (Figure 9) create stress risers that substantially reduce the endurance limit of the affected strands.

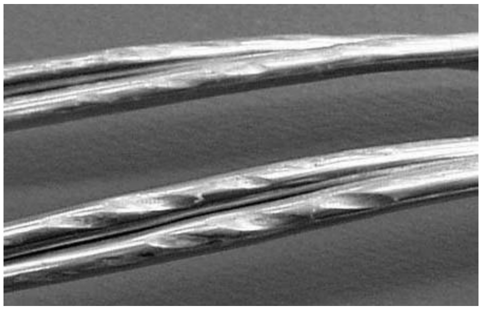

Figure 9 – Notching of Aluminum Strands Under Bolted Suspension Clamp

It is clear that care must be taken when removing Armor Rods from a line that has been subjected to moderate or severe aeolian vibration activity.

Suspension assemblies, such as the ARMOR-GRIP® Suspension and the CUSHION-GRIP™ Suspension which use elastomer cushions, with or without factory-formed rods, hold the conductor with a minimal amount of compression force (Figure 10).

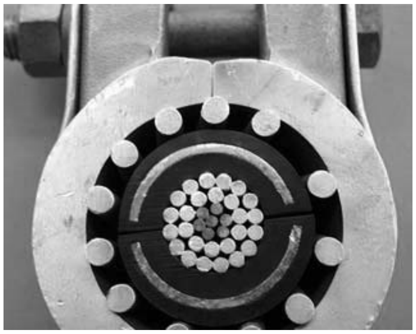

Figure 10 – Cut-Away of ARMOR-GRIP Suspension

The conductor in the elastomer cushions bends gradually, compared to the abrupt bending at the edge of a bolted clamp's keeper, and notching of the aluminum strands does not occur. The net result is that a conductor or OHSW in a suspension assembly that uses elastomer cushions can withstand higher levels of aeolian vibration activity without fatigue failure.

SAFE DESIGN TENSION WITH RESPECT TO AEOLIAN VIBRATION

There are a number of factors taken into account in choosing a design tension for a transmission or distribution line. These factors include:

- Average Span Length
- Overall Height of Structures
- Maximum Tension at Highest Wind and/or Ice Loading
- Clearances at Highest Operating Temperature
- Susceptibility to Aeolian Vibration

Of these factors the susceptibility to aeolian vibration has been the only one that is difficult to quantify. 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 [14]. It was suggested that the everyday stress (EDS) be limited to 18% of the conductor rated breaking strength (RBS) to assure safe operation with regard to aeolian vibration. More recent surveys of the performance of actual lines [15] that had been in service for 10 to 20 years revealed that up to 45% of lines installed using an EDS <18% experienced fatigue failures. A new guideline was clearly needed.

The work that led to the publishing of CIGRE Report #273, "Overhead Conductor Safe Design Tension With Respect To Aeolian Vibrations" in June, 2005 [15] was based on the ratio of the horizontal conductor tension, *H*, and the conductor weight per unit length, *w*. The effects of terrain on the turbulence intensity of the wind were also studied and included as part of the overall recommendations.

The horizontal conductor tension used to calculate the *H/w* ratio is the initial, unloaded tension at the average temperature of the coldest month at the location of the line.

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 undamped, unarmored conductors. 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 or hoarfrost, spans equipped with aircraft warning devices, and spans using non-conventional conductors" were examples cited of special situations.

Terrain Category	Terrain Characteristics	*H/w* (ft)
1	Open, flat, no trees, no obstruction, with snow cover, or near/across large bodies of water; flat desert.	3,281
2	Open, flat, no obstruction, no snow; e.g., farmland without any obstruction, summertime.	3,691
3	Open, flat, or undulating with very few obstacles; e.g., open grass or farmland with few trees, hedgerows or other barriers; prairie, tundra.	4,019
4	Built-up with some trees and buildings; e.g., residential suburbs; small towns; woodlands and shrubs; small fields with bushes, trees and hedges.	4,675

Table 1 – Safe Design Tension for Single, Undamped, Unarmored Conductors

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

INFLUENCE OF SUSPENSION HARDWARE

The use of Armor Rods (Figure 11) or high performance suspension assemblies (Figures 12 & 13) reduces the level of dynamic bending stress on a vibrating conductor.

Figure 11 – Armor Rods Applied to Conductor Within a Suspension Clamp

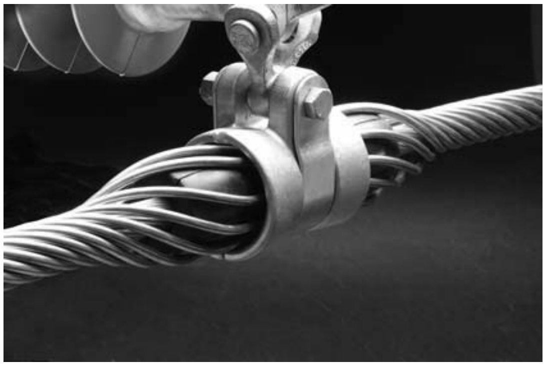

Figure 12 – ARMOR-GRIP® Suspension (AGS)

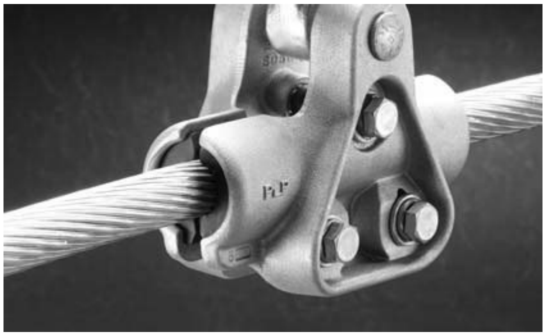

Figure 13 – CUSHION-GRIP™ Suspension (CGS)

As reported earlier Armor Rods will absorb a portion of the bending stress at the edges of the suspension clamp, but do nothing to reduce the effects of the compression loading and resulting notching of the aluminum strands.

Consequently, there is negligible influence of Armor Rods on the recommendations for safe design tensions (with or without dampers).

The use of elastomer cushions on high performance suspensions, such as the AGS and CGS, provide two benefits. First, within the elastomer cushion the vibrating conductor is bent in a gradual manner along the cushion, rather than bending abruptly at the edge of a metallic keeper (suspension clamp).

Secondly, the elastomer cushions, with or without externally applied rods (as with the AGS) minimize or eliminate the compression loading on the conductor, which causes notching of the aluminum strands.

As a result high performance suspensions will allow higher safe design tensions (*H/w*) and have a positive influence on the “protectable” span length of a damper.

The amount of positive influence and additional protection provided by performance suspensions is difficult to reduce to a simple table. Contact PLP with specific line design and environmental (terrain and temperatures) data for more information.

DAMPERS: HOW THEY WORK

Dampers of many different types have been used since the early 1900s to reduce the level of aeolian vibration within the span and, more importantly, at the supporting structures.

The damper most commonly used for conductors is the Stockbridge type damper, named after the original invention by G.H. Stockbridge about 1924. The original design has evolved over the years but the basic principle remains: weights are suspended from the ends of specially designed and manufactured steel strand, which is secured to the conductor with a clamp (Figure 14).

Figure 14 – VORTX™ Damper

When the damper is placed on a vibrating conductor, movement of the weights will produce bending of the steel strand. The bending of the strand causes the individual wires of the strand to rub together, thus dissipating energy. The size and shape of the weights and the overall geometry of the damper influence the amount of energy that will be dissipated for specific vibration frequencies. Since, as presented earlier, a span of tensioned conductor will vibrate at a number of different resonant frequencies under the influence of a range of wind velocities, an effective damper design must have the proper response over the range of frequencies expected for a specific conductor and span parameters.

Some dampers, such as the VORTX Damper (Figure 14), utilize two different weights and an asymmetric placement on the strand to provide the broadest effective frequency range possible.

An effective damper is capable of dissipating all of the energy imparted to a conductor by the wind (ranging from 2 to 15 MPH) for the specified "protectable" span length. The same applies to longer spans where multiple dampers are required to dissipate the energy from the wind.

Placement programs, such as those developed by PLP for the VORTX Damper, take into account span and terrain conditions, suspension types, conductor self-damping, and other factors to provide a specific location in the span where the damper or dampers will be most effective.

For smaller diameter conductors (< 0.75"), overhead shield wires, and optical ground wires (OPGW), a different type of damper is available that is generally more effective than a Stockbridge type damper. The Spiral Vibration Damper (Figure 15) has been used successfully for over 35 years to control aeolian vibration on these smaller sizes of conductors and wires.

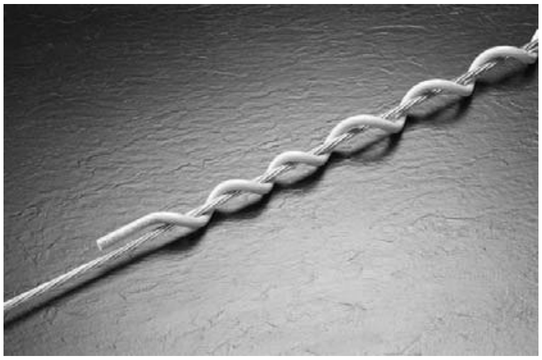

Figure 15 – Spiral Vibration Damper

The Spiral Vibration Damper is an "impact" type damper made of a rugged non-metallic material that has a tight helix on one end that grips the conductor or wire. The remaining helixes have an inner diameter that is larger than the conductor or wire, such that they impact during aeolian vibration activity. The impact pulses from the damper disrupt and negate the motion produced by the wind.

The Spiral Vibration Damper is so effective because it can be placed anywhere in the span and has no specific resonant frequencies. It responds to all frequencies, especially the high frequencies associated with smaller diameter conductors and wires (see MECHANISM OF AEOLIAN VIBRATION section).

The Spiral Vibration Damper also has a limit to the length of the span protected by one damper. Longer spans require more than one damper per span (see Table 2). Up to three Spiral Vibration Dampers can be spun together during installation to avoid having to reach further out into the span.

Span Length	Dampers per Span	
	Standard	Hi-Mass
100' to 800'	2	1
800' to 1600'	4	2
1600' to 2400'	6	3

Note: Increase number of dampers by 50% for spans crossing rivers or canyons.

Table 2 – Spiral Vibration Damper Recommendations

DAMPER: INDUSTRY SPECIFICATIONS

The most up-to-date and comprehensive industry specification for aeolian vibration dampers is IEC 61897:1998, "Overhead Lines – Requirements and Tests for Stockbridge Type Aeolian Vibration Dampers".

IEC 61897:1998 describes the requirements for materials and protective coatings used in the manufacture of a damper, and laboratory and field testing to demonstrate the effectiveness and durability of a damper. The testing includes:

- Damper Fatigue
- Clamp Slip Load
- Weight Slip Load
- Damper Response
- Laboratory In-Span Damper Performance
- Electrical (Corona) Performance
- Field Performance

The damper response test is performed before and after the fatigue test on a number of dampers in the laboratory to confirm that the response of the damper will not change during its service life in the field.

DAMPER: LABORATORY TESTING

The damper response test is performed in the laboratory by attaching the damper to a shaker (Figure 16).

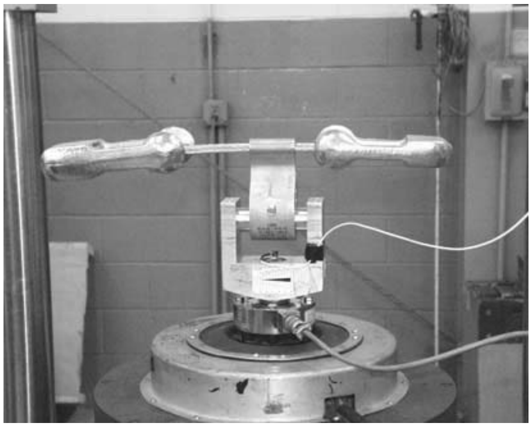

Figure 16 – Damper Response Test Set-Up

By exciting the damper over a range of frequencies the force between the damper and the shaker can be measured and plotted (Figure 17).

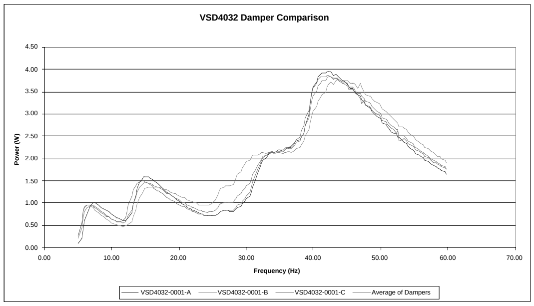

Figure 17 – Damper Response Curve

Figure 17 shows the power (in watts) delivered to the damper by the shaker (vertical axis) over a range of frequencies. The results are shown for three of the same damper design, along with the average. This plot shows four distinct peaks in the power curve. These represent the resonant frequencies of the damper weights. Each weight has two resonant frequencies: one where the furthest end of the weight has the maximum movement, and the other where the end nearest the clamp has the maximum movement (higher frequency). The VORTX Damper shown in the curve has two different weights, each with different resonant frequencies, which accounts for the four peaks in the curve.

The damper response test is not a measure of a damper's effectiveness in a span, but is typically used to assure that the basic design has a correct frequency range for the conductors on which it will be used, and to compare dampers before and after being subjected to fatigue testing.

The damper fatigue testing uses the same test set-up, without the force transducer between the shaker and the damper. In this test the damper is vibrated for 10 million cycles at a shaker amplitude of 1mm (peak-to-peak) for the highest resonant frequency of the damper.

The in-span damper performance testing in the laboratory gives a clear indication of the anticipated performance of the damper in the field. For this test the damper is attached to a tensioned conductor and positioned where it would be on a span in the field. Blocks of steel plates with grooves for the conductor are used to eliminate any effects from the dead-end hardware (Figure 18).

Figure 18 – In-Span Damper Performance Test

The power dissipated by the damper over a range of frequencies was determined by the Inverse Standing Wave method in accordance with IEEE Standard 664-1993, "IEEE Guide for Laboratory Measurement of the Power Dissipation Characteristics of Aeolian Vibration Dampers for Single Conductors".

Sensitive equipment was used to determine the vertical movement of the span at one of the free nodes and anti-nodes. The output from the measurement equipment was analyzed by a computer system (Figure 19) to calculate the power dissipated over the frequency range.

Figure 19 – Computer Analysis System

The results of the testing produce a plot of the power dissipated by the damper, in watts (vertical axis) for a number of frequencies (or equivalent wind velocities) in the range expected for the conductor being tested. By plotting the wind energy for the maximum "protectable" span length for each frequency, the effectiveness of the damper is clearly shown (Figure 20).

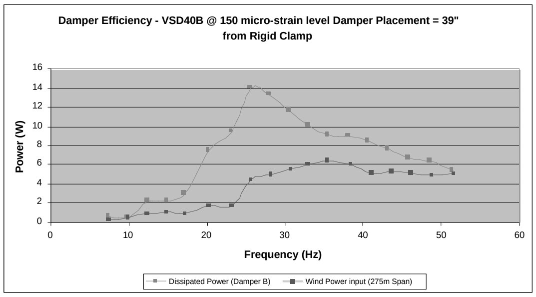

Figure 20 – In-Span Performance Test Results

In the above figure, the lower curve is the wind energy for a 900' (275meter) span, and the top curve is the energy dissipated by the damper. For the entire range of frequencies, the damper can dissipate at least, and generally more than, the wind can impart on the span.

The remaining laboratory tests (weight and clamp slip on strand, and corona) are self explanatory, but equally important in the overall assessment of a damper.

DAMPER: FIELD TESTING

Beginning in the late 1950s considerable work was completed on the development of rugged equipment for the field measurement of aeolian vibration [16], and on the interpretation and presentation of the results [17], [18], [19].

In 1966 the IEEE Committee on Overhead Line Conductors published a "standardized" method for measurement and presentation of results [18] that is still used today.

The field vibration recorder developed by Ontario Hydro in the early 1960s (Figure 21) is an analog device that is still being utilized. Recorders more recently developed use digital technology to record and store the data.

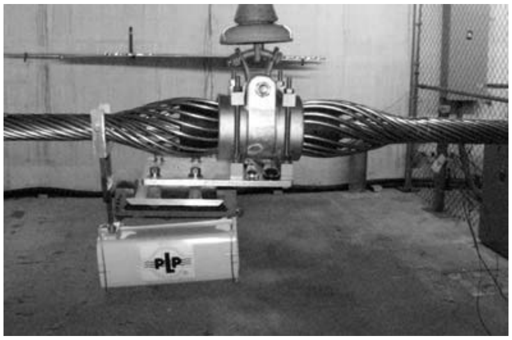

Figure 21 – Ontario Hydro Vibration Recorder Mounted on ARMOR-GRIP Suspension

The best way to understand the process of recording and interpreting field vibration data is to follow the process that is used with the Ontario Hydro Recorder (analog). In this way you will understand the steps that are done automatically in the newer (digital) recorders.

As shown in Figure 21 special mounting hardware is used to establish a very rigid attachment between the recorder and the suspension hardware. The recorder measures the differential displacement between the suspension and the conductor during vibration activity. The input arm of the recorder is secured to the conductor (or Armor Rod or AGS Rod) at a specified distance from the suspension hardware. The IEEE recommended distance is 3.5" from the edge of a keeper on a bolted suspension clamp. A larger distance is required for AGS due to the area where the rods transition from the conductor to the outer surface of the elastomer cushions (Figure 21). The distance used in the field is recorded and taken into account in the interpretation of the data.

Looking inside the Ontario Hydro vibration recorder (Figure 22), the arm connected to the conductor is connected to an assembly of linkages that multiply the vertical displacement. At the end of the assembly is a thin plate with a sharp stylus that is positioned over the clear Mylar film.

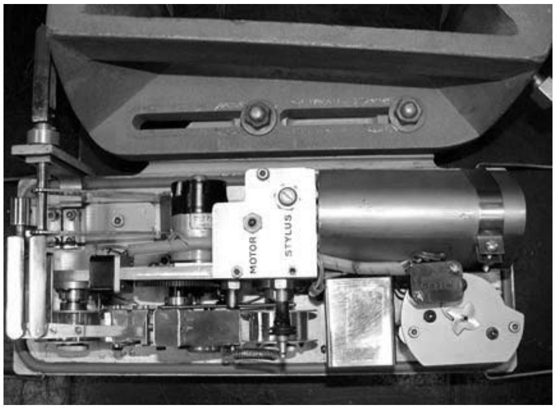

Figure 22 – Ontario Hydro Recorder (Inside View)

The clock (lower right side) works with a micro switch and a timing circuit to switch on the motor (top center) and advance the film for a one second period once every 15 minutes (96 traces per day). At the same time an electro magnet pulls the stylus down onto the Mylar film. The rechargeable battery (upper right) is capable of operating the recorder for a two-week period, even at extremely cold temperatures.

Each one-second trace on the Mylar film (Figure 23) is an actual representation of the motion of the conductor (differential displacement) during that period.

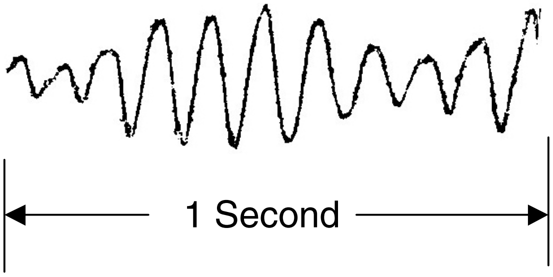

Figure 23 – Vibration Recorded on 1272 kcmil 45/7 ACSR Conductor (11 Hertz)

The Mylar tapes are read with a calibrated magnified viewer that allows the technician to record the number of cycles in the one-second period (frequency), and the maximum amplitude (in mils) of the conductor movement (differential displacement).

The next step is to summarize, or add up the total number of recorded traces for each frequency and amplitude. When done manually this procedure is referred to as a dot plot because the technician adds a dot in a box that represents a specific frequency and amplitude for each trace. When all the traces are read and recorded, the dots are added up to get the total number of occurrences for each frequency and amplitude. The newer digital recorders determine the frequency and amplitude for each record (one per 15-minute period) automatically and add them to a built-in histogram that can be downloaded into a computer when the recorder is removed from the line. The only advantage of the analog recorder is that it is possible to determine the approximate time and date for each individual trace.

It is assumed that the vibration activity that is captured in each one-second trace is indicative of the vibration during the entire 15-minute period. Using this it is possible to calculate the number of total cycles in the 15-minute period (based on the frequency) for each specific amplitude recorded during the study period.

The bending strain (in micro-strain) on the conductor for each amplitude is determined from the Poffenberger-Swart equation [17], with consideration given to the distance between the suspension hardware and the attachment to the conductor.

The standard IEEE representation of the results of a field vibration study is a graph with the number of millions of cycles per day (MC/day) on the vertical axis, and the micro-strain level on the horizontal axis (see Figure 24 for an example).

Figure 24 shows the recorded field vibration on a test line with a single 795 kcmil 26/7 ACSR ("Drake") conductor on one phase and twin (18" horizontal separation, with spacers) on a second phase. The tensions were the same for the purpose of this study.

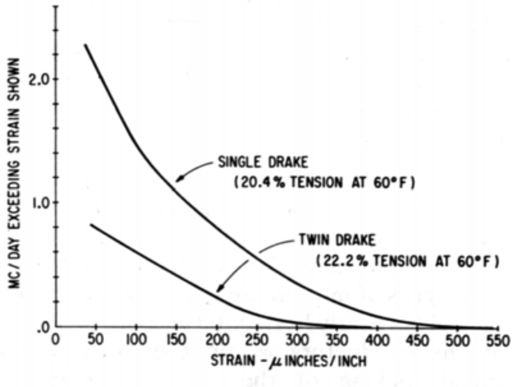

Figure 24 – Example of IEEE Output for Field Vibration Study

It is clear from this study that the vibration levels on a single conductor are higher than the levels for a twin configuration (with spacers) under the same conditions.

It is common to use a similar comparison of curves to show the effectiveness of vibration dampers in the field.

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