Welcome to Vibrationdata

Acoustics • Shock • Vibration • Signal Processing **May 2006 Newsletter**

Greetings

Mechanical vibration is usually undesirable in a structure because it can lead to fatigue and other types of failures. Vibration does have its beneficial uses, however. For example, dither vibration is used to ensure that the Space Shuttle's Ku-Band antenna operates properly, as discussed in the first article. This vibration may be a concern for microgravity experiments, on the other hand.

The second article discusses wind-driven vibration of power lines. Galloping vibration can cause catastrophic failure of transmission lines and towers. This type of vibration is similar to that which caused the Tacoma Narrows Bridge to collapse in November 1940.

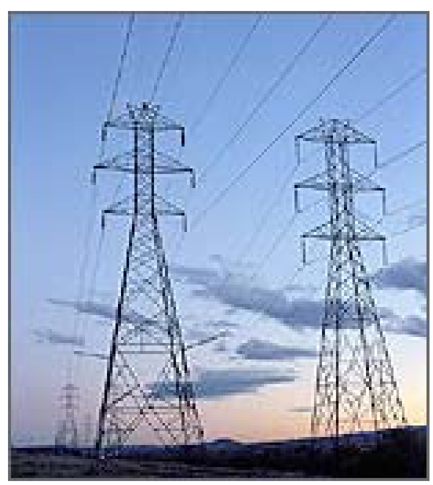
Another form of excitation, aeolian vibration, produces smaller amplitudes in the conductor lines but may cause fatigue and fretting failures after a period of months or years.

Also note that I am available for consulting work. Please let me know how I can help you with your shock, vibration, and acoustic projects.

Sincerely,

Tom Irvine
Email: tomirvine@aol.com

Feature Articles



Ku-Band Antenna Dither Vibration

by Tom Irvine

Figure 1. Orbiter

A file picture taken from space station Mir shows the space shuttle's dish-shaped Ku-band antenna extending over the right-hand side of the forward payload bay. Photo: NASA

Introduction

Dither is a British colloquialism for "undecidedness." It comes from the Middle English verb *didderen* meaning "to tremble."

The term dither in engineering has several meanings, which are somewhat related. Here are three examples;

1. Dither is a low level random noise added to an audio signal to mask digital distortion.
2. Dither is a vibration employed in some mechanical systems to avoid stiction and to ensure smooth motion. Stiction is short for *static friction.*
3. Dither is a small vibration of a solenoid current superimposed over the average value. It has the purpose of reducing the hysteresis or sticking of a valve by keeping its moving parts vibrating.

Historical Background

The following account is based on an article by Nika Aldrich.

The British naval air fleet had problems with their navigation systems during World War II. These systems were analog computers that used cranks, gears, and cogs, somewhat similar to the mechanisms in an antique grandfather's clock. Unfortunately, the gears and cogs would operate in a sluggish manner due to internal static friction. The system was thus difficult to calibrate prior to flight.

The navigation systems, however, gave better performance once the aircraft was airborne.

Engineers determined that the vibrations from the planes engines were in effect "lubricating" the cogs and gears, so that the system worked more properly and predictably.

This "noise" added to the system helped the accuracy of the system by removing the opportunity for the gears to stick. As a result, the British installed small motors on their navigation systems to vibrate the mechanisms on the ground during preflight calibration.

The vibration of the motors added to the navigation systems provided "dither" to help the rigid cogs and gears operate more fluidly.

Space Shuttle Orbiter Ku-band Antenna

The Orbiter Ku-band antenna system is used to transmit voice, data, and video images to the ground via the Tracking and Data Relay Satellite System (TDRSS).

The Ku-band antenna supplements the S-band antenna system. The Ku-band antenna can transmit data at a higher rate that the S-band system, but the S-band antenna has a larger beam width.

The Ku-band antenna can also be used as a radar system for tracking objects in space.

This antenna is located in the payload bay. It is used only after the Orbiter has reached its orbit and opened its payload doors.

The deployed assembly consists of a two-axis, gimbal-mounted, high-gain antenna; an integral gyro assembly; and a radio frequency electronics box.

The gimbal motors position the Ku-band antenna. The rate sensors determine how fast the antenna is moving.

The antenna is a parabolic dish, 3 feet in diameter. It is made from graphite epoxy.

Antenna Dither

The Ku-band antenna is dithered via a command signal at a frequency of 17 Hz to maintain its ability to smoothly search for and track the TDRSS satellites.

The dithering is intermittent, depending on a number of factors.

The 17 Hz dither frequency is clearly seen in acceleration data collected on-orbit, when the dither is on, as shown in Figure 2.

The dither may also have integer harmonics at 34 and 51 Hz as shown in Figure 3.

Additional frequencies are given in Table 1. Each of these frequencies may affect the performance of microgravity experiments.

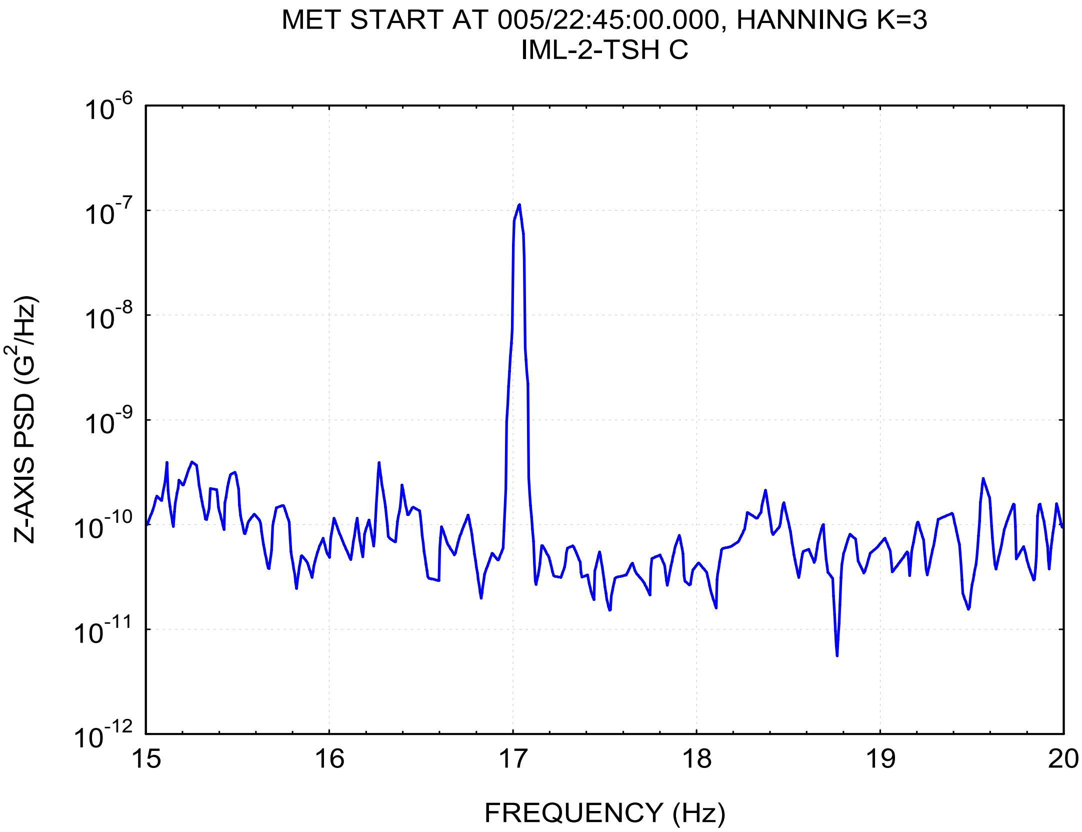


Figure 2. Power Spectral Density Plot

The overall level is 80 micro G, over the domain shown in the figure.

The data is from the STS-65 mission on the Columbia Orbiter. The Orbiter carried the International Microgravity Laboratory (IML-2).

The vibration level is a concern because it could interfere with crystal growth, dendritic solidification of molten materials, and other microgravity experiments.

Reference: http://gltrs.grc.nasa.gov/reports/1999/TM-1999-209048.pdf

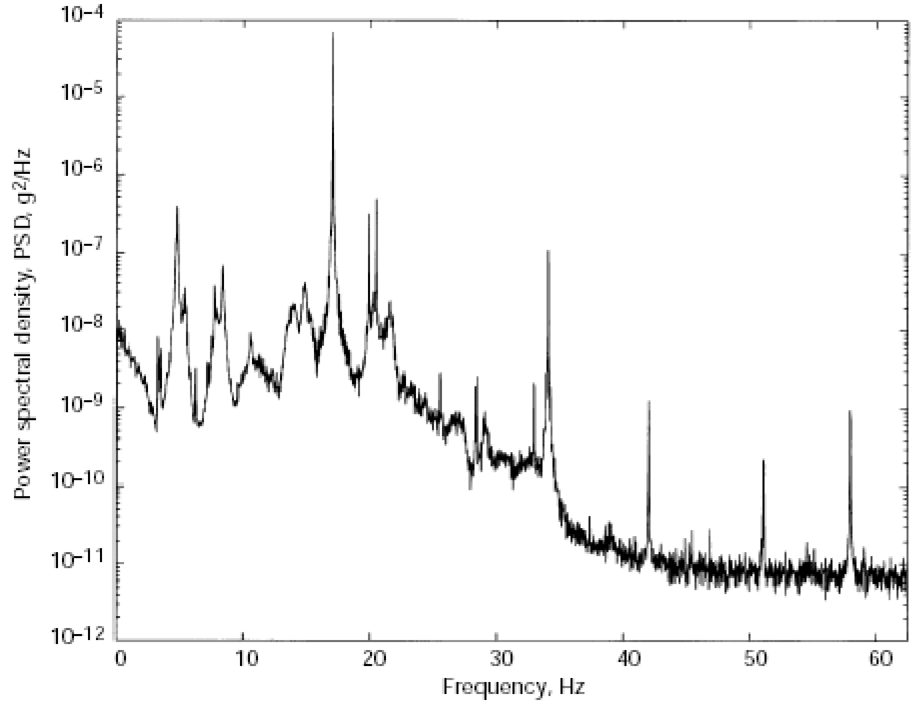


Figure 3.   Power Spectral Density, STS-62 Mission

Reference: http://gltrs.grc.nasa.gov/reports/1996/TM-107032.pdf

Table 1. Vibration Frequencies Commonly Seen in Orbiter Accelerometer Data

Freq (Hz)	Disturbance Source
0.43	Cargo bay doors
3.5	Orbiter fuselage torsion
3.66	Structural frequency of Orbiter
4.64	Structural frequency of Orbiter
5.2	Orbiter fuselage normal bending
7.4	Orbiter fuselage lateral bending
17	Ku-band antenna dither
20	Experiment air circulation fan
22	Refrigerator freezer compressor
38	Experiment air circulation fan
39.8	Experiment centrifuge rotation speed
43	Experiment air circulation fan
48	Experiment air circulation fan
53	Experiment air circulation fan
60	Refrigerator piston compressor
80	Experiment water pump
166.7	Orbiter hydraulic circulation pump

Reference: http://quest.nasa.gov/space/teachers/microgravity/giml.html

Transmission Line Vibration

By Tom Irvine

Introduction

Wind drives mechanical oscillations in high-tension power lines. There are three common excitation mechanisms: aeolian vibration, conductor galloping, and wake-induced vibration. Each of the types may cause fatigue, fretting, and other failure modes.

In addition, power lines may have corona discharge which generates acoustic noise, as described in the March 2003 Vibrationdata Newsletter.

The three types are summarized in Table 1. This table is taken from Reference 1.

Note that the terms power line, transmission line, cable, and conductor are used interchangeably in this article.

Aeolian Vibration

Aeolus was the Greek god of wind. The ancient Greeks observed that a passing wind would cause a tensioned string to vibrate. They invented a musical instrument based on the principle called the aeolian harp.

A gentle wind perpendicular to a cable may cause vortex-shedding in the wake. The vortex type depends on the wind speed and Reynold's number. A diagram of a laminar vortex street is shown in Figure 1.

Two key parameters for analyzing vortex shedding are the Reynolds number and the Strouhal number. An empirical relationship between these numbers for a circular section is given in Table 2.

Table 1. Comparison of Types of Conductor Motion

Parameter	Aeolian	Galloping	Wake Induced
Type of Overhead Lines Affected	All	All	Bundled Conductors (Parallel Lines in the Horizontal Plane)
Frequency Range	3 to 150 Hz	0.08 to 3 Hz	0.15 to 10 Hz
Peak-Peak Amplitude (Expressed in Conductor Diameter)	0.01 to 1	5 to 300	0.5 to 80
Type of Wind Provoking Motion	Steady	Steady	Steady
Wind Velocity	2 to 15 mph	15 to 40 mph	10 to 40 mph
Conductor Surface	Bare or Uniformly Iced (i.e. hoarfrost)	Asymmetrical Ice Deposit	Bare, Dry

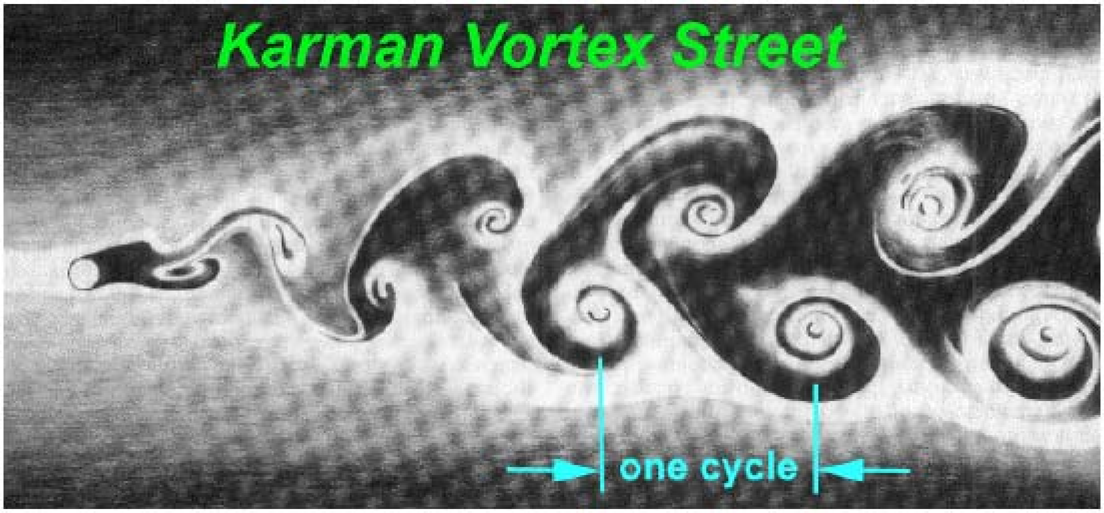


Figure 1.

Table 2. Strouhal Number vs. Reynolds Number for a Circular Section	
Reynolds Number Re	Strouhal Number S
< 30	0
50	0.13
500	0.20
1000	0.21
10^4	0.20
10^5	0.19
10^6	0.21
10^7	0.23

Figure 1 is taken from Reference 2. Table 2 is taken from Reference 3.

Note that the Reynolds number Re is defined as

$$Re = UD/\nu \qquad (1)$$

where

- U is the free stream velocity
- D is the diameter
- ν is the kinematic viscosity coefficient

The coefficient for air under normal conditions, $\nu \approx 1.6\ (10^{-4})\ ft^2/sec$.

The vortex type as a function of Reynold's number is shown in Table 3.

The Strouhal number S is defined as

$$S = f_S\ D/U \qquad (2)$$

where f_S is the frequency of full cycles of vortex shedding in Hertz.

The f_S value shall be called the "Strouhal frequency" rather than the "vortex shedding frequency" in this article because periodic vortex shedding does not occur for all flow regimes, as is apparent in Table 3.

Note that the Strouhal frequency is also referred to as the "lift oscillation frequency" by some sources.

The Strouhal frequency is thus

$$f_S = S\ U/D \qquad (3)$$

Resonance may occur if the Strouhal frequency matches the natural frequency of the transmission line.

<u>Conductor Galloping</u>

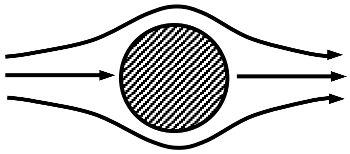
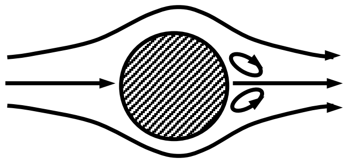
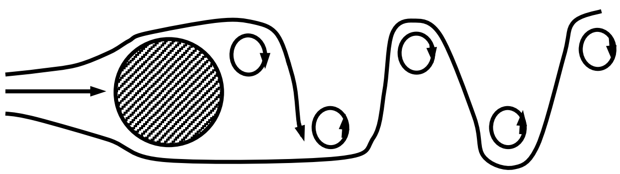
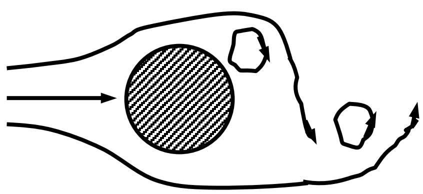
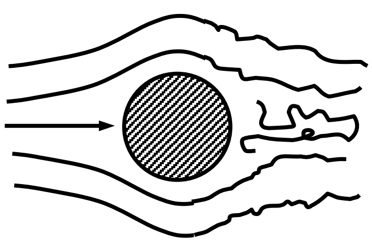
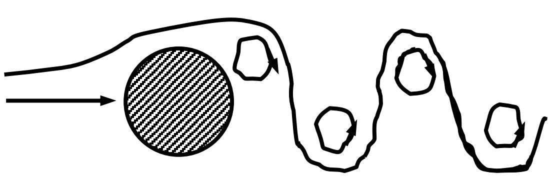
Galloping may occur in Northern climates when the temperature hovers around 32°F, accompanied by a moderate or strong wind. It occurs when ice or sleet has formed on the line, thus modifying its normally circular cross-section into a shape somewhat similar to an airfoil.

Galloping is due to aerodynamic instability. It is an example of self-excited vibration, as shown in Figure 2.

Galloping is not an example of resonance, because galloping may occur during a steady wind that does not have a forcing frequency coincident with a natural frequency of the transmission line.

The resulting motion takes the shape of an elongated ellipse, with its major axis predominantly in the vertical direction. This statement refers to the motion as seen by an observer looking down the length of the conductor lines.

Table 3. Regimes of Fluid Flow across Circular Cylinders

	$Re < 5$	Unseparated Flow Regime
	$5 \leq Re < 40$	A fixed pair of vortices in wake
	$40 \leq Re < 90$	Vortex street is laminar
	$90 \leq Re < 150$	Vortex street is laminar
	$150 \leq Re < 300$	Transition range to turbulence in vortex
	$300 \leq Re < 3(10^5)$	Vortex street is fully turbulent
	$3(10^5) \leq Re < 3.5(10^6)$	Laminar boundary layer has undergone turbulent transition and wake is narrower and **disorganized**
	$3.5(10^6) \leq Re$	Reestablishment of turbulent vortex street

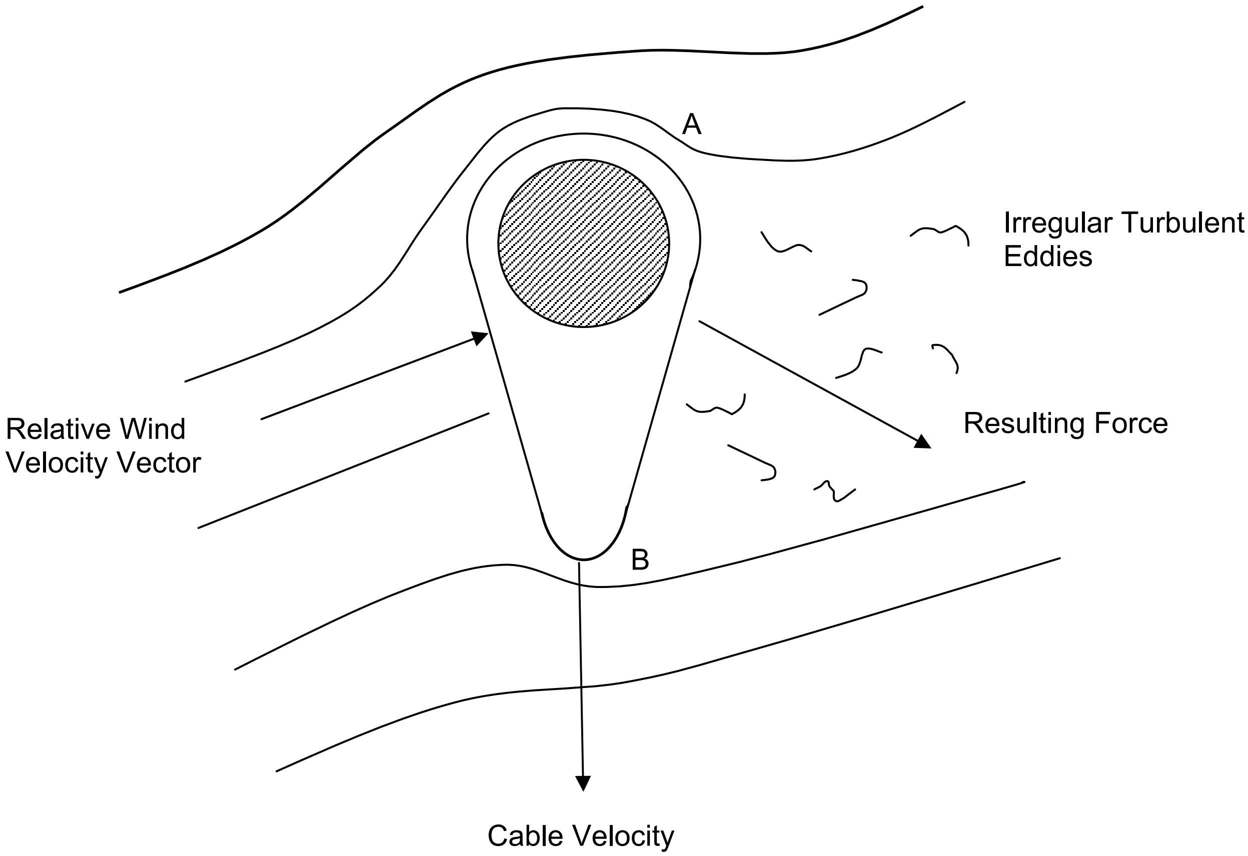


Figure 2. Wind Blowing against an Ice-Coated Cable

The following explanation is based on Reference 4.

The true wind direction is horizontal. The cable is moving downward, however, so the relative wind vector points upward. The resulting streamlines are shown. The pressure exerted by the streamlines is greater than that exerted by the eddies. The pressure in the eddie region is approximately ambient. Furthermore, the pressure at point A is greater than that at point B, thus creating a downward force component that reinforces the downward velocity.

The cable thus continues moving downward until the cable's own stiffness force causes the motion to reverse. The cable then moves upward, but it overshoots its equilibrium position. Meanwhile, the relative wind velocity points downward as the cable moves upward. Furthermore, the resulting force points upward during this cycle, thus reinforcing the motion.

The cycles are repeated until, perhaps, the cable fails altogether due to yielding, ultimate stress failure, or fatigue.

This is an example of aerodynamic instability or negative damping. The Tacoma Narrows Bridge failed in 1940 due to a similar mechanism.

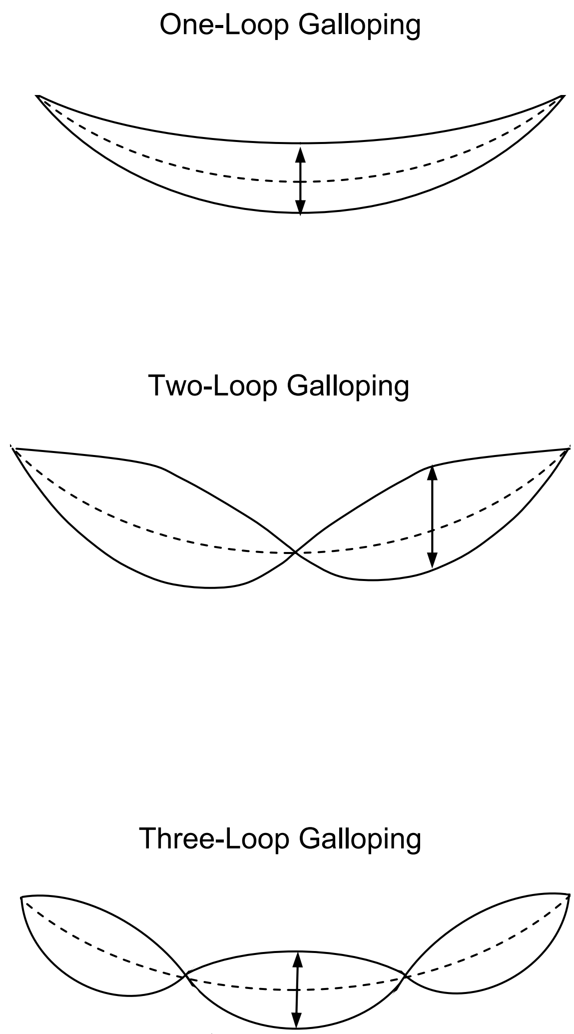


Figure 3. Possible Galloping Modes for a Subspan, Exaggerated

The actual motion of the conductor lines may be a combination of the modes shown in Figure 3. These are the mode shapes as seen from a view perpendicular to the lines.

The formula for the corresponding natural frequency for each mode is given later in this article.

The double arrow represents the amplitude of motion.

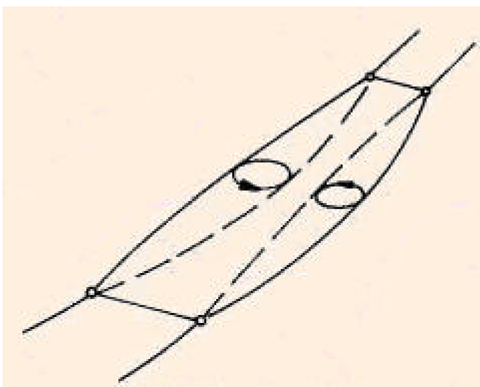
The dashed line represents the static catenary shape, which is the shape of a hanging flexible chain or cable when supported at its ends and acted upon by a uniform gravitational force, or its own weight. The slope of the chain is largest near the points of suspension because this part of the chain has the most weight pulling down on it. The slope of the chain decreases toward the bottom because the cable is supporting less weight.

Wake-Induced Vibration

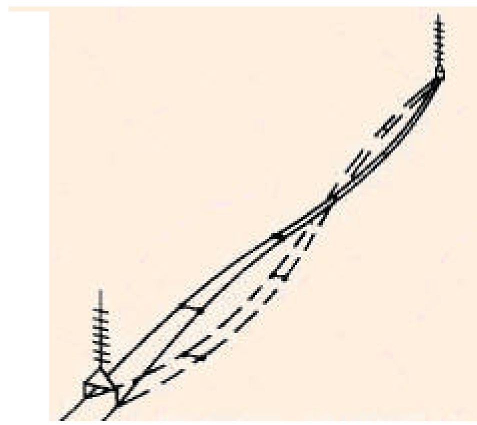
Consider two conductor lines side-by-side which are separated by a spacer. The wake from the windward line induces lower drag and creates lift forces on the leeward line. The conductors which share a spacer, or a support yoke, influence one another's motions by coupling through the spacer.

The resulting motion may be in the vertical or horizontal plane. Alternatively, the motion may be torsional. Four possible vibration modes for a system with two conductors are shown in Figure 4.

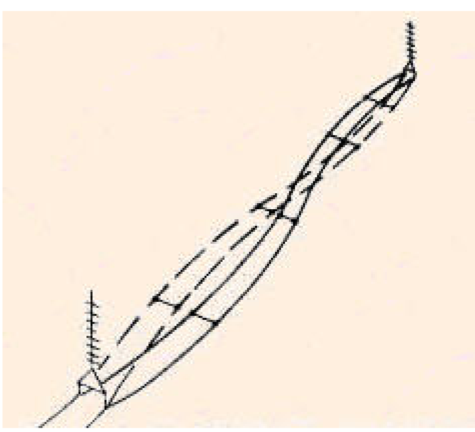
Figure 4. Wake-Induced Vibration Modes in Parallel Conductors



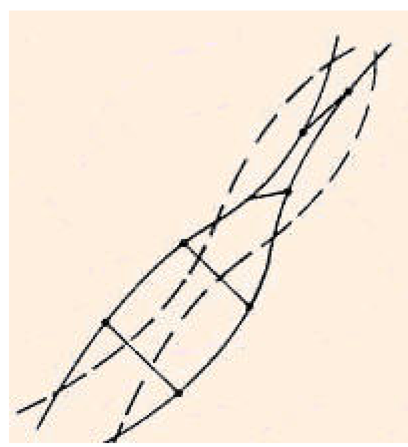
Breathing Mode in Horizontal Plane



Vertical Mode



Horizontal Mode



Torsional Mode

The diagrams are taken from Reference 1.

Conductor Natural Frequency

The following variables apply to the formulas in this section.

Vt	=	Traveling Wave Velocity
L	=	Loop Length
f	=	Natural Frequency
n	=	Number of Standing Wave Loops (or antinodes)
S	=	Span Length
H	=	Tension
m	=	Mass per Length
λ	=	Wavelength

The following equations are taken from Reference 1.

The traveling velocity is

$$Vt = \lambda f = 2f\ L \quad (4)$$

The traveling velocity can also be calculated from the tension and mass density

$$Vt = \sqrt{\frac{H}{m}} \quad (5)$$

The number of standing wave loops on a span is

$$n = S / L \quad (6)$$

The previous equations can be rearranged to calculate the natural frequency as

$$f = \frac{nVt}{2S} \quad (7)$$

Consider a 1200 foot span of a Drake conductor tensioned at 6300 lbf. The mass per length is 1.094 lbm/ft.

$$Vt = \sqrt{\frac{\left[6300\ \text{lbf}\right]\left[\dfrac{32.2\ \text{lbm}}{\text{lbf sec}^2\ \text{ft}}\right]}{1.094\ \text{lbm/ft}}} \quad (8)$$

$$Vt = 431\ \text{ft/sec} \quad (9)$$

$$f = \frac{n\left[431\ \text{ft/sec}\right]}{2\left[1200\ \text{ft}\right]} = n\,0.179\ \text{Hz} \quad (10)$$

The first three natural frequencies rounded to two decimal points are: 0.18, 0.36 and 0.54 Hz.

Note that a given conductor may have a mode with over 100 loops. The frequency corresponding to 168 loops is 30 Hz, for example.

The equations given in this section are somewhat simplified. A more rigorous set of equations would consider that conductors have bending stiffness as well as tension-induced stiffness. The bending stiffness is represented by the term EI, where

E is the elastic modulus

I is the area moment of inertia

Figure 5.

Downed power lines in Halifax, Nova Scotia after a storm. Courtesy CBC News.

Material

The transmission lines are typically made from aluminum or galvanized steel.

Potential Damage

Transmission line vibration may induce a number of mechanical and electrical failure modes.

Galloping may produces failure in 1 to 48 hours. Aeolian and wake-induced vibration each generate fatigue cycles that may accumulate for months or years before a failure occurs.

The galloping amplitudes may approach or even exceed the sag of the span. If the distances between lines of differing phase become too small, phase-to-phase flashovers occur. The conductors are then damaged by the power arc.

Each of the three excitation types generates mechanical stress in the towers, clamps, spacers and other supporting hardware components. Fatigue or fretting failures may occur as a result.

Fretting is failure mode that occurs when two surfaces rub against one another repeatedly. Fretting may include both mechanical and chemical corrosion effects.

In addition, fasteners may loosen or dislodge altogether.

Vibration Control Devices

There a number of damping devices that can be added to transmission lines.

The dampers are primarily effective at attenuating aeolian vibration. Galloping, on the other hand, is difficult to control.

Dampers may be mounted near an anti-node of a given vibration loop of concern. Each mode has its own anti-node locations, however.

Dampers are often placed near one end of a span, which is effective for attenuating traveling waves.

Note that a vibration mode is a standing wave which may be considered as summation of traveling waves.

Stockbridge Damper

The most common type is the Stockbridge damper, also called a dog bone damper.

This device has two weights, or bells, on the end of a flexible shaft that can be tuned based on the natural frequency of the structure to provide maximum absorption. This process requires special consideration, however, as discussed later in this section.

The damper can function both as a tuned vibration absorber and as a dissipation mechanism.

Figure 6. Stockbridge Damper

The clamp oscillates up and down when a vibration wave passes the damper location. This causes a flexure of the damper cable, creating relative motion between the damper clamp and damper weights.

Furthermore, there are two common types of Stockbridge dampers.

Symmetrical Stockbridge Damper

The first type is symmetrical, with equal masses. This type has two modes.

1. Maximum motion occurs at the outer ends of the bells for the first mode.

2. Maximum motion occurs at the inner lips of the bells for the second mode.

The greatest dissipation occurs at the damper clamp's natural frequencies when the clamp is considered by itself. The dynamics change, however, when the clamp is mounted on a conductor line. The damper clamp presents high mechanical impedance to the vibrating conductor. It tends to force a point of low amplitude or even a nodal point to occur at the damper location. This reduces the effectiveness of the damper at its own natural frequencies. Other frequencies of reduced performance occur when the damper is driven too easily by the conductor.

Reference 1 states that

> The choice of the best weight of the damper, in any case, involves a balancing act between performance at those frequencies where it resists conductor motion too weakly, and those (at resonance) where it resists too strongly.

Selecting the optimum weight of the bells thus requires finding an optimum balance between these frequencies.

One approach is to use a number of closely-spaced natural frequencies in the damper so that at least one is partially excited.

Another approach is to use a damper cable, or flexible shaft, with a high loss factor, which produces broad spectral peaks in the damper frequency response function. This is achieved by making the shaft from a bundle of cable strands, so that energy is dissipated by friction between the strands.

Asymmetrical Stockbridge Damper

A modified Stockbridge damper is asymmetrical, with different bell weights. Furthermore, the weights may be spaced unequally from the clamp point. This arrangement creates additional natural frequencies and it tends to flatten the frequency response curve.

Other Damping Devices

Additional damper designs include torsional, pendulum, impact, bretelle and festoon devices.

Another type is a spiral or helix vibration damper for small-diameter conductors.

References

1. Transmission Line Reference Book, Wind-Induced Vibration, Electric Power Research Institute, 1979,

2. James Koughan, "The Collapse of the Tacoma Narrows Bridge, Evaluation of Competing Theories of its Demise, and the Effects of the Disaster of Succeeding Bridge Designs," The University of Texas at Austin, 1996.

3. R. Blevins, Fluid Dynamics Handbook, Van Norstrand Reinhold, New York, 1984.

4. Den Hartog, Mechanical Vibrations, McGraw-Hill, New York, 1940.