VIBRATION DAMPING REQUIRED FOR OVERHEAD LINES

By A.S. Richardson, Jr.

RESEARCH CONSULTING ASSOCIATES
Lexington, Massachusetts

SUMMARY

Transmission line engineers have sought an easy method for evaluating if external dampers are required on any new transmission line. In the past this question has been given to the damper manufacturer who has a vested interest in an affirmative answer. For single conductors (and for bundled conductors)the vibration level of a power line conductor is the result of a complicated aerodynamic process in which energy is taken into the motion from vortex action on the lee side of the conductor. The amount of energy taken in is a non-linear function of vibration amplitude, frequency, conductor diameter, and wind speed. The amount of energy taken out is a non-linear function of vibration amplitude, frequency, conductor mass, conductor tension, and a certain friction constant that varies from conductor to conductor. It is known that a small amount of vibration is allowed without endangering the conductor. This has been called the "IEEE limit loop velocity", and is numerically equal to 200 mm/second.

This paper explains a simple procedure, applicable to single conductors, which calculates a comparison of energy in vs. energy out. From this process it is shown how to select the initial tension in the conductor so that no external dampers are required.

The paper introduces an analytical expression for power/energy input from the wind based on wind tunnel testing of two dimensional flow over vibrating circular cylinders.

$$P=9x10^{-8}xLxd^4xf^3x[2200x(y/d)^2-13000x(y/d)^3+36300x(y/d)^4]....(1)$$

The expression is applied to two popular ACSR conductors known by the code names Drake and Cardinal. The energy input to a 1,000ft. span vibrating at 200mm/sec. loop velocity is shown to follow a smooth monotonically increasing curve when plotted against wind speed. The effect of the different diameters for the two conductors is clearly visible. Wind energy input does not depend upon conductor tension.

The energy loss in a vibrating span of 1,000ft. is calculated from another formula which includes the ratio of tension to conductor mass.

$$Wr = 1/2 \quad H\, u^2\, m^{1.5}\, S^{-1.5}\, L\, f^4............(2)$$

The T/m factor is clearly important for energy loss. In addition the energy loss in the vibrating conductor increases with the vibration frequency (raised to the power of four), and the vibration amplitude (raised to the power of two). An important proportion factor is a constant that increases non-linearly with the diameter of the conductor, slightly decreases with conductor tension, and accounts for the friction loss in the vibrating conductor. In this study the friction constant is based on actual laboratory measurements of similar conductors.

Calculations for a Cardinal conductor are performed at two different levels of conductor tension - 18% and 26% rated breaking strength (RBS). The energy loss curves are compared with the energy input curve for the Cardinal conductor vibrating at the IEEE limit loop velocity limit. The comparison shows that the higher tension will allow the wind energy input to exceed the energy loss, while the lower tension will not allow the wind energy to exceed the energy loss.

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ABSTRACT

Transmission line engineers have sought an easy method for evaluating if external dampers are required on any new transmission line. In the past this question has been given to the damper manufacturer who has a vested interest in a affirmative answer. For single conductors (and for bundled conductors) the vibration level of a power line conductor is the result of a complicated aerodynamic process in which energy is taken into the motion from vortex action on the lee side of the conductor. The amount of energy taken in is a non-linear function of vibration amplitude, frequency, conductor diameter, and wind speed. The amount of energy taken out is a non-linear function of vibration amplitude, frequency, conductor mass, conductor tension, and a certain friction constant that varies from conductor to conductor. It is known that a small amount of vibration is allowed without endangering the conductor. This has been called the IEEE limit loop velocity, and is numerically equal to 200 mm/second.

This paper explains a simple procedure, applicable to single conductors, which calculates a comparison of energy in vs. energy out. From this process it is shown how to select the initial tension in the conductor so that no external dampers are required.

INTRODUCTION

The vibration of aerial cables is a subject of study by research workers and practitioners alike. In air, the vibration is aeolian vibration. A parameter, known as the Scruton number, is a measure of the damping or vibrating system's ability to resist destructive levels of vibration. It is based on the response of a single-degree-of-freedom system subject to aerodynamic excitation at the Strouhal frequency. The latter is the dimensionless number that relates vibration frequency to wind speed and cable diameter. The Strouhal frequency is a constant number equal to 0.2. Strouhal frequency is equal to vibration frequency times diameter divided by wind speed, all in consistent units. A thorough discussion of these concepts may be found in Sachs 1982, [1] The basic mechanism for the fluid-dynamic excitation lift force was first set down by Theodore von Karman near the turn of the century. A note of recognition is due also to work by Ramberg and Griffin, 1975, [2].

The cable vibration in a transmission line may be characterized by a high mode density, that is, the number of modes in a one Hz. bandwidth often is in the range of three to seven. Each mode will have as many as 50-100 loops per span. An accelerometer mounted to the cable will generate a signal having the appearance of narrow-band noise. The average frequency can readily be determined. The envelope of the signal fluctuates randomly, but its RMS value is closely approximated by the RMS value of an equivalent sine wave having the same frequency. Experiments that have been made in wind tunnels as reported by Diana 1971, [3] and Farquharson & McHugh 1956 [4] may be used to estimate vibration aerodynamic input energy per cycle.

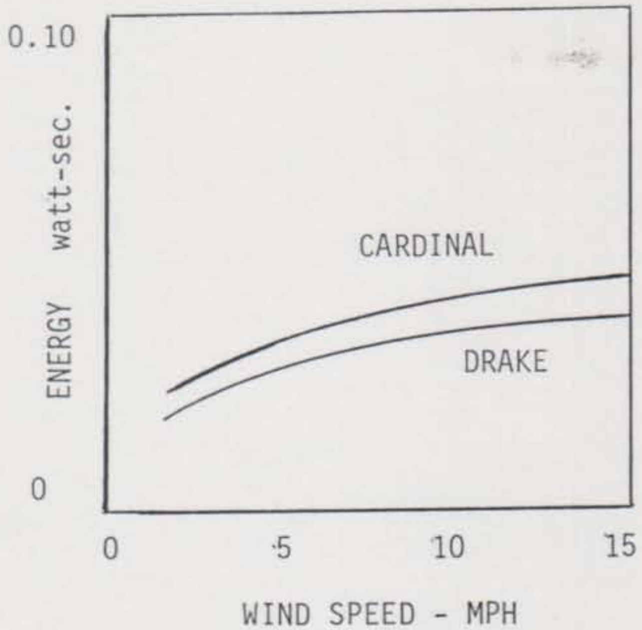

FIG.(1) Wind energy input at 200 mm/sec. loop velocity, on a span length of 1,000 ft.

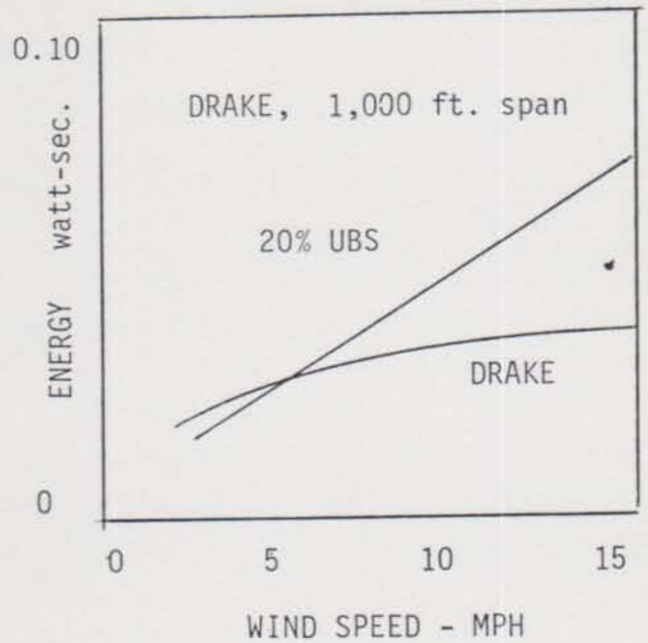

FIG.(2) Energy dissipated by DRAKE conductor at 200 mm/sec. loop velocity & 20% UBS tension

the ordinate is the wind energy and the units are respectively, miles per hour and watt-seconds. The vibration is at the IEEE limit of about 8 in. per second (200 mm/sec.). At this amplitude of loop velocity the line may vibrate indefinitely with no damage to the conductor. Thus, if the wind energy is less than the energy dissipated in the conductor no dampers will be needed.

To find out if the line can control itself without external dampers it becomes necessary to find a curve of energy dissipation for the conductor under the same conditions of vibration. The DRAKE ACSR conductor has a diameter of 1.092 in. compared to CARDINAL of 1.196 in. The rated breaking strength of DRAKE is 31.5kip, while the ultimate rated strength of CARDINAL is 33.8kip.

The energy loss for DRAKE conductor is compared to the wind energy input for DRAKE conductor in Fig.(2). The tension for the DRAKE conductor is 20%. The data were obtained in a testing laboratory in Italy by Prof. G. Diana, et al and reported in an IEEE paper in 1987. [7] The comparison in Fig.(2) shows that the self-damping of the DRAKE conductor at a tension of 20% is high enough to overcome the wind energy input above a wind speed of 5MPH. This illustrates the energy dissipation at a fixed loop velocity (200 mm/s) for DRAKE conductor. It is based on actual power measurement on a laboratory span, Diana (1987), [7]

There is another approach better suited to the present objective. This also is based on the work of Diana, and Rudolfo Claren (1971). [8] In this approach a formula is presented that has a more universal application. It is the hysteretic damping formula:

$$Wr = 1/2 \quad H\, u^2\, m^{1.5}\, S^{-1.5}\, L\, f^4 \ldots\ldots\ldots\ldots (2)$$

where, H = hysteretic damping constant (ft.-lb.)
u = vibration anti-node (ft.)
m = conductor mass (slug/ft.)
S = conductor tension (lb.)
L = span length (ft.)
f = vibration frequency (Hz.)
Wr = energy dissipation per cycle (ft.lb.)

Notice that the energy dissipation is inversely proportional to the conductor tension raised to the 1.5 power.

The hysteretic damping constant (H) allows the analysis to be performed at several values of conductor tension, rather than require the use of data from laboratory tests at various conductor tensions.

It will be noted that Equation (1) leads to results expressed in units of inch-pounds-per second, and the graph is presented in units of watt-seconds. The conversion factor between the equation results and the graph results requires first, divide by frequency (Hz), second, multiply by 1.345/12.

The conversion for Equation (2) requires only multiplication by 1.345. The Strouhal number was used to convert frequency to wind speed.

Based on the work of Diana and Claren we will use a numerical value for the hysteretic damping constant equal to 10,900 ft-lb. The conductor tested by Diana and Claren is one that is similar to the CARDINAL conductor. Results for the CARDINAL conductor are seen in Fig. (3). The energy loss follows a straight (linear) line in agreement with the experimental results for the DRAKE conductor, Fig. (2). The energy loss is calculated for two tensions, 18%UBS, and 26%RBS. Notice that the energy dissipation at 18%RBS exceeds the wind energy input over the entire wind speed range, 0-15MPH.Calculations could be made for other conductor tensions by use of Equation (2).

TENSION SELECTION:

The act of selecting tension in the CARDINAL conductor is straightforward. The 18%RBS tension is the operating tension. It has been given the name: Everyday Tension, in the literature. It is defined as the final tension, unloaded at 60 deg. F. The 18%RBS tension is therefore that tension which will assure no damaging vibration to the conductor when unloaded at a temperature of 60 deg. F.

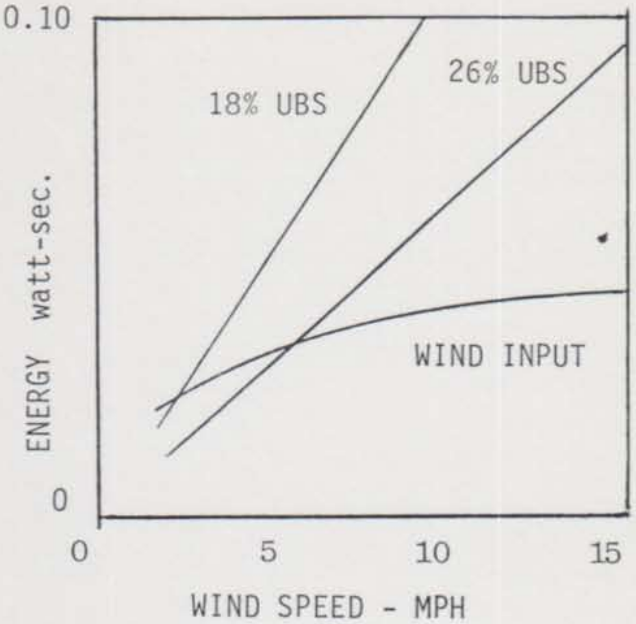

FIG.(3) Damping of CARDINAL conductor at two values of tension compared with wind energy input. Span length is 1,000 ft. Loop velocity is 200 mm/sec.

The concept of every day tension is subject to some debate, even though it has been used for more than 25 years. The applications of the results here actually are to a new transmission line being constructed in the Florida Keys. Thus, the 60 degree temperature is low compared to average for the region. In the case of a conductor in the northern regions, such as Wisconsin or one of the western Canadian provinces, the temperature should be reduced accordingly. Also, the present paper deals only with a simple illustrative energy balance methodology. In another paper, the questions of span length (longer than the present 400ft.), lower temperature exposure, and the potential trade-off between no-dampers with large sags, and dampers with shallow sags (on long spans), are to be examined. Bundled conductors will also be considered.

For a new line the tension is higher. It is called the initial tension. The initial tension drops to the final tension over a period of time because of conductor creep. The drop is most pronounced in

Table (1) Ratio of initial to final tension for 400 ft. span at 60deg.F.

Conductor I.D.	945 kcmil	336.4 kcmil	7 no. 7
Conductor Name:	CARDINAL	ORIOLE	ALUMOWELD
INITIAL TENSION %UBS	---------- RATIO INITIAL/FINAL ---------		
20	1.47	1.56	1.24
22	1.46	1.56	1.24
24	1.46	1.56	1.23
26	1.46	1.54	1.23
28	1.45	1.52	1.22
30	1.44	1.49	1.22

short spans because the creep elongation is a larger fraction of the slack. in a span of 400 ft. the ratio of initial to final tension at 60 deg. F is seen in Table 1

Reference to Table 1 indicates the ratio of initial to final tension. The table can be used to calculate the required initial tension that will allow the conductor to come to 18%UBS final, as follows:

Table 2. Initial tensions required at 60 deg.F for final tension of 18%.

Conductor	Initial Tension (%)
CARDINAL	26%
ORIOLE	26%
ALUMOWELD	22%

* Each of the above initial tension values was obtained from sag/tension table for each conductor.

* Additional analyses are required for ORIOLE and ALUMOWELD conductors to examine self-damping at 18%UBS.

CONCLUSION

(1) Wind energy input to conductor vibration is calculated from an empirical formula fitted to wind tunnel data.

(2) Conductor dissipation energy for DRAKE conductor and wind energy vibration levels are calculated from laboratory test data on a vibrating span at 20% tension.

(3) The level of vibration is at the IEEE limit of 200 mm/sec., loop velocity.

(4) An analysis of conductor test data on ACSR conductor fixes a maximum tension limit of 18% final for suitable self-damping of the CARDINAL conductor.

(5) An application of these principles leads to the maximum recommended initial tension of 26% for the conductors and 22% for the static wire, at 60 deg. F, on a span of 400 feet.

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BIOGRAPHY

Mr. Richardson is a graduate of Massachusetts Institute of Technology, having Bachelor of Science and Master of Science degrees in Aeronautical Engineering. During the 1950's he became Executive Officer of the Aeroelastic and Structures Research Laboratory, building the size of the laboratory from 50 to 100 people while also managing his own research projects with NASA and the U.S. Air Force.

In 1961, he left the laboratory, forming his own business firm known as the Research Consulting Associates. The Research Consulting Associates is augmented and supported by several other consultants, research facilities, manufacturing licensees, and other contractor firms.

Mr. Richardson is a member of the Institute of Electrical and Electronics Engineers, the Power Engineering Society, CIGRE, the American Society of Mechanical Engineers, and other business and professional groups. He has written fifty papers, technical notes, and discussions of other papers that have been published in IEEE, ASCE, IEE, CIGRE, and other journals. He has also written several articles for the trade press.

Mr. Richardson holds 19 patents, some of which have been licensed to five manufacturers. He also owns two registered trademarks, and several copyright properties.

METHODOLOGY

The wind tunnel measurements in references (3) and (4), were made in a smooth flow using single degree-of-freedom dynamic models whose axis was always perpendicular to the wind. End plates were used to encourage two-dimensional flow around the cylinders. The amplitude of vibration was limited to a maximum of one diameter or less. From the Strouhal number the maximum dynamic angle of attack was thus limited (by maximum amplitude) to approximately 40 degrees. Such large dynamic excursions of angle of attack often are accompanied by non-linear limit cycle behavior.

The investigation of Farquharson and McHugh suggested a non-linear formula to estimate the power input of a vibrating cable, when the mode shape is an assumed sine-wave

$$P = 9x10^{-8} x L x d^4 x f^3 x [2200x(y/d)^2 - 13000x(y/d)^3 + 36300x(y/d)^4] \ldots (1)$$

where, L = span length, ft.
d = cable diameter, in.
f = frequency, Hz.
y = vibration amplitude, in.
P = wind power input to vibrating cable, in.lb./sec.

This formula gives a good fit to the experimental data so long as the double amplitude (2y/d) does not exceed unity.

Most engineers would like to know if the cable requires additional damping beyond that which is already present in the cable, that is with no dampers. This can be determined by use of the above equation and certain test data on the power loss of the particular cable based on laboratory tests. The test data must be for the specific cable in the specific range of amplitudes and frequencies at the specific cable tension to be used in service. Regrettably, no manufacturer can provide this complete set of data.

An alternative methodology is illustrated herewith.

We here adopt the conservative assumption that the power input from the wind is an upper boundary which is used to SPECIFY minimum damping needed for effective vibration control. In other words, we pick a limit amplitude known to be safe, and require that dampers supply the power loss calculated from the equation at the safe amplitude. If dampers rely on a portion of the cable damping then it should be the obligation of the damper vendor to show the amount of damping for each component - damper device and cable. On the other hand, if the damper vendor can show that his device meets or exceeds the limit of power required without reliance on the cable damping, then that too is an acceptable demonstration.

Reference (5) suggests a limit of 150 parts per million as the maximum allowed microstrain in aluminum strand. This has been interpreted as the peak-to-peak maximum excursion of microstrain. For aluminum, this corresponds to a maximum peak-to-peak stress amounting to 1,500 psi.

The limit stress was related to the limit loop velocity of the vibrating cable in a paper by Pullen 1970. [6] He showed that the strain limit could be interpreted as a limit of about 8 inches per second loop velocity. Thus, the Equation (1) may be used to calculate allowed limits of amplitude y, at various vibration frequencies, subject to the Pullen loop velocity limit of 8 in./sec. Having such a combination set of y and f, the required damping can be calculated directly from Eq. (l). If a lower velocity limit is desired such as to limit the strain even more, then that too may be carried out in the same manner. The Pullen Limit in metric units is 200mm/1sec.

ANALYSIS

In Figure 1, wind energy is calculated for two different conductors from Eq.(1) on the assumption of a 1,000 ft. span. Any other span length, such as 400 ft., will be calculated by ratio of 0.4. Cable diameter affects the wind energy input in a significant way. The upper curve is for a diameter of 1.2 in. and the lower curve is for a diameter of 1.1 in. The abscissa is the wind speed, and