ELSEVIER

Electric Power Systems Research 36 (1996) 21–28

ELECTRIC POWER SYSTEMS RESEARCH

Performance requirements for vibration dampers

Albert S. Richardson

Research Consulting Associates, 3 Wingate Road, Lexington, MA 02173, USA

Received 14 July 1995

Abstract

An analysis method introduced in a recent paper has been applied to four ACSR conductors. Calculations are carried out to further illustrate the method, showing the relationship between wind energy input to the conductor and energy loss from the conductor when it is vibrating at a constant loop velocity equal to 200 mm/s. The difference between the two energy curves defines an energy gap or shortfall that must be supplied by vibration dampers. This energy gap is seen to depend strongly on the conductor tension, the conductor diameter, and the conductor span length. An illustration is given showing how well a Stockbridge damper or an impact damper fills the energy gap. One additional illustration is given applying the same principles to a triple-conductor bundle and an impact type of damping spacer. Finally, field tests conducted earlier on the four sample conductors are compared with the calculated results.

Keywords: Damping devices; Vibration dampers; Transmission line vibration; Conductor vibration

1. Introduction

It has been more than seventy years since G.H. Stockbridge, Superintendant of California Edison Company, experimented with a 230 kV transmission span of 1000 ft (300 m) length [1]. His experiments included: (i) a solid 6 ft (1.8 m) aluminum spiral wrap over a 300 ft (90 m) length of the conductor; (ii) a festoon of 660 kcmil ACSR conductor; (iii) a 30 in. (0.8 m) length of cable with two 7 lb (3.2 kg) concrete weights; and (iv) a canvass bag of loose iron pieces.

The first two did not work very well in the control of conductor vibration. The last two worked quite well. The third type has become known as the Stockbridge type of damper, and the fourth type as the impact type of damper. Both enjoy widespread use in the control of aeolian vibration today.

This paper considers the quantitative prediction of damper requirements in terms of energy or power dissipation as a function of either frequency or wind speed. The two are interchangeable through the Strouhal relation, which also involves the conductor diameter.

In a recent paper, Richardson developed the general methodology including the wind energy input and the conductor energy loss [2]. A clearly defined energy deficit exists which must be made up by external dampers. The wind energy input is based on the early work of Farquharson and McHugh [3] and the analysis of the dynamic features of the conductor span on the work of Claren and Diana [4]. The conductor span is considered to have an infinite number of vibration modes, each occurring at a discrete vibration frequency, and each having an integer number of loops in the span. At any particular time the wind may excite two or three modes which combine to form a vibration characterized by beats, or by narrow-band noise.

The maximum loop (antinode) amplitude is considered to be moving at a maximum loop velocity of 200 mm/s. Damper requirements are developed for that loop velocity (IEEE limit).

Recently a revised *IEEE Guide on the Measurement of the Performance of Aeolian Vibration Dampers for Single Conductors* [5] was published and included several recommended methods for laboratory testing of dampers. This paper is written to be consistent with that guide. In another paper, by Diana et al. [6], power measurements are presented based on the testing of a damper on a laboratory span. Two examples are given in the present paper, showing how to match either Stockbridge damper tests as in Ref. [6] or impact damper tests as in Ref. [5] with specific requirements obtained by calculation.

SSDI 0378-7796(95)01008-B

Table 1
ACSR conductors for wind energy calculation

Case no.	Ref. no	Conductor diameter		Span length	
		(in)	(mm)	(ft)	(m)
1	[7]	1.24	31.5	1484	452
2	[8]	1.24	31.5	2165	660
3	[9]	1.20	30.5	1201	366
4	[9]	1.38	35.0	1201	366

The calculation method is introduced by way of four specific examples chosen to illustrate a range of diameters and span lengths. A calculation example is also included for a triple-conductor bundle. In the case of a single conductor the effect of changing tension on vibration damper requirements is illustrated. In the case of a triple-conductor bundle an impact type of damper is matched to the power required.

Finally, the calculated results for the four case studies are compared with field test data for each case [7–9]. The method of comparison uses the loop velocity of 200 mm/s to define a 'cross-over wind speed'. That wind speed is where a balance is achieved between wind energy and conductor loss. The calculations compare favorably with the field tests.

2. Calculations

Calculations were performed using the methods described in Ref. [2]. The wind energy is based on the formula fitted to the wind tunnel data of Ref. [3]. The energy loss in the vibrating conductor is based on the formula introduced in Ref. [2], and on actual vibration tests on a span length of 144 ft (44 m) of an Ortolan ACSR conductor. Four case studies are considered having the parameters listed in Table 1. The four case studies are shown in graphical form in Fig. 1(a)–(d). The format of the graph is a plot of wind energy input and of energy loss versus wind speed.

The wind energy is a series of computed points while the energy loss is a linear curve. Each is calculated assuming that the given conductor is vibrating in sine

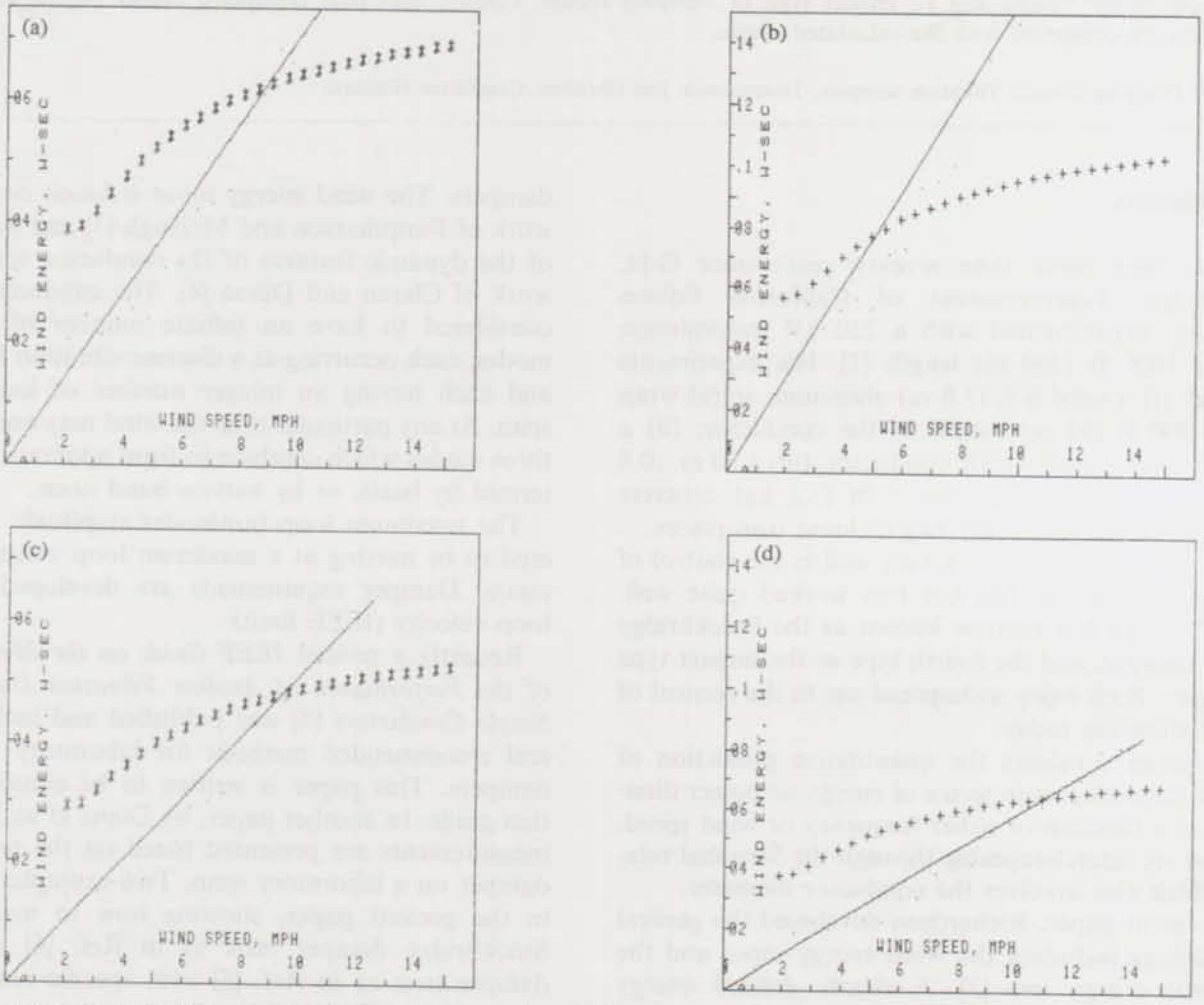

Fig. 1. Wind energy input (broken curves) and conductor energy loss (full curves) vs. wind speed: (a) case 1; (b) case 2; (c) case 3; (d) case 4.

wave motion along the span at a loop velocity of 200 mm/s. The significance of that numerical value is that it is the IEEE limit, or that vibration which will not create fatigue damage in the conductor.

Each figure shows that the wind energy exceeds the energy loss at wind speeds less than a 'critical wind speed'. Above the critical wind speed the energy loss exceeds the wind energy. Another way to look at it is to say that "above the critical wind speed no dampers are needed on that conductor span". The corollary statement is: "below the critical wind speed dampers are needed, and the difference between the two curves is the amount of damping required by dampers". By this simple interpretation it is possible to determine if dampers are needed, and how much energy the dampers must provide as a function of wind speed (or frequency).

For the present, it is sufficient to know that all four cases require dampers, and the amount of damping to be provided in each case is different. The conductors considered here in the four case studies are all ACSR conductors under tension equal to 20% of the respective UBS (ultimate breaking strength). The first two cases show the effect of span length on the same diameter, while the second two cases show the effect of diameter on the same span length. An important feature of each graph is the linear relationship between energy loss and wind speed. This linear relationship allows the introduction of a new parameter which shall be called the 'loss gradient'. It is the rate at which the vibrating conductor loses energy per unit wind speed while vibrating at the IEEE limit of loop velocity equal to 200 mm/s. Table 2 illustrates the calculated loss gradient for each of the four cases. In general, the loss gradient is a function of the conductor tension, mass per unit length, span length, and conductor diameter. It is a very important parameter in the establishment of the critical wind speed, previously defined. The critical wind speed occurs at the point of intersection of the two curves in Fig. 1.

Table 2
Loss gradient for ACSR conductors

Case no.	Stranding	Mass/unit Length		Loss gradient[a] (Ws/(mi/h))
		(lb/ft)	(kg/m)	
1	19/54	1.28	1.92	0.00722
2	19/54	1.28	1.92	0.0108
3	42/7	1.10	1.65	0.00533
4	42/7	1.45	2.18	0.00611

[a] Loss gradient here is based on 20% UBS (ultimate breaking strength).

3. Analysis of damper requirements

The question whether or not dampers are needed is a matter of balance between the energy input from the wind and the energy loss from the conductor. Here, we have assumed that any vibration of an aluminum stranded conductor that is less than the IEEE limit will not do damage to the conductor, and will therefore not need dampers if the energy loss exceeds the energy input from the wind.

To answer this fundamental question we assume that the conductor is vibrating at the IEEE limit of 200 mm/s loop velocity. We then calculate the energy input from the wind as a function of the wind speed. Next, we calculate the energy loss from the conductor, also as a function of wind speed. Comparing the two on the same graph gives the answer to the question "does this conductor need dampers, and if so how much damping is needed?".

The difference between the wind energy and the energy loss represents an energy shortfall that must be supplied by dampers. If no dampers are used the amplitude of the vibration will grow to more than the IEEE limit and reach an energy balance at a level sufficient to cause damage to the conductor. If dampers are used the amount of damping supplied must overcome the energy shortfall already identified. This is illustrated in Fig. 2. Here, the conductor studied as case 4 is under three different tension levels, 15%, 20%, and 25% (Fig. 2(a)). The wind energy remains the same but the energy loss changes according to the inverse 1.5 power of the tension [2]. The result, seen in the graph, is to enlarge the energy shortfall as the tension is increased. Numerical values of the loss gradient are, respectively, 0.00940, 0.00611, and 0.00437 at tensions of 15%, 20%, and 25%.

The actual shortfall (in watts) is plotted in Fig. 2(b) and includes a tension of 30% UBS with a corresponding loss gradient equal to 0.00332 W s/(mi/h). This shortfall must be exceeded by any proposed damper when the conductor is vibrating at 200 mm/s. Hence, the shortfall becomes a performance requirement for the damper. The performance requirement could easily be plotted as a function of frequency by employing the Strouhal relation between frequency and wind speed, namely,

$$S = \text{frequency} \times \text{diameter}/\text{wind speed} = 0.185$$

The units must be consistent.

Two types of dampers are considered. The Stockbridge type of damper (Fig. 2(c)) was tested on a laboratory test span on a conductor smaller than the conductor of case 4 [6]. The loop velocity was 200 mm/s. The impact type of damper (Fig. 2(d)) was tested on a laboratory shaker at 100 and 200 mm/s. Either method is considered satisfactory by the new IEEE guide [5].

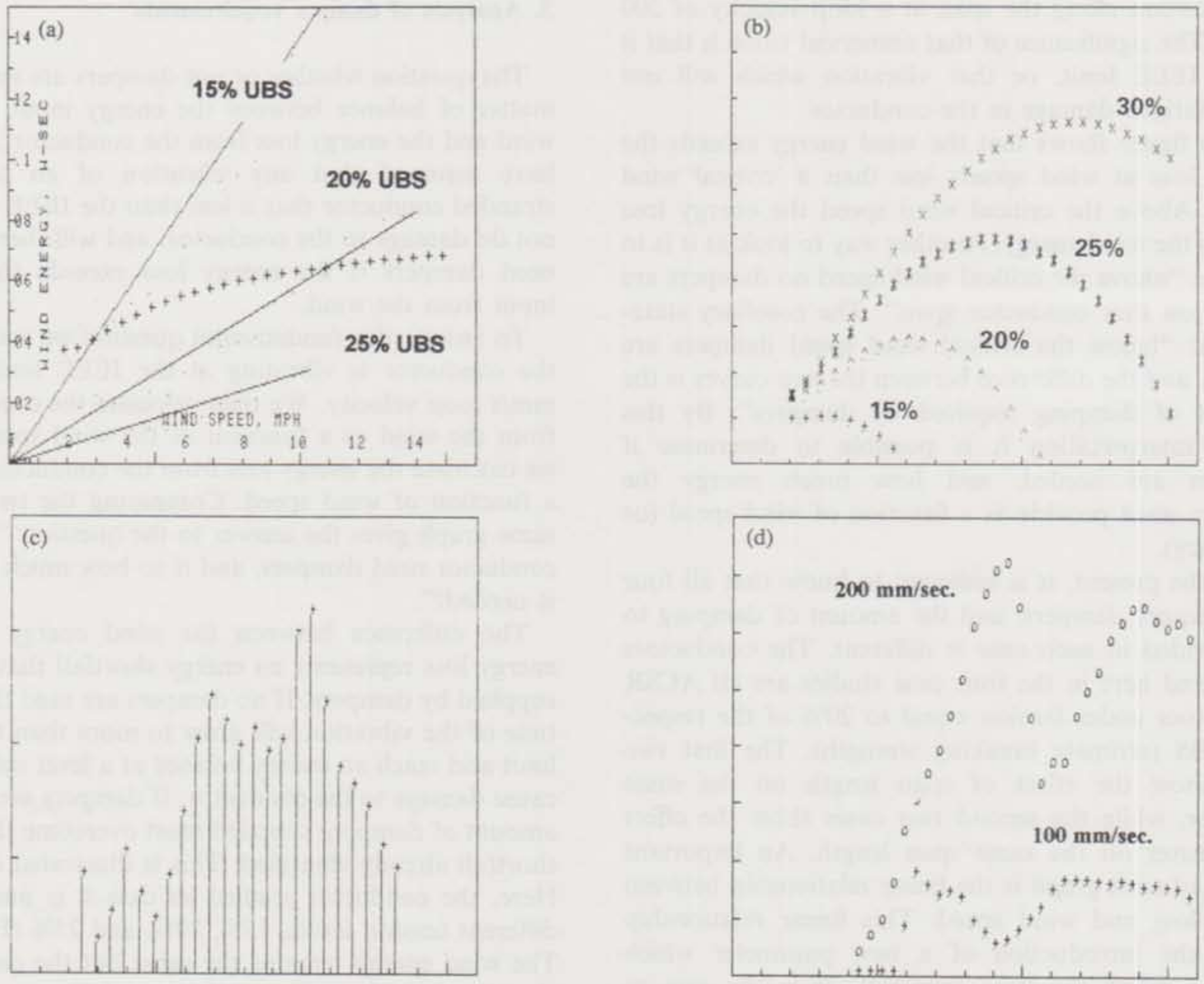

Fig. 2. Illustration of conductor case 4: (a) energy vs. wind speed; (b) power vs. wind speed; (c) Stockbridge damper; (d) impact damper. (For (b), (c) and (d): vertical scale, power (0–4 W); horizontal scale, wind speed (0–16 mi/h).)

The weight of the Stockbridge damper is 12 lb (5.5 kg) and that of the impact damper is 4 lb (1.8 kg). The velocity of the Stockbridge damper during the test varied even though the loop velocity was constant. The velocity of the impact damper was constant (100 or 200 mm/s) during its test. The lower velocity is used to simulate the lower velocity on an actual conductor when the damper is in a fixed position. The position of the impact damper on the conductor is usually chosen so that the 100 mm/s level is exceeded more than 85% of the time when the conductor is vibrating at 200 mm/s. In other words, the performance of the impact damper lies between the two curves in Fig. 2(d) 85% of the time if the damper is placed correctly.

Comparing the performance of the two dampers against the requirements seen in Fig. 2(b), it can be seen that the Stockbridge damper meets the performance requirements for tensions up to about 25% UBS; the impact damper meets the performance requirements for all tensions, except at the lowest wind speeds below 4 mi/h (1.8 m/s).

A separate study was carried out (to be reported at a future date) on the effect of modeling the conductor vibration as a sum of three neighboring vibration modes rather than a single mode. The result of that study was: (i) no effect was observed when the dampers are placed near the support point within the end vibration loop, but (ii) the vibration level out on the span is significantly out of phase among the three modes, and dampers located there are driven harder than are end-point dampers.

This suggests the use of more rugged dampers out on the span and for dampers that could combine the control of aeolian vibration with the control of galloping in a single unit. The study showed that a location at least 25% span from the support would produce the desired result.

4. Bundled conductors

The same methods may be used with bundled conductors and spacer/damper devices. The spacer/damper

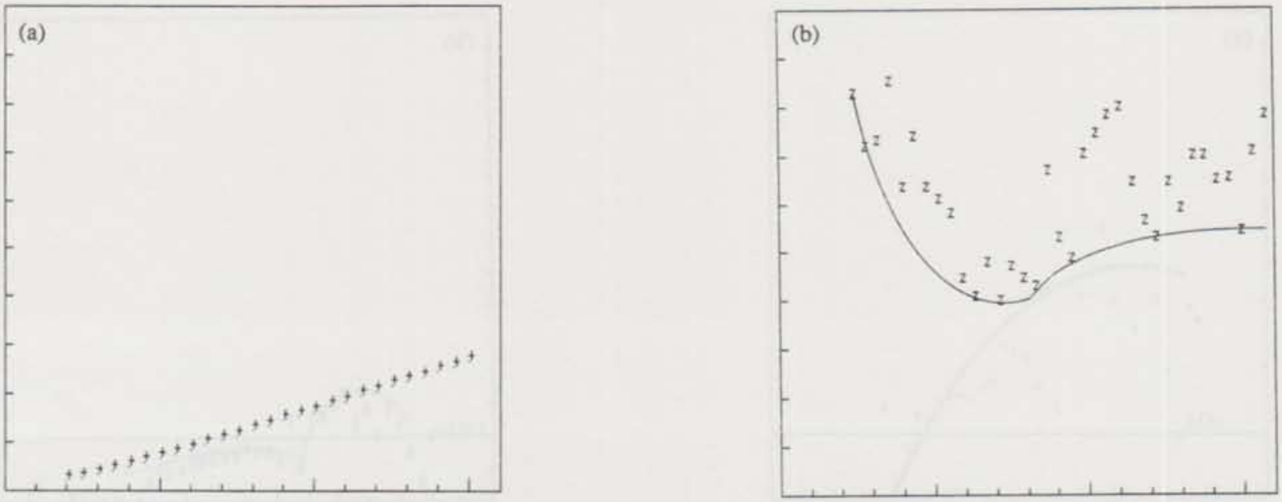

Fig. 3. Bundled conductor analysis: (a) wind power input for a triple bundled Ortolan conductor of 250 ft spacing; (b) power loss for a triple bundle spacer/damper. (Vertical scale: power (0–5 W); horizontal scale: wind speed (0–16 mi/h).)

can be mounted on a vibrator in the laboratory and tested at a constant vibration velocity over the frequency range expected to occur in service. Measurement of the power/energy versus frequency can be made in the same manner as in the cases already described. The wind energy input to the bundle can be calculated in the same way as before, but including two, three, or four conductors on the subspan length desired. Some typical results for three Ortolan conductors on a triple bundle spacer/damper having a subspan of 250 ft (75 m) are shown in Fig. 3.

Wind energy input for the Ortolan conductor is the same as for a single conductor on a span length of 750 ft (225 m). The result seen in Fig. 3(a) is the power required (in watts) assuming that there is no help in damping from the conductor; the loss gradient is assumed zero. The measured power in the triple spacer/dampers is seen in Fig. 3(b). The data points in the figure were obtained in a vibrator test on a special jig designed for the test of triple bundle spacer/dampers. The tests were conducted at the Georgia Power Research Center.

The vibrator was operated at 100 mm/s and the frequencies ran from 5 to 50 Hz. The figure shows the result of calculating the wind speed from the Strouhal number based on these frequencies and on the diameter of the Ortolan conductor. Also seen in the figure is the calculation of the wind input to a bundle of three conductors moving at a loop velocity of 200 mm/s. The difference between the wind calculation at 200 mm/s and the test velocity of 100 mm/s is because no spacer/damper ever operates at an antinode all the time. A value of 100 mm/s is considered to be a good way to account for that.

The figure shows that the triple bundle spacer/damper energy exceeds the wind energy over the entire wind speed range. No account of conductor damping is needed to verify the performance of the spacer/damper. The subspan length of 250 ft (75 m) used to calculate the wind energy for the triple bundle is somewhat larger than conventional spacing, yet the energy loss from the spacer/damper at 100 mm/s will more than cover the wind energy input at 200 mm/s.

If the span length of the bundle is 1000 ft (300 m) the number of spacer/dampers needed is three; if the span length is 1500 ft (450 m) the number of spacer/dampers needed is five. The exact location in the span is not too critical so long as all units are not exactly 250 ft (75 m) apart. Beginning at the midspan the layout of spacing for three units should be: (i) midspan at 4 ft (1.2 m) offset; (ii) one-quarter span at 8 ft (2.4 m) offset; three-quarter span at 6 ft (1.8 m) offset. The tolerance of the spacing could be ± 2 ft (0.6 m). After laying out the spacing, calculations should be made to see if any units are at whole number multiples from any other units. If so, then an adjustment in spacing is recommended.

Thus, the selection of spacer/damper units is seen to be a simple process based on some simple calculations and on laboratory test data supplied by the spacer manufacturer.

5. Comparison with field tests

The foregoing calculation results can be compared with field test results on these same conductor spans. The field tests are reported in Refs. [7–9].

The field test data are in the form of antinode amplitude plotted as a function of frequency. For the present purpose the field test results were translated to loop velocity plotted as a function of wind speed. The Strouhal number was used to translate frequency to wind speed, while the harmonic radian frequency was multiplied by the antinode amplitude to obtain loop velocity. These translated results are seen in Fig. 4.

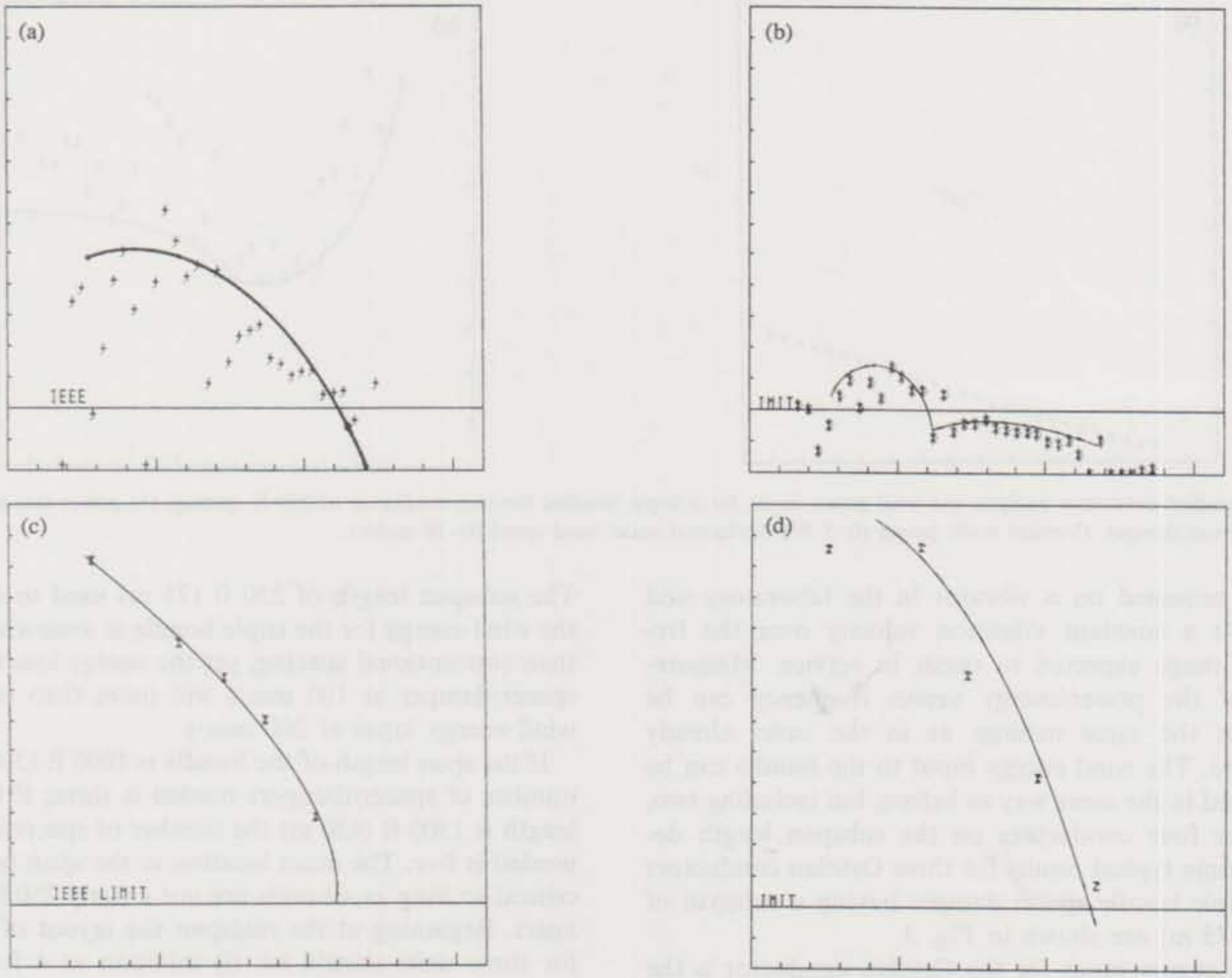

Fig. 4. Field test data of loop velocity vs. wind speed: (a) case 1, (b) case 2, (c) case 3, (d) case 4. (Vertical scale, loop velocity (0–1500 mm/s); horizontal scale, wind speed (0–16 mi/h).)

The numerical scale of the graphs is loop velocity (mm/s), from zero to 1500, versus wind speed (mi/h), from zero to 16. A numerical value equal to 5 m/s may be spotted on the wind speed scale at 11 mi/h.

Fig. 3(a) indicates a maximum loop velocity equal to 800 mm/s occurring at a wind speed at 5.6 mi/h (2.5 m/s). The wind speed at which the vibration diminishes below the IEEE limit of 200 mm/s is equal to 11 mi/h (5 m/s). The damping of the conductor is balanced by the wind input at this point. Above this wind speed the damping of the conductor exceeds the wind input, and the amplitude of vibration diminishes.

It is of interest to compare this experimental result with the crossover point calculated earlier by the intersection of wind energy and conductor loss. For example, by inspection of Fig. 1(a), that point occurs at a wind speed equal to 9 mi/h (4 m/s). This is considered to be good agreement between theory and field tests.

Continuing this process, the results seen in Table 3 were obtained. The agreement between theory and field tests is good in all four cases.

Finally, the effect of changing tensions, seen in Fig. 2(a), illustrates the sensitivity of this crossover point to small changes in tension. While the calculations were all based on a uniform tension equal to 20% of the respective breaking strength of the conductor, a small change in the tension during the field test could account for a shift in the crossover point. Considering all of the variables that enter into the field measurement of vibration, and the calculation of the energy from theory, it is remarkable that the agreement is so good.

Table 3
Comparison of field tests and calculations

Case no.	Cross-over wind speed				Max. loop velocity (mm/s)
	Field test		Calculations		
	(m/s)	(mi/h)	(m/s)	(mi/h)	
1	4.0	9	4.9	11	900
2	2.2	5	2.7	6	350
3	4.5	10	4.9	11	1300
4	4.9	11	5.3	12	1350

6. Discussion

The wind energy input to vibrating conductors is easily calculated from the formula given in Ref. [2]. The energy loss in a vibrating conductor is readily obtained from tests on laboratory spans [2]. These two energy calculations are sufficient to answer the question: "does the conductor need dampers?". If the answer is in the affirmative, then it is necessary to gather together the information from damper suppliers in a form that is suitable for analysis. The method of analysis shown here is simple, and can be used by engineers that are not skilled in the art/science of vibration. The basic question is "if dampers are needed then which damper, in combination with the conductor damping, gives the best value?"

Testing of dampers in the laboratory is most often left to the supplier of the dampers. The tests that use a conductor span are the most expensive, and those that use a vibrator are the least expensive. Typical costs for span tests are in the range of $2000–3000 including setup fees. Tests using a vibrator are in the range of $200–300 including setup. Of course, manufacturers include the cost of testing in the price of the product.

The art of vibration control is old. It goes back at least 70 years. It is time that transmission engineers apply the basics to basic design questions, and it is with the help of certain concepts and tools that the design of transmission lines with or without dampers may be achieved.

This paper has presented a simple method of calculation which determines if dampers are needed or not. It allows the engineer to vary the tension of the conductor and see immediately how that affects the problem. When dampers are needed the method yields a quantitative measure of how much damping is needed. It defines how the damping must vary according to wind speed or frequency when the loop velocity of the vibrating conductor is equal to the IEEE limit. The resulting damper performance specification is used to evaluate two types of dampers: Stockbridge and impact. The Stockbridge type of damper tends to lose effectiveness at high frequency, and the impact type at low frequency. A damper that would combine the best features of each type would appear to be the most cost effective, especially on long spans and at high tensions.

The calculations were also compared with field test data. The basis of comparison was the crossover wind speed. The wind speed is where the wind energy and the conductor loss are in balance at a loop velocity equal to 200 mm/s (IEEE limit). The comparison between field tests and calculation shows a consistent result: the calculations are 10%–20% higher than the field tests. This is a conservative result, indicating that the theory overpredicts the damper requirement.

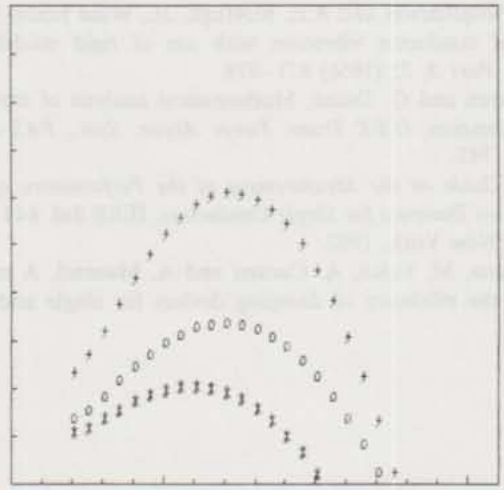

Fig. 5. Effect of conductor diameter and span length on power required: +, diameter = 31.5 mm, span = 732 m; ○, diameter = 35.6 mm; span = 366 m; *, diameter = 31.5 mm, span = 366 m. (Vertical scale, power (0–1 W); horizontal scale, wind speed (0–16 mi/h).)

Bundled conductors may also be subjected to the analysis method. An illustrative example shows how to do it. A triple bundle Ortolan conductor was chosen for analysis. Wind energy input to the bundle was based on calculations for a 750 ft (225 m) span. This is considered the equivalent of a triple bundle damper spacing equal to 250 ft (75 m), somewhat more than the usual spacing. The spacer/damper was seen to cover the frequency range with sufficient power to overcome the wind energy input without relying on any damping from the conductor itself.

Calculations were made for two conductor diameters and two span lengths of a fictitious conductor model subject to a tension equal to 30% UBS. The results are seen in Fig. 5. As expected, the larger diameter requires more damping to be supplied by vibration dampers, as does the longer span length. Notice also that longer spans and larger conductor diameters expand the bandwidth of wind speeds and frequencies over which the damper must perform.

7. Conclusions

A simple method for calculating wind energy input and energy loss in conductors has been described. The method allows the evaluation of single-conductor and bundled-conductor dampers by comparing laboratory test results with the calculations.

References

[1] G.H. Stockbridge, Overcoming vibration in transmission cables, *Electr. World*, (Dec.) (1925) 1305.

[2] A.S. Richardson, Vibration damping required for overhead lines, *IEEE Trans. Power Delivery*, *10* (2) (1995) 934.

[3] F.B. Farquharson and R.E. McHugh, Jr., Wind tunnel investigation of conductor vibration with use of rigid models, *Trans. AIEE, Part 3, 75* (1956) 871–878.

[4] R. Claren and G. Diana, Mathematical analysis of transmission line vibration, *IEEE Trans. Power Appar. Syst., PAS-88* (1969) 1741–1747.

[5] *IEEE Guide on the Measurement of the Performance of Aeolian Vibration Dampers for Single Conductors*, IEEE Std. 644 (revised), IEEE, New York, 1992.

[6] G. Diana, M. Falco, A. Curami and A. Manenti, A method to define the efficiency of damping devices for single and bundled conductors of EHV and UHV lines, *IEEE Trans. Power Delivery, PWRD-2* (2) (1987) 464–476.

[7] Aeolian vibration on single conductors: comparison between experimental and theoretical results, *CIGRE SC22 WG11 TF1, Vibration Principles, 1993*, CIGRE Paper 22-93 (WG11) 98.

[8] G.F. Diana et al., Field measurement and field data processing on conductor vibration (comparison between experimental and analytical results), CIGRE Paper 22-11, 1982.

[9] G.F. Diana et al., Comparison between analytical and experimental results of conductor vibration in turbulence conditions, CIGRE Paper 22-94 (WG11) 102, 1992, Figs. 4 and 5.