Galloping Data Base on Single and Bundle Conductors Prediction of Maximum Amplitudes

J. L. Lilien, *Member, IEEE,* and D. G. Havard, *Member, IEEE*

***Abstract*—A data base of 166 observations of galloping on single, twin, triple and quad bundle lines has been analyzed. The data base is sufficiently detailed to define the variation of maximum amplitudes of galloping motion for single conductors in 50 to 450 m spans, and for twin and quad bundles in 200 to 450 m spans. Conventional design expectations are exceeded, for maximum galloping motions on short spans, and through the existence of single loop galloping on long spans.**

New proposals are presented for estimating the maximum Galloping, motions for spans without galloping controls. The best fit numerical model for single conductors uses the peak to peak galloping amplitude over subconductor diameter, versus "conductor span parameter", the conductor diameter over the sag. The best fit model for bundle conductors uses the peak to peak galloping amplitude over subconductor diameter as a function of the "conductor span parameter".

***Index Terms*—Clearances, Conductors, Design methodology, Field data, Galloping, Mechanical factors, Modeling, Power transmission lines, Towers.**

I. INTRODUCTION

GALLOPING is a severe problem for overhead lines in some climatic conditions. Phase-to-phase flashovers may occur, leading to widespread power outages, and the conductor motions may cause high dynamic stresses on towers, damage to hardware, tower steelwork, and insulator tension strings, as well as fatigue of conductors. A useful survey of the state of the art on galloping and its control is given in [1].

Despite 60 years of observation and studies since galloping was defined [2], no fully effective way to control it has been found. Design rules for locations subject to icing normally include anti-galloping design of tower heads, which provides clearances to avoid flashovers between phases and overhead ground wires. Design procedures used, based on practical experience, are summarized in [3]. Rawlins [4], [5] presented a valuable analysis based on many galloping observations on single conductor lines. To the knowledge of the authors, no similar studies have been published for bundle conductors.

The main purpose of this paper is to suggest new trends for maximum amplitudes of galloping on single conductors and to introduce a proposal for bundle conductors. These proposals are basically deduced from 166 well documented observation cases. The data are mainly from North American power lines under freezing rain exposure. These were obtained from field studies coordinated by the Edison Electric Institute, Ontario Hydro, the Electric Power Research Institute [6], and the Canadian Electric Association [7], [8]. These data were also the subject of a simpler analysis in a recent paper [9].

II. DATA BASE RANGES

An attempt has been made to create a consistent set of information on each galloping occurrence. However, the sets of data are not complete, and some of the values provided, particularly the tension in the conductor, are not always reliable. Information on the ice coating is frequently missing, which is not surprising, considering that the ice is transparent, and there is usually poor visibility during most galloping events.

Whenever possible, supporting data describing the line were also obtained. The conductor data stored for the line section are: diameter, weight, stranding, total cross-sectional area, cross-sectional area of the aluminum, and tension at a specific temperature and ice loading condition. For each span and conductor observed, the line data stored are: description of the support system, span length, maximum galloping amplitude, number of loops, sag in the conductor at a specific temperature and ice loading condition.

The data base includes 95 cases of galloping on single conductor lines, and about 40 for twin, 3 for triple bundle and about 30 for quad bundle lines. These cases include one, two and three loop galloping. Span lengths were in the range of 40 m to about 600 meters. Figs. 1 to 5 summarize the range of key parameters, such as number of loops during galloping, span length, conductor diameter, wind speed, and unloaded sag/span length, span length, and number of subconductors.

III. DESIGN APPROACH

A global design approach must be independent of data that are unknown or unavailable for particular cases and for which only ranges are known, like wind speed, ice accretion, etc. It is desirable to find dimensionless parameters for which maximum amplitude would follow some "universal" curve which can be fitted to the data available. There are so many parameters included in the galloping phenomena that the best way to investigate is to start from a physical point of view, which can be deduced from the basic equations of galloping [10]–[15].

Also in the development of the earlier analysis of single conductor galloping Rawlins [4], [5] noted the importance of the *catenary parameter* of the line, that is T/w, the ratio between the tension per conductor (T) and the weight of the conductor ($w = mg$). The catenary parameter in our data base is in the range of 500 to 2500 meters. Rawlins also introduced a factor

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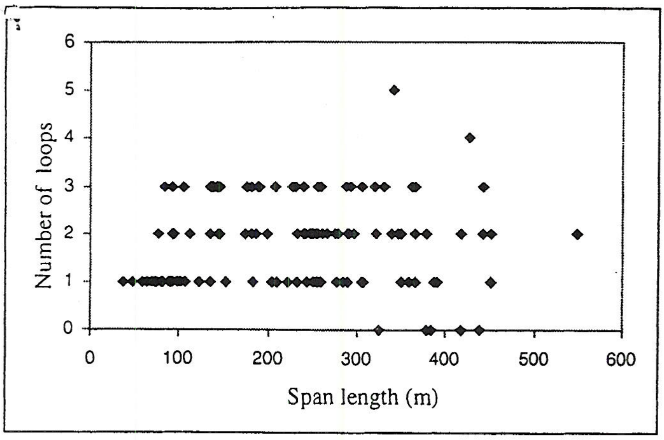

Fig. 1. Data base range for galloping loops observed vs. span length. Mixed modes, travelling waves or no data are shown as zero loops. Note good distribution of one, two and three loop modes for span lengths between 50 and 0 m.

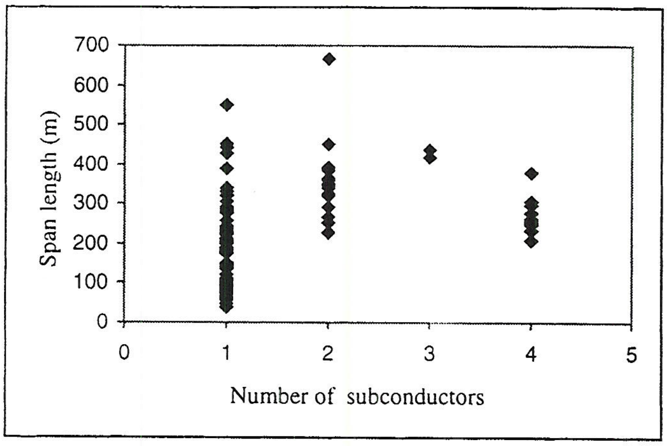

Fig. 2. Data base range for span length vs. different kinds of bundle. Logically there are no short spans for bundles. There are too few cases for analysis of triple bundles.

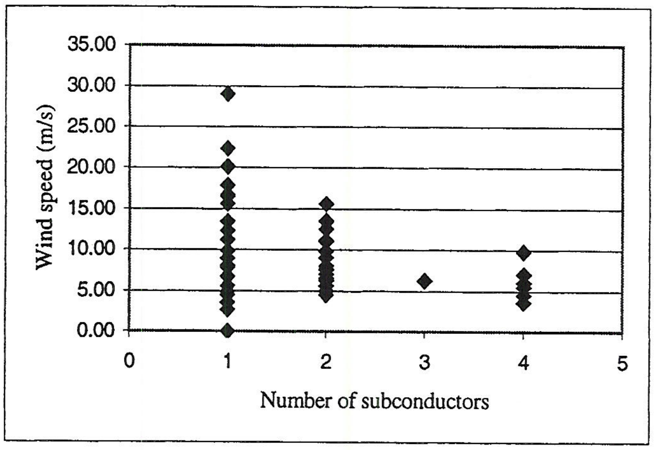

Fig. 3. Data base range for wind speed vs the number of subconductors. There is good coverage for single and twin bundle cases.

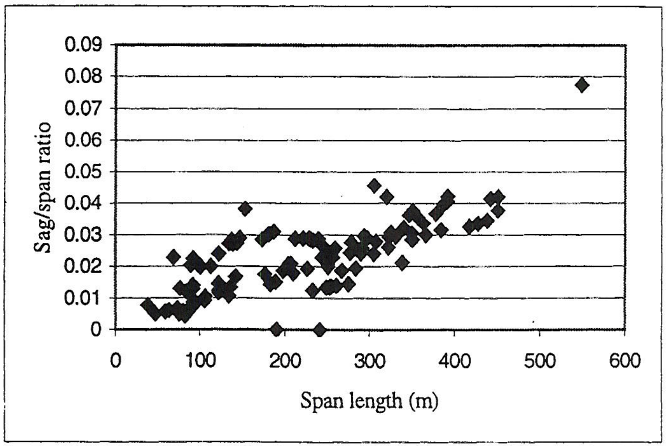

Fig. 4. Data base range for sag/span ratio. There is good coverage for span lengths between 50 and 450 m.

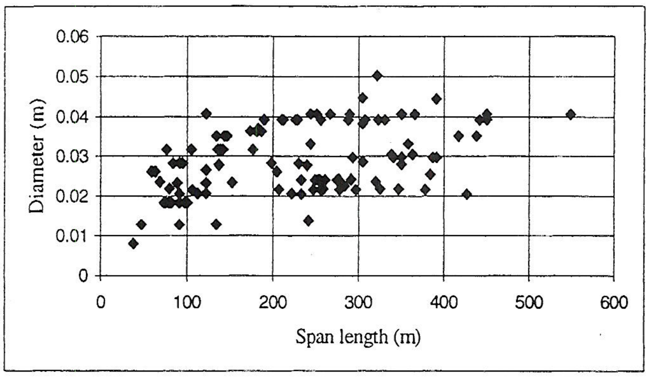

Fig. 5. Data base range for subconductor diameter versus span length. Note that there is good overall coverage

"M" very close to the *structural factor* defined by Irvine [16], but also depending on the suspension hardware. That factor was in direct relationship with the basic vertical frequencies of the line, which suggests why dead-end spans and suspension span have different one loop galloping modes due to the interaction between spans.

There was not enough information on the line section for all cases, so that such factors could not be included in this analysis. But a design approach is of greatest application to suspension spans, the most frequent design, and this study focuses on that arrangement.

IV. THE CONDUCTOR SPAN PARAMETER

This study employs the *reduced amplitude*, which is the ratio of peak-to-peak galloping amplitude ($A_{pk\text{-}pk}$) over conductor diameter (ϕ), both in m:

$$\frac{A_{pk\text{-}pk}}{\phi} \tag{1}$$

This reduced amplitude has a range between 0 and 500.

The *conductor span parameter* is a combination of the catenary parameter with the ratio of conductor diameter (ϕ) over the square of the span length (L), which can also be expressed as the ratio of conductor diameter over the sag The conductor span parameter is dimensionless:

$$100\,\frac{T.\phi}{mg.L^2} = \frac{100.\phi}{8f} \tag{2}$$

This parameter has a range of 0 to 1.1 with tension in N, mass in kg/m, span length, sag and diameter in m.

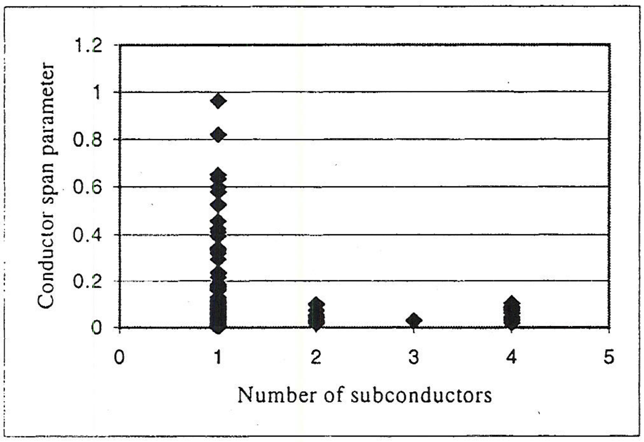

Fig. 6. Conductor span parameter as a function of number of subconductors. This shows a clear distinction between single and bundle conductors, and the similarity among all types of bundle conductor.

It must be pointed out that the introduction of the ratio, diameter over the square of the span length, has already been discussed by Rawlins [4] and called the *torsional compliance parameter*. But another parameter was used in his approach, where he defined a combined parameter which ultimately reduced to the catenary parameter. The dimensionless conductor span parameter is preferred which shows clear trends on the global data base.

The conductor span parameter has the range of values in the data base as shown in Fig. 6.

V. DATA BASE INVESTIGATIONS

Figs. 7 and 8 show how the observed maximum amplitudes of galloping from the data bases for single and bundle conductors respectively, vary as functions of the two chosen parameters. The process used for fitting the curves for the maximum values is explained in the next paragraph. These two curves have been chosen after extensive investigation and were the only ones for which clear trends could be seen.

VI. FITTED CURVES FOR MAXIMUM AMPLITUDE

For single conductors, the fitted curve to the maximum amplitude over conductor diameter, which is included in Fig. 7, is given by:

$$\frac{A_{pk\text{-}pk}}{\phi} = 80.\ln\frac{8f}{50.\phi} \tag{3}$$

This is valid only in the 0–1 range of the conductor span parameter, which corresponds to the data base range.

For bundle conductors, the corresponding fitted curve, which is reproduced in Fig. 8 as the estimated maximum, is given by:

$$\frac{A_{pk\text{-}pk}}{\phi} = 170.\ln\frac{8f}{500.\phi}. \tag{4}$$

This is valid in the range 0–0.15 of the conductor span parameter.

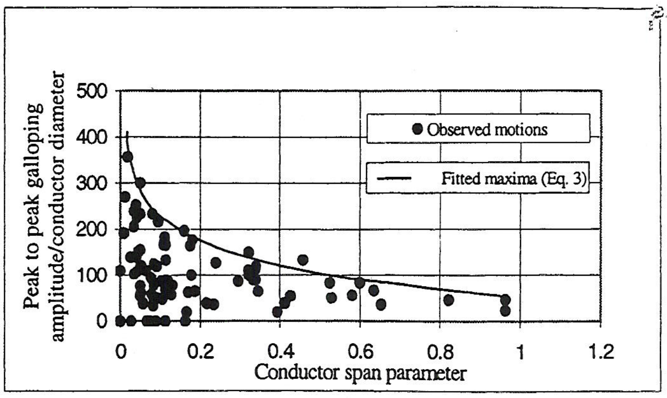

Fig. 7. Variation of observed maximum peak to peak galloping amplitude/diameter on single conductors as a function of the conductor span parameter

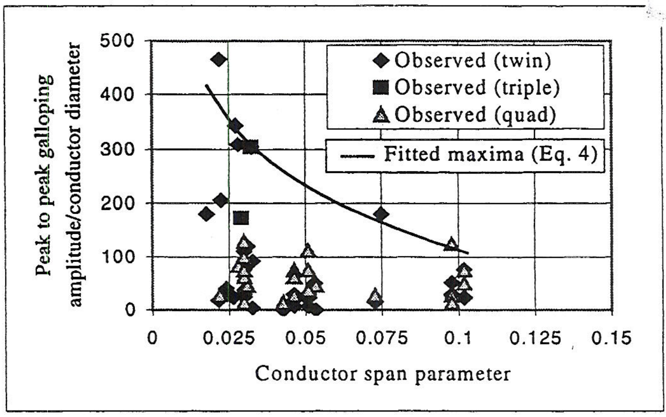

Fig. 8. Variation of observed maximum peak to peak galloping amplitude/diameter on bundle conductors as a function of the conductor span parameter.

It may be noted that the expressions have the same form, but single conductors have up to about 2.5 times larger values of galloping amplitude/diameter for values of the conductor span parameter between 0.015 and 0.10.

Another way of showing the same result, would be to express the ratio of galloping amplitude to the sag, by adapting former formulas to obtain:

$$\frac{A_{pk\text{-}pk}}{f} = 80.\frac{\phi}{f}\ln\frac{8f}{50.\phi} \tag{5}$$

for single and

$$\frac{A_{pk\text{-}pk}}{f} = 170.\frac{\phi}{f}\ln\frac{8f}{500.\phi} \tag{6}$$

for bundle conductors.

The resulting curves are shown in Figs. 9 and 10. No clear trends have been found based on these curves, showing that amplitude over diameter correlates better with the data than amplitude over sag.

It should be noted that the observed galloping amplitude on single conductors can reach up to 5 times the unloaded sag. In the context of distribution line conductor spans and sag, this indicates much larger galloping motions than conventionally considered in design [17]. Also the data show a significant number of single loop galloping events on long spans, which is at variance with the above design guide.

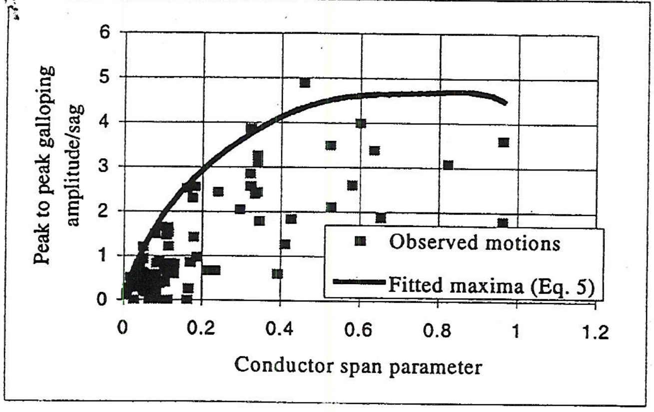

Fig. 9. Variation of observed maximum peak to peak galloping amplitude/sag on single conductors as a function of the conductor span parameter.

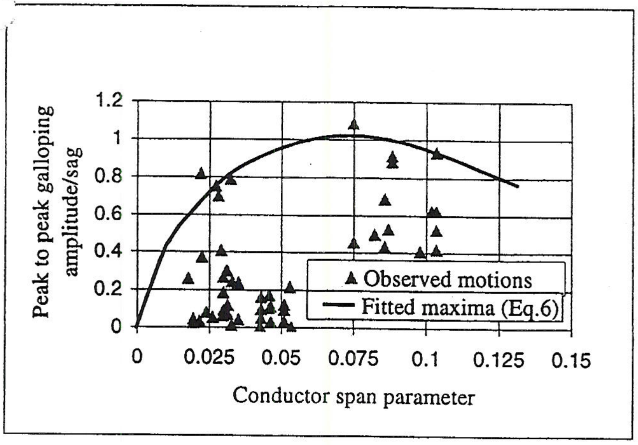

Fig. 10. Variation of observed maximum peak to peak galloping amplitude/sag on bundle conductors as a function of the conductor span parameter.

As illustrated in Fig. 10, the data base is a little too sparse for bundle conductors. The maximum amplitudes are thought to be lower than reported anecdotally.

There are well known cases of severe galloping which could not be included due to lack of supporting data such as the line parameters, notably tension. One example is the famous video taken during a four day episode of galloping on a quad bundle line in the United Kingdom in 1986 and shown during the CIGRE session which clearly showed large amplitudes, similar in magnitude to the sag. This is not indicated for similar size bundle conductors in the data base. In fact, physical differences, such as the tuning between vertical and torsional frequencies can be different on a quad compared to a twin bundle, but this is very dependent on anchoring and suspension hardware. The effects of such differences on galloping amplitudes may only become apparent in a much larger data base.

VII. Numerical Simulations

Numerical simulations were mainly performed using the model described in [15], with some using a more recent finite element approach. These are full 3 dimensional simulations, including torsional freedom, and they model a full line section. They use a data base of aerodynamic lift, drag and moment properties of ice coatings from many different sources. Single

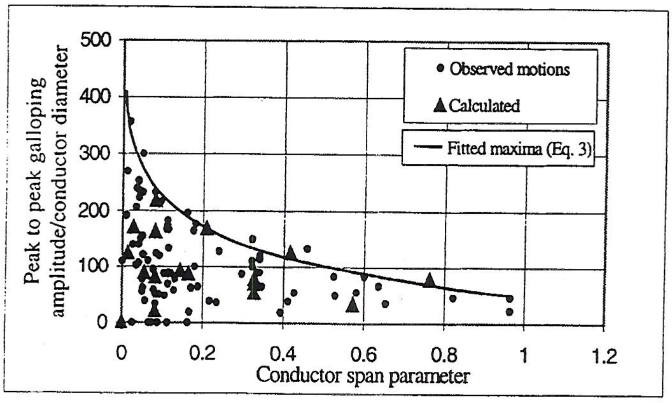

Fig. 11. Numerical simulations of 17 single conductor galloping events added to Fig. 7 showing amplitude/diameter as a function of the conductor span parameter.

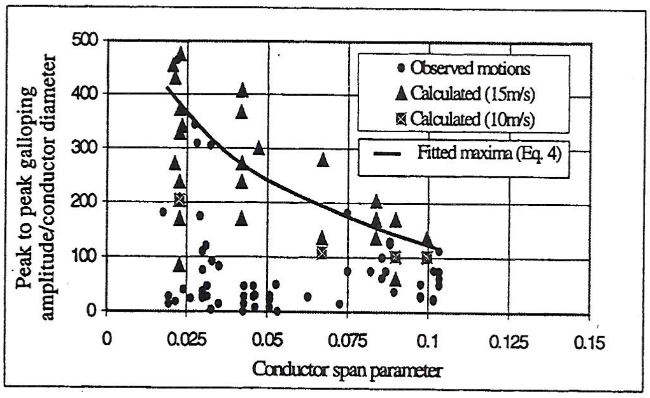

Fig. 12. Numerical simulation of 25 bundle conductor events superimposed on Fig. 8 showing amplitude/diameter as a function of the conductor span parameter.

conductor computations were performed on span lengths between 40 and 450 m with conductor of either 1.8 or 2.8 cm outside diameter. The ratios of line parameters used, e.g. sag/span, were chosen to represent the values in the data base of field observations.

The ice profile chosen was very unstable in the sense of the Den Hartog criterion. Wind speed and ice position were varied in order to obtain maximum possible amplitudes. Some 17 cases are reported in Fig. 11. Galloping amplitudes can be as large as several times the initial sag (with ice), mainly occurring on very short spans. In those cases, there is very often a mixed mode combining one, two and three loops, giving the impression of travelling waves.

For bundle conductors, as shown in Fig. 12, the conductor span parameter range is much smaller than for single conductors. Also the wind speeds in the data base are limited to <10 m/s for values of conductor span parameter larger than 0.04, except one case. The wind speed reached 15 m/s only for small values of the conductor span parameter.

Bundle conductor galloping is much more influenced by structural data and coupling with torsion is an important factor. There is a need to increase the number of cases to determine trends, if any. The numerical simulation was of a twin bundle, 2.95 cm subconductor diameter with 0.457 m subconductor spacing, in a section of two 340 m spans, with 7 different ice profiles. For each case, the most dangerous ice position and wind speed in the range 0 to 15 m/s have been evaluated. The general trend is similar to the observed cases, but the predicted amplitudes, for wind speed of 15 m/s are higher than observed data for all values of the conductor span parameter.

There is no clear explanation for this but the limited range of wind speeds for the field data may exclude extreme values. Fig. 12 includes four calculated data points with winds of 10 m/s, and these amplitudes are similar to the maxima of the observed data with the same wind speed, but sensibly lower than actual maximum fitted curve on the few observed cases at higher wind speed. There is also one experimental data point located beyond the best fit curve, and which is indeed closer to the simulated results. But it is clear that more field data on bundle conductor galloping are needed before maximum values can be defined to compare with calculated maxima, as well as to define a design rule.

VIII. CONCLUSIONS

The study described here is a step toward more rational design of clearances in tower heads to avoid clashing of single or bundle conductors due to galloping.

The conductor span parameter is identified as useful basis for scaling maximum amplitudes of galloping on both single and bundle conductors.

When the amplitude is divided by the conductor diameter a similar form of dependency on the conductor span parameter is identified. The extreme values of relative motions (amplitude/sag) on single conductors are found to be up to 2.5 times as large as on bundle conductors in the common range of conductor span parameter.

When the galloping amplitude is divided by sag, as conventionally done in design of galloping clearance ellipses, a poorer correlation with the conductor span parameter is obtained.

More experimental data are needed for bundle configurations to get better confidence in the suggested curves describing maximum galloping motions.

Numerical simulation of galloping events using 3 degree of freedom modeling is shown to represent observed results reasonably well, especially for single conductors.

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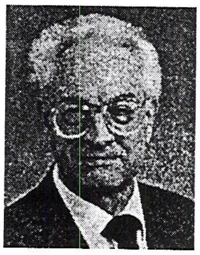

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