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Predicting galloping fatigue cycles in quad bundles

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Summary

The prediction of fatigue damage in a transmission line span is complicated by the wide range of possible ice, wind, frozen snow, time duration, and other variables. Present state of the art will not allow a deterministic prediction of fatigue damage, or fatigue life. The mechanism responsible for galloping itself is not subject to universal agreement, even after 50 years of research. Curiously, there is a better accord amoung the experts regarding the root cause of galloping in bundles than in singles.

Here, we use an analysis and a gallop scenario that is a representative consensus, as applied to a quad bundle gallop. The object is to predict worst case fatigue cycles, and associates worst case loading of support structures. The methodology is inclusive of (1) aerodynamic loading based on actual ice shape wind tunel tests, (2) quad bundle dynamics, twisting plus gallop, (3) structural loads on both suspension and strain towers, (4) special effects of torsional damping and other parameters. An illustrative example is used to bring out the important conclusions where the example is selected from recent reported actual cases of severe galloping in quad bundled line in the U.K.[19] and in Japan[21]

Keywords

Galloping - tension variations - frequency - amplitude - stability - damping - anti-galloping device -

I. Galloping loading and dynamic tension

1) Frequency domain of mechanical tension oscillation.

Loads applied to strain towers :

Taken into account the anchoring tower stiffness(K), tension variation for a whole section (total length L) of Ns spans (of length Ls) is given by (A=cross section of one phase , E Young modulus) :

$$\Delta T = \frac{EA}{L}\left(\Delta l - \frac{\Delta T}{K}\right) = K_{ev}\,\Delta l \quad \text{(Hooke's law)} \qquad (1)$$

$$\text{where } L = \sum_{s=1}^{Ns} L_s \quad \text{and} \quad \frac{1}{K_{ev}} = \frac{L}{EA} + \frac{1}{K} \qquad (2)$$

In order to compute length modification of the whole section, an original approach is given by modal decomposition (let's "k" be the number of the mode, generally restricted to 1 , 2 or 3) of the cable oscillation in each spans and to deduce the length, by the rectification formula.

If $y(z,t)$ is the sag value at abscissa z and time t, let's $y_{s,k}$ be the sag modal amplitude of the mode k on the span s; in such a way we obtain (see notation in appendix) :

$$\Delta T = K_{ev} \sum_{s=1}^{Ns} L_s \sum_{k=1}^{modes} \left(\frac{k\pi}{2L_s}\right)^2 \left(y_{s,k}^2 - y_{s,ko}^2\right) \qquad (3)$$

with $y_{s,ko}$ the modal sag value in static equilibrium

example 1 :

mode :only one mode is concerned (one loop galloping)

L_s :constant on each span = L/Ns

$$\Delta T = K_{ev} \frac{\pi^2 N_s}{4L} \sum_s \left(y_s^2 - y_{so}^2\right) \quad \text{or} \qquad (4)$$

$$\Delta T = K_{ev} \frac{\pi^2 N_s}{4L} \sum_s \left(2y_{so} + \Delta y_s\right)\Delta y_s \qquad (5)$$

with $\Delta y_s = y_s - y_{so}$

a simple formula from which we can deduce the frequency domain of mechanical tension oscillation :

- for a dead-ended span the dominant frequency is the frequency of the sag oscillation (we neglect Δy_s before the sag)
- for a multi-span section we generally observe the so called "up and down" galloping (one loop down,

one loop up, etc.. on following spans). In this case it exists a full compensation $\left(\sum_s \Delta y_s = 0\right)$, the second order term only remains and the frequency will be the double of sag oscillation.

- Due to the non-linear structure of the equations it is possible to show that starting from a pure up and down mode, an "in-phase" galloping (each span oscillates in phase) will appear. Despite the fact that its amplitude , superimposed to the up and down mode, can be rather small (not visible at a first glance), the corresponding tension variation is generally not negligible. Finally it is a matter of fact that tension oscillation frequencies include both upper values.

example 2 :

mode :only the second mode is concerned (two loops galloping)

Ls : constant on each span = L

The tension variations are simply reduced to the simple form (see (3)):

$$\Delta T = K_{ev} \frac{\pi^2 N_s}{L} \sum_{span} \Delta y_s^2 \qquad (6)$$

Those considerations point out that ΔT has the same oscillation frequency as Δy_s^2 for the two loops modes galloping , that means the double frequency of the sag oscillation.

Important remark.

In the preceeding discussion we only detailed the behaviour of transverse wave oscillations, which are clearly visible by any galloping spectator. But there is another , sometimes dangerous one, which is only visible on tension oscillogramms. This wave, the longitudinal one, has a fundamental frequency higher than usual frequency of galloping. But harmonics of tension related to vertical galloping may be tuned to the longitudinal frequency. This fact has been recently pointed out during a galloping in Belgium on april 1989. The danger is the proximity of this wave with the first frequency of the anchoring tower. Fatigue cycles can then be occured during several hours at a frequency about 2 Hz. The Belgium recording clearly showed a 1.52 Hz (four times the tension frequency) of 5kN amplitude which lasts during about 10 hours. This oscillation occured during a two loops galloping mainly active (about 3 m peak to peak) on one span of the four spans section (unspacered twin bundle 2 x 620 AMS)

The 1.52 Hz observed frequency can be explained by longitudinal wave propagation all along the section (1548 m). In fact the speed of this wave is about 5000 m/s following the relationship :

$$\text{speed} = \sqrt{\frac{E}{\rho}} \qquad \text{frequency} = \frac{1}{2L}\sqrt{\frac{E}{\rho}} \qquad (7)$$

with ρ : volumic mass of the cable (Kg/m^3)

E : Young modulus (N/m^2)

L : section span length (m)

Taken into account the Villeroux test station characteristics :

$\rho = 2700\ Kg/m^3$

$E = 5.9\ 10^{10}\ N/m^2$ ==>frequency= **1.51 Hz**

$L = 1548\ m$

(four suspended spans of 361, 361,397,429 m)

Thus a very clear recommendation about section length can be done in direct correlation with strain tower frequency : avoid this resonance case.

<u>Galloping numerical simulation</u>

We have simulated (fig.1) a free two loops oscillation (see fig.1) on the section of Villeroux. The software used was SAMCEF-CABLE, written in the university of Liège. The two loops were imposed only on the second span of the section. The results shows very clearly the three observed frequencies The simulated phenomenon fit quite accurately with the experimental oscillogram.

Moreover mechanical tension variation of 5kN , close to the recordings, has been obtained for a peak-to peak amplitude (at a quarter of the span 2) of 3 meters which is exactly the measured amplitude (owing to the film taken during the observation).

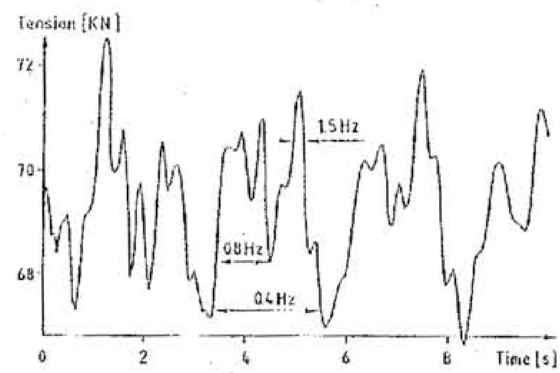

Fig.1 Two loops in the second span of Villeroux test station.
Tension in the strain insulator at end of the section (simulation by SAMCEF)

<u>A few words about loads on suspension strings</u>

At the suspension point the slopes of both adjacent spans are different so in spite of the fact that axial tension is rather constant all along the section, the suspension string exhibit tension variations.

The string displacement will oscillate at the same frequency as the mechanical tension applied to strain towers. Let's notice that we neglect inertial effect of the chain.

As far as the mechanical tension in the string is concerned, as we can see on the drawing, this value is mainly concerned by the vertical component of the mechanical tension in the cable. Thus both the *displacement* of the *conductors* and the tension in the conductors will influence it . In a first approximation (see fig.2) :

$$T_{iso} = (T_0 + \Delta T)\ (\varphi_1(t) + \varphi_2(t)) \qquad (8)$$

$\varphi(t)$ is depending of the modal shape at time t thus T_{iso} exhibits always a frequency equal to those of the displacements and frequencies which are combination of ΔT and displacements .

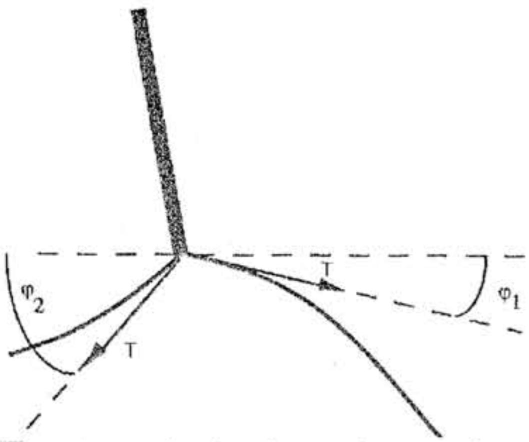

Fig.2 Suspension insulator string at a given position during galloping.

2) Amplitude of tension variations

The problem of galloping is a very complex one. The problem which is still open is to know, for a given line, the possible galloping modes and the respective amplitudes.
The main difficulties are connected to ice shapes prediction and corresponding aerodynamic coefficients of drag,lift and moment. The wind action (amplitude and orientation) and the characteristics of the line (torsional stiffness, etc..) will fix initial conditions prone to galloping or not. It is nowadays a matter of fact that on quad bundle , Den-Hartog mechanism is possible on very thin ice shape facing the wind . Another easier way, but artificial, to force Den-Hartog is to put a D shape profile on the cables but this shape is completely unprobabilistic in practice.
The most general case of quad bundle instability is connected to the coupling between torsion and vertical frequency. Despite the fact that a quad bundle has a very high torsional stiffness, the natural resonance between those two movements make the bundle unstable for a wide range of ice orientation facing the wind. The most critical ice orientation is generally around 0° facing the wind. The torsional characteristics of the phase has a very big impact on the instability and on the amplitude. So that it can be proved that it exists a minimum and a maximum wind speed for which galloping could occur.

In order to compute tension oscillation , we have to know which kind of modes are possible (one, two, three loops or mixed) and of which amplitude.

When Den-Hartog criterion is satisfied, a lot of modes can be excited and any mixture is possible. Provided that wind speed is high above critical speeds, with torsional instabilities only the modes for which both vertical and torsional frequencies (evaluated in the presence of wind and ice) will be close enough, will rise to significant amplitude. It has been demonstrated [20] that for quad bundle vertical and torsional first frequency may significantly differ, this is not the case for horizontal twin bundle. Thus for quad bundle, higher modes (two and three loops) are generally more prone to galloping.

3)Applications to quad bundle geommetry

A very interesting report published in CIGRE 1974 [21] mentionned a lot of experiments results on two quad geommetry (4x410 ACSR , 4x950 ACSR). Artificial D foil has been inserted on the 4x410 bundle, so that many occurences have been recorded. Only few cases with natural icing on 4x950 have been recorded . The major interest of a large set of records is to guess what could be the extreme values of tension variations and amplitudes (with modal shape) for the given geommetry, and a given kind of instability; very probably a Den-Hartog one due to particular artificial D profile.

phase characteristics of the Kasatori-Yama line [21] :

cross section 4x410
mass per unit of length (including D profile) : 6.7 kg/m
extensional stiffness : $EA = 123 \; 10^6$ N
mechanical tension (without wind) : 61500 N per chain = 123000 N per phase
we have made the calculations for infinite anchoring stiffness of the towers.

calculated sag : 6.5 m

vertical modal analysis (2 spans of 312 and 319 m) :

one loop (up and down)	:	0.23 Hz
pseudo-one loop	:	0.36 Hz
two loops	:	0.46 and 0.47 Hz
three loops	:	0.68 and 0.70Hz

Observed amplitudes (peak-to-peak) :

two loops(dominant) + one loop : between 2 and 4 m , some occurences reached 5 m.
The superposition of one and two loops give the impression of a travelling wave to the observer , but it is only an impression !!
Wind conditions : wind bigger than 12 m/s.
Corresponding tension variations :
strain insulators : 20000 to 74000 N per chain (2 chains per phase)
suspension insulator : 10000 to 35000 N

Three loops : between 1.5 and 2 m,
Wind conditions : only for wind between 7 and 12 m/s
Corresponding tension variations :
strain insulators : 20000 to 35000 N per chain (2 chains per phase)
suspension insulator : 15000 to 25000 N

Pseudo-one loop : between 0.5 and 1.5 m,
Wind conditions : only for wind between 7 and 18 m/s
Corresponding tension variations :
strain insulators : 10000 to 45000 N per chain (2 chains per phase)
suspension insulator : 2500 to 15000 N

Observations are limited to wind speed between 0 and 25 m/s

Assuming a Den Hartog galloping , it is possible to deduce, from amplitude , frequency and wind speed, the range of angle of attack : it is about 0.7 radians or 40° peak to peak . Let's notice that that value could have been deduced more precisely from aerodynamic properties of the D type profile used , but we haven't received any information about it.
We know that , even with Den-Hartog instabilities , there is a saturation phenomena , or evanescence when the wind is increasing , due to quasi-static torsional effect. This effect is very clear on the figures detailed in [21].

A very important conclusion can be drawn from the numerous observations on the Kasatori-Yama line :
For the same aerodynamic profile (artificial D foil) and the same wind speed (at about 14 m/s) it is possible to have no galloping, galloping with "pseudo one loop" of *any* amplitude between 0 and 1.5 m , galloping with "pseudo+two loops" of *any* amplitude between 1.5 to more than 5 meters. And the obvious corollary that tension variations both in the strain insulators and in the suspension insulators can be , in the same condition of galloping, in a very large range between 2500 and 70000 Newtons. *From another side the same galloping amplitude (say 3 meters) can be obtained from very different tension variations (between 20000 and 60000 N for strain insulators and from 10000 to 30000 for suspension insulators)*
So it is not obvious at all that galloping amplitudes may be deduced from tension recordings.
The physical reason of such big range of tension variations for a given amplitude is connected to possible mode "mixture". In fact the presence of the pseudo-one loop in the two loops mode can have a major influence in the tension variation as explained earlier.

Some simulations will give to the reader some more clear idea about this complex situation.

First simulation on the Kasatori-Yama line : Den-Hartog galloping on the 4x410 ACSR, with 4m amplitude for the two loops and 0.6 m amplitude for the one loop superimposed, wind speed about 14 m/s. Fig . 3 is the detailed tension oscillogramms both in strain insulator and in suspension insulator. We have joined the Fourier analysis of the same curves.

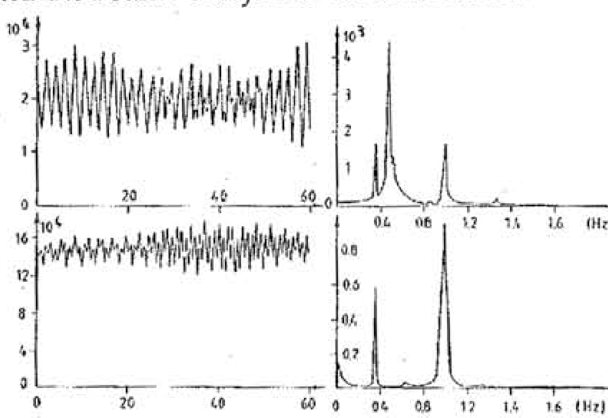

Fig. 3 Computed tension oscillation and corresponding Fourier analysis during mixed one (0.6m) and two (4 m) loops galloping. on a 4x410 ACSR.
Upper part : suspension string (initial value=21000 N)
Lower part : anchoring string (initial value=123000 N)

The simulated results shows a peak to peak 60000N (that means a 30000 N per chain) variation not symmetrical to initial value. The frequencies are mainly 0.36 Hz (pseudo-one loop) and 0.94 Hz (the double of the two loops oscillation at 0.47 Hz) . In the suspension string a peak to peak 20000 N tension variation rather symmetrically distributed around initial value (21000 N) with frequencies 0.36 Hz, 0.46 Hz (dominant) and 0.92 Hz. The 0.46 Hz is the frequency of cable two loops oscillation, the presence of which has already been discussed.

Second simulation on the Kasatori-Yama line : Den-Hartog galloping on the 4x410 ACSR, with 4m amplitude for the two loops and 2 m amplitude for the one loop superimposed,
wind speed about 14 m/s. Fig . 4 is the detailed tension recordings both in strain insulator and in suspension insulator. We have joined the Fourier analysis of the same curves.

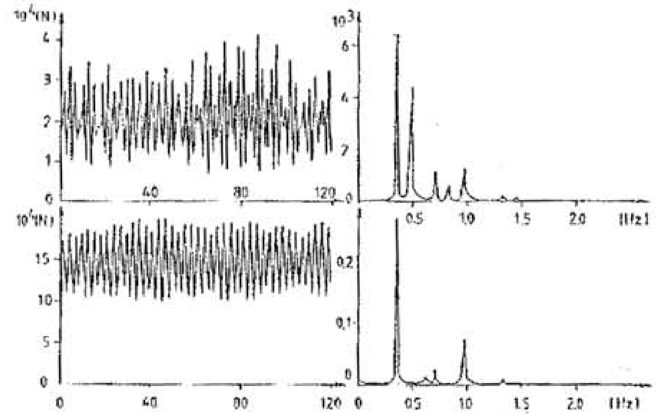

Fig.4 Computed tension oscillation and corresponding Fourier analysis during mixed one (2 m) and two (4 m) loops galloping. on a 4x410 ACSR.
Upper part : suspension string (initial value=21000 N)
Lower part : anchoring string (initial value=123000 N)

The simulated results shows in the strain insulator a peak to peak 90000N (that means a 45000 N per chain) variation not symmetrical to initial value. The frequencies are mainly 0.36 Hz (pseudo-one loop) and 0.94 Hz (the double of the two loops oscillation at 0.47 Hz) . In the suspension string a peak to peak 30000 N tension variation rather symmetrically distributed around initial value (21000 N) with frequencies 0.36 Hz(dominant) , 0.46 Hz and 0.92 Hz. The 0.46 Hz is the frequency of cable two loops oscillation, the presence of which has already been discussed. As a complementary information deduced from the simulation, the displacement of the suspension string was about 12 cm peak to peak.

The two upper cases fit very well with the possible cases experimentally measured on the Kasatori-Yama line.

Third simulation on the Kasatori-Yama line : Den-Hartog galloping on the 4x950ACSR, with 3m amplitude for the one loop (up and down) and 1 m amplitude for the three loops superimposed, wind speed about 7m/s. Fig . 5 is the detailed tension oscillogramms both in strain insulator and in suspension insulator. We have joined the Fourier analysis of the same curves.

A frequency analysis of the section has been easily performed to find out the following results :

one loop (up and down)	0.2 Hz
pseudo-one loop	0.47 Hz
two loops	about 0.4 Hz
three loops	about 0.6 Hz

The simulated results shows in the strain insulator a peak to peak 90000N (that means a 45000 N per chain) variation not symmetrical to initial value. The frequencies are mainly 0.47 Hz (pseudo-one loop), 0.6 Hz (the three loops oscillation) and 1.2 Hz (the double of the three loops oscillation) . In the suspension string a peak to peak 20000 N tension variation not symmetrically distributed around initial value (41000 N) with the same frequencies as for the strain insulators. As a complementary information deduced from the simulation, the displacement of the suspension string was about 30 cm peak to peak.

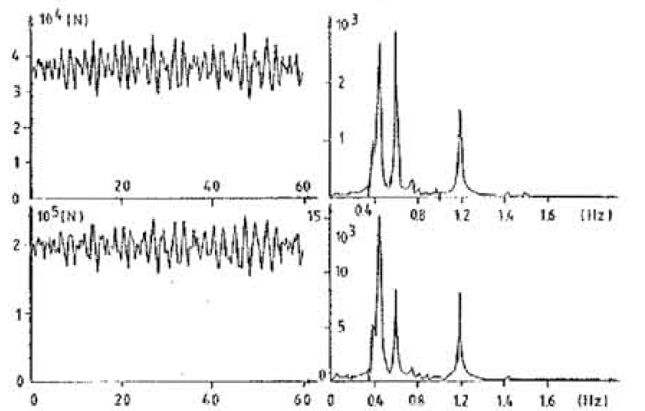

Fig. 5 Computed tension oscillation and corresponding Fourier analysis during mixed one (3m) and three (1m) loops galloping, on a 4x950 ACSR.
Upper part : suspension string (initial value=40700 N)
Lower part : anchoring string (initial value=186000 N)

We could have simulated a lot of other cases, including torsion-vertical instability. But for tension variation discussion, the situation is sufficiently complex to limit the number of features.

What to say after those observations !! Everything is possible?

As design engineer we need informations for phase clearances and tower design. The best way is certainly to find out a efficient antigalloping device, but it is not so clear to-day !! Winddamper[R] seems to be efficient against Den-Hartog galloping because it causes a blow-back angle pushing previously accreted ice in other range of angle of attack than the Den-Hartog one. Detuning pendulum, if well calculated, will be of some efficiency for galloping due to aerodynamic coupling between vertical and torsional movement (the most frequent one at our opinion, on bundle configuration), air-flow spoiler, rotating clamp spacer, hoop spacers will have some influence on ice accretion eccentricity and could be efficient for particular thin ice conditions. Interphase spacer is an expensive possibility to solve the clearance problem but not necessary the mechanical tension oscillation problem which could be emphasised by synchronising the tension variation in the three phases...

As a first approximation one could evaluate by the simple formula :

$$\Delta T = K_{ev} \frac{\pi^2 N_s}{4L} \sum_s (2\, y_{so} + \Delta y_s)\, \Delta y_s \qquad (9)$$

an order of amplitude of the maximum tension oscillation. It is a matter of fact that it is very rare to have galloping amplitude bigger than the sag (one might get a probabilistic approach on this fact, if you could get data) . Just to have an idea of the order of magnitude we shall consider for tension oscillation a 40% variation of the sag on the pseudo-one loop mode[1] (the most dangerous for tension variation, but not for sag variation). So that tower design must ensure a tension variation of about :

$$\Delta T = K_{ev} \frac{\pi^2 N_s^2}{4L}\, y_{s,c}^2 \qquad (10)$$

(K_{ev} the section stiffness define in (1) , Ns the number of spans in the section, L the *section* length, y_{so} the mean sag)

the frequency of which can be between the first mode (up and down) and the third mode. This last being the most dangerous for fatigue phenomena, but has generally lower rate of tension variation.

It is obvious that a reduction of tower anchoring stiffness would be of very big help. The number of suspended spans must be limited , but in practice it is so. For section with more than 3 spans , it seems to be reasonable to limit Ns to 3 in the calculation. Some more investigations could be done in that field in order to refine sag oscillation and to adapt a correction factor as a function of the location of the line in relation with ice accretion characteristics.

With pendulums and supposing that amplitude will be reduced of 75% , as mentioned by their inventors, tension variation could be reduced of 30% to 60% as it may be calculated from the above formula.

example of application :

For the 4x410 of the Kasatori line :
Kev=123 10^6/631=1.9 10^5 N/m; y_{so}=6.5 m; N_s=2; L=312+319=631m
and ΔT=126000N (2x74000=148000 N observed)
For the 4x950 of the Kasatori line :
Kev=285 10^6/631=4.5 10^5 N/m; y_{so}=7.8 m; N_s=2; L=312+319=631m
and ΔT=400000N (2x78000=156000 N observed)

For suspension towers, moreover to the horizontal wind force, galloping applied loads could be rather high (but in quasi-vertical direction). With the same supposition as for strain tower, it is about 10x(y_o/L_s)xΔT that means about 20 to 30% of the variation loads applied to strain towers.

example of application :

For the 4x410 of the Kasatori line :
ΔT=0.3 x 126000 = 38000N (35000 N observed)
For the 4x950 of the Kasatori line :
ΔT=0.3 x 400000 = 120000N (25000 N observed)

[1] This is also equivalent to a pure two loops oscillation of amplitude equal to the sag on each span.

II Galloping amplitudes prediction

1) Gallop without twisting

The simplest form of gallop is single-degree-of-freedom, and involves only the vertical motion or slant motion of the conductor. This is also known as Den Hartog type of galloping. Sometimes it could be accompanied by twisting as well, but such twisting is not essential - rather, it is incidental to the gallop. This type was studied by Scruton [1], Parkinson [2], Novak [3], Ratkowski [4] Richardson [5-8], Lilien-Dubois [20] and others. It is often characterized by a thin ice shape, and having no means of twist coupling, either aerodynamically or inertially. In the United States, it is the most common type of gallop, as it often has been reported with little (a few millimeters) ice, [9].

The primary driving mechanism is the Den Hartog mechanics, and may be expressed simply in terms of the lift curve variation with the angle of attack of the wind. A curve which approximates the variation of lift for thin ice on a round conductor is :

$$C_L = -A_m \sin(\pi\alpha/\alpha_o) \tag{11}$$

Where,

C_L = lift coefficient

α = angle of attack

α_o = angle of attack of lift reversal

A_m = maximum lift coefficient.

The principle feature of the lift is negative slope at the origin, or zero degree angle of attack. When it is negative and exceeds the numerical value of the drag coefficient (about unity), galloping is possible by the Den Hartog theory, [10], [11]

Whether gallop will actually occur depends upon whether the wind speed is above the critical wind speed or not. If not, no gallop will build up. If the wind speed does exceed the critical wind speed, the gallop that occurs depends upon how much it is actually exceeded. Prediction of the numerical value for the critical wind under the theory of Den Hartog was illustrated by Parkinson [2], and by others. It depends upon the mechanical damping, mass of the conductor, and natural frequency of the span.

The build-up to full span gallop for two cases is illustrated in Figs (6) and (7). In Fig (6), the peak angle of attack (radians) is plotted against the wind speed. There are two critical wind speeds, 5 M/s and 10M/s. The conditions are similar to an example span that was used by Richardson [12]. The higher critical speed may have the same natural frequency with twice the damping, or a damping which is the same, but a natural frequency that is twice as much. The latter could occur on suspension spans of the same line where one span gallops with only one loop per span, and another span - having the same span length, gallops in two loops.

Figure 6 illustrates an asymptotic approach to a value of α = 0.5 peak dynamic angle of attack. Figure 7 shows that peak-peak gallop amplitude increases with the wind speed. These results are obtained from the Describing Function Method, Richardson [7], [8]. Here, the calculations are based on a span of quad bundle line that is identified as the C.E.G.B. line, [12].

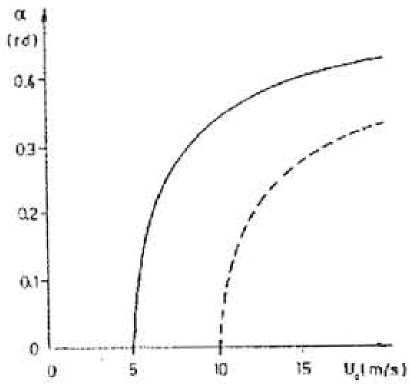

Fig. (6) Angle of attack vs. wind

——— : critical wind speed = 5 m/s

- - - - - - - : critical wind speed = 10 m/s

Light ice shape, 10% thickness.

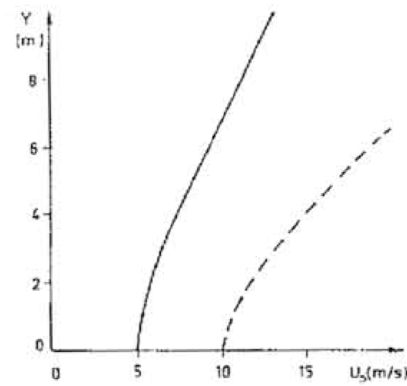

Fig. (7) Galloping amplitude vs. wind

——— : critical wind speed = 5 m/s

- - - - - - - : critical wind speed = 10 m/s

Light ice shape, 10% thickness

2) Galloping with twisting :

In bundled conductors, there is often a twisting motion as well as a vertical gallop motion. This is because a bundle has the twisting natural frequency close to the gallop natural frequency. Coupling can occur between the twist motion and the gallop motion. Coupling mechanisms that have been studied include both inertial and aerodynamic forces and moments. Such mechanisms have been the object of study by Richardson [13], Nakamura [14], Hack [15], Lilien-Dubois [16,20], Mukhopadhayay [17], Chadha [18], and others. Earlier studies were limited to the theory of a coupled linear system, while most recent studies have a major emphasis on non-linear aerodynamic force and moment Describing Functions.

While bundled conductors often do gallop by thin ice or in accord with the Den Hartog theory, they may also be subject to gallop when the lift curve slope is positive at the origin, (zero initial angle of attack). Recently, studies of ice shapes taken from lines which galloped showed that the aerodynamic lift and moment was in fact along a positive slope near α = 0, Tunstall [19]. From those data an analytical model was developed based on a Describing Function of lift and moment. Richardson [12]. Those analytical models have been extended to include a broader range of the parameters for the C.E.G.B. line.

Some of the results are seen in Fig. (8) and Fig. (9). A comparison between different levels of detuning is made in Fig. (8) for a constant level of damping in the gallop. The two detuning levels compared yield the same build up of gallop amplitude. In Fig. (9) a comparison of different damping values from zero to 15% illustrate the differences. When damping is low gallop amplitudes increase at a faster rate with the wind speed. Detuning is constant at 5% for all three cases. It is noted that the practical achievement of 15% damping in the gallop mode would be very difficult indeed. *Also, while such a high damping in the gallop mode would eliminate the Den Hartog type of gallop, it does little to control bundle gallop along a positive lift slope.*

A careful study of the motion involving gallop/twisting coupling shows that the energy input to the motion must be due to positive lift acting in phase with the gallop velocity. Since lift is a function of dynamic angle of attack, the twist motion must be in phase with gallop velocity and greater than the dynamic angle of attack due to gallop motion. This will be illustrated later.

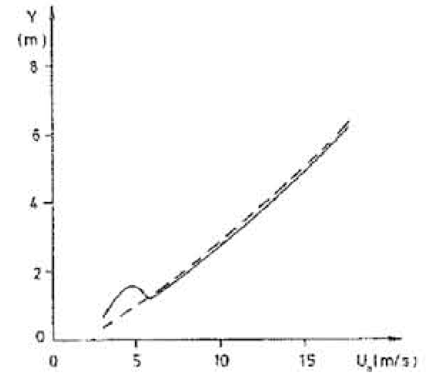

Fig. (8) Galloping amplitude vs. wind
——— : 5% detuning
- - - - - - - : 2,5% detuning
Damping : 15% gallop mode
Damping : 0 twist mode
C.E.G.B. ice shape.

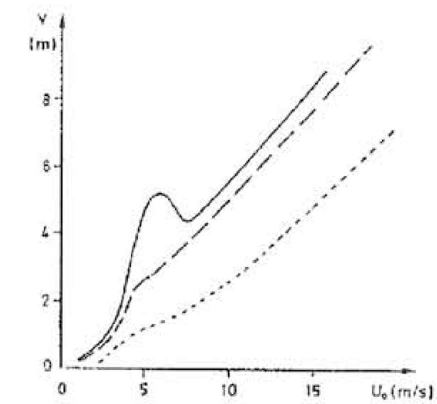

Fig. (9) Galloping amplitude vs. wind
- - - - - - : 15% damping
– – – – : 1,67% damping
———: 0.0% damping
twist Damping = 0, & 5% detuning
C.E.G.B. ice shape.

In mathematical terms, the angle of attack is :

$$\alpha = \Theta - \omega y/U_o \qquad (12)$$

Where,

Θ = dynamic twist angle
y = peak amplitude of gallop
U_o = wind speed
ω = radian frequency of gallop.

For the purpose of illustration, we have assumed that the ω = 1.0 rad/s. The detuning of 5% means that the twist natural frequency exceeds the gallop natural frequency

Twisting motion :

The amount of twisting motion that a bundle experiences is controlled by the total angle of attack. This is so because the total angle of attack is made up of two important components - twisting and galloping; see Eq. (12). No gallop can occur unless energy is fed to the gallop mode by the wind. This occurs when the aerodynamic lift wave form has a component that is in phase with gallop velocity. The basis of the Describing Function Method is the determination of that component from the static lift coefficient curve, Richardson [12], Lilien-Dubois [20]. When the dynamic coupled equations of motion are solved, the result takes into account aerodynamic lift, drag, and pitching moment. The drag is the component that may always be relied upon for damping. Here, we have neglected all pitch damping in spite of the fact that the twisting motion may also be a source of damping.. Only gallop damping has been included in the analysis.

Never-the-less, the pitch motion, or twisting, is the primary cause of galloping when there is positive lift slope. As already explained, when pitch/twist motion is in phase with gallop velocity, the maximum lift force occurs when the gallop amplitude passes through zero on the up stroke, and the minimum lift force occurs when the gallop amplitude passes through zero on a downward stroke. This action feeds energy into the motion until equilibrium is reached with the damping sources such as aerodynamic drag and gallop mode damping. The balance of energy occurs at higher levels as the wind speed increases. More galloping amplitude is required at higher wind speeds to reach equilibrium.

For the C.E.G.B. bundle the result is seen in Fig. (10) with the variation of pitch angle (mid -span twist). An effect is seen at low wind speeds that is related to a non-linear Describing Function; namely, pitch angle saturates at wind speeds above 7 meters per second. It is apparent from previous graphs that this action does not limit gallop amplitude. Rather, gallop amplitude grows continuously. The pitch amplitude is large, the order of 70 degrees single peak or 140 degrees peak-to peak.

In Figure (11) the effect of increased/decreased damping in the gallop mode is seen. The detuning is constant at 5%, while damping varies from zero to 5%. There is a small effect of damping, but not enough to cause a search for a remedy in that direction. If detuning is increased to 15%, while maintaining damping at 5%, pitch motion is slightly modified at low values of the wind speed. The same saturation level is reached at a

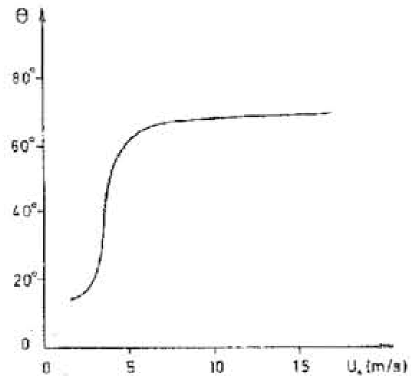

Fig. (10) Pitch amplitude vs. wind
Damping & Detuning = 5%
C.E.G.B. Ice shape

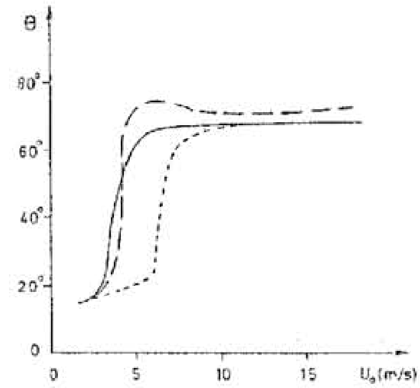

Fig. (11) Pitch amplitude vs. wind
———: Damping & Detuning = 5%
- - - - -: Damping = 0, Detuning =5%
- - - - - - - -: Damping = 5%, Detuning = 15%
C.E.G.B. ice shape.

higher wind speed; namely, 70 degrees peak for winds above 8 meters per second.

Thus, neither changes in damping nor changes in detuning can produce much change in the pitch motion of the C.E.G.B. quad bundled conductor.

Another comparison can be made now with results now available from Figures (8) - (11). Knowing the numerical values of the gallop amplitudes and the pitch amplitudes, one may compute the kinetic energy of each of these motions. The mass per unit length of the bundle is 2 kg/m per subconductor. The quad spacers are 305 meters per square side. The radian frequency of the coupled mode is unity. The mode shape is one loop per span. From these data, we reach the conclusion that a ratio of kinetic energy of gallop to pitch motion can easily approach 150 to one.

Negative detuning :

So far only positive detuning ratios have been studied. That is for the cases when the twist natural frequency is greater than the gallop natural frequency. A detune of 5% means the ratio of twist to gallop frequencies is equal to 1.05. Contrary to that, a negative detuning of minus 5% means that the ratio is equal to 0.95.

Negative detunings are commonly found in spans of double dead-end configuration; not because the twist natural frequency is less than the one for a corresponding suspension span, but because the gallop natural frequency is greater than the corresponding suspension span. This is the result of strong coupling between the mechanical strain energy of the cable and that of the dead-end structure in which yoke plate design plays a key role for negative detuning. Yoke plate modelling should have to be thoroughly investigated. In suspension spans the coupling is weak, and the detuning in usually positive, being mainly due to added torsion stiffness of the individual sub-conductor assembly.

Experimentaly negative detunings seems to be more dangerous because they also reflect a condition for which the dynamic loadings are much larger than in a corresponding suspension span. It places greater demands on the strength of the structure and hardware. An example of this effect was reported in a C.I.G.R.E. discussion in 1986, Akiyama, [22]. The cap and ball insulators were found broken due to excessive gallop loadings. The insulator tension variation (peak to peak) was measured in excess of 40 kN, with fatigue cycles greater than 1,000 times per year. This type of damage may be typical of large span bundled lines. It points to isolated occurance, on strain insulator assemblies, on double dead-end spans, and having extreme stress loading a relatively few times per year. It is a fatigue situation best characterized as high stress/low-cycle fatigue.

It was further explained by Akiyama that a previously tried remedy did not work; namely, the substitution of towers having more electrical clearance between phases so as to reduce line faults. The faults were indeed no more, but the damage to insulators actually increased. Thus, a lesson learned is that certain damage-prone line configurations do exist in comparison to others that are not so damage-prone, such as suspension spans and the like.

While the negative detuning may characterize a danger as to gallop dynamic loading, it seems to have little to distinguish its character as to amplitude build up as seen in Fig. (12). Here, both positive and negative detuning is compared. Except for a slight difference in the wind speed range of 5 meters per second, there is little to distinguish between the two. At the high speeds the positive detuning yields slightly higher gallop amplitudes.

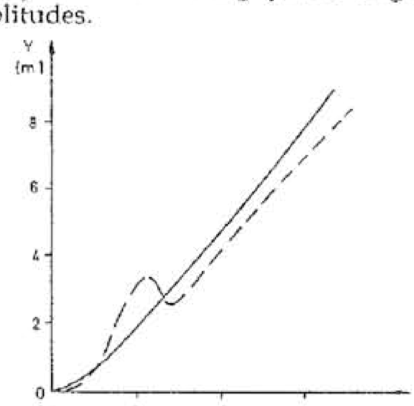

Fig. (12) Gallop amplitude v. wind
———: detuning = +5%
- - - - - - -: detuning = -5%
Damping = 5% gallop mode only
C.E.G.B. ice shape

However, the pitch angle does produce significant differences over the whole range of wind speed, Fig. (13). Positive detuning produces much greater dynamic twisting than negative detuning up to 350% greater. Further, as seen in Fig. (13) greater twist motion will certainly torture hardware more severely, leading to a greater potentiel for fatigue damage.

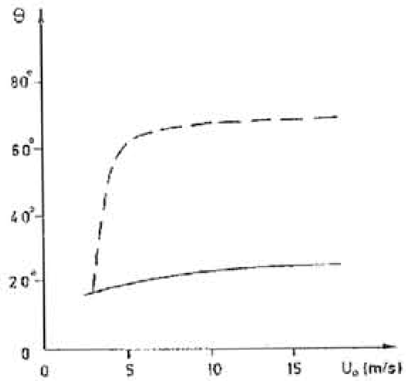

Fig. (13) Pitch amplitude vs.wind
- - - - - - - : detuning = +5%
——— : detuning = -5%
Damping = 5% gallop mode only
C.E.G.B. ice chape.

Wind energy input

The galloping motion requires a continuous flow of energy to sustain itself. The wind provides that energy. Lift is the driving mechanism. Lift is intimately related to the angle of attack. In a bundled conductor, having both gallop and twist motion, the angle of attack has two parts, the part due to twisting, and the part due to gallop; see the Equ. (12). The energy input from the wind consists of two parts; the energy due to lift acting on the gallop, and the energy due to moment acting on twist motion. Both components can be calculated if the motion is known. The motion has already been found for the illustration; namely, the C.E.G.B. quad bundled conductor. The aerodynamic lift and moment - found from wind tunnel tests - were expressed in terms of the lift and moment Describing Function, [12]. A necessary condition for positive energy input to motion is that forces (and moments) be in phase with the motion itself. Here, we have already established that condition. It remains only to quantify the condition.

A parameter that often is used to quantify damping is the log decrement. It is most commonly used in single degree of freedom systems to relate damping ratio or loss factor to the motion. It can be used in two degree of freedom systems, but often the phenomenom of beating between mode contributions limits its practical use. A qualitative use of the negative log decrement is useful in systems which are subject to self-excitation. That is the case here. A calculation of negative log decrement, called log increment has been made for the two components of motion. The log increment may be used to estimate the relative input of energy per cycle. . Each vibration cycle receives energy from the wind. The amount of energy received can be large or small as the log increment is large or small. The following equation may be used :

$$E = 2 \times Li \times KE \qquad (13)$$

Where,

E = energy input per cycle
KE = maximum kinetic energy of motion
Li = log increment

For the gallop motion :

$$KE = 1/2 \times M \times (\omega Y)^2 \qquad (14)$$

The mass M is the generalized mass of the whole span, or one-half the total mass of the span if the mode shape is approximately a cosine centered at mid-span.

For the C.E.G.B. span (355 meters), the mass M is 1420 kilograms. At a gallop amplitude of 5 meters the KE is equal to 17,750 newton-meters.

The energy input to the twist motion is far less. First, the log increment is less than 10% over the whole range of wind speed. Second, the kinetic energy in the twist motion is nearly two orders of magnitude less.

When the detuning is negative, the log increment for the gallop is about the same, see Fig. (15). But the log increment for the twist motion is much larger. However, in terms of energy input from the wind, the result is about the same as for positive detuning. The reason is because the kinetic energy of twist is even smaller due to the reduced twist motion; see Fig. (13).

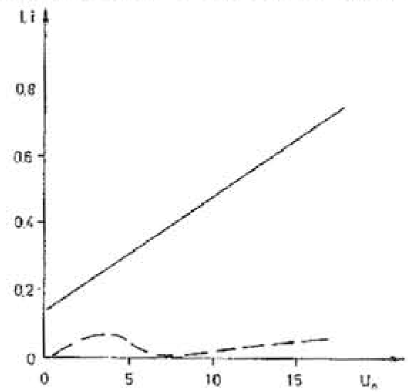

Fig. (14) Log-increment vs. wind
——— = gallop mode;
- - - - - - - = twist mode
Damping = 5%; detuning = 5%
C.E.G.B. ice shape

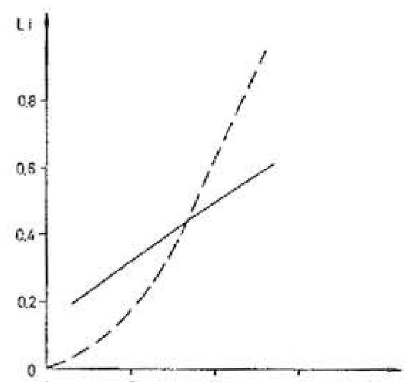

Fig. (15) Log-increment vs. wind
——— = gallop mode;
- - - - - - - = twist mode
Damping = 5%; detuning = -5%
C.E.G.B. ice shape

Summary of CEGB line analysis :

The response of a quad-bundle span to thin ice is characterized by a critical wind speed and a gradual build up of gallop amplitude as the wind speed increases above the critical value. The critical wind speed depend upon damping in the gallop mode, the natural frequency, and the mass of the iced conductor. Sensitivity of the critical wind speed is dominated by natural frequency when span length changes. Damping and mass per unit length are not influenced by span length appreciably.
Here, we have examined the response of a span of 355 meters length, having a thin crescent ice shape only ten percent thick oriented with axis of symmetry to the relative oncoming wind at zero angle of attack. The span is chosen as a typical span from a C.E.G.B. span which was known to have galloped. The second mode having two loops per span starts at a higher wind; it builds up in the same manner as the first, and in the very high wind speed range reaches less than gallop amplitude of the first mode. The illustrated results apply equally as well to a single conductor span, or a twin bundle span, having the same damping, mass, and frequencies for first and second modes. No twisting will occur for any of these cases. The reason for that is because there is no coupling mechanism such as inertia offset, or aerodynamic pitching moment. The natural frequencies of twist and gallop remain unaffected by the thin ice.

The gallop of the C.E.G.B. bundle with thick ice (about equal to 0.3 kg/meter) develops into a coupled twisting motion as well. The ice shape produces an aerodynamic pitching moment as well as an aerodynamic lift force. This is the primary coupling mechanism. The damping in the twist mode has been neglected in the study while damping in the gallop mode was varied. A significant effect on the gallop amplitude due to damping was not found, even for damping up to 15% (loss factor). This corresponds to damping ratio equal to 7,5%. Vertical damping has little effect on the twist motion.

The detuning effect is also studied. Detuning has little effect on the gallop mode response up to 20 m/s wind speed. Detuning was varied from 2,5% to 15%. The highest detuning delays the onset of high amplitude twist motion from about 4 m/s to about 8 m/s wind speed. Above that range of wind the twist motion reaches a numerical value of 140 degrees peak-peak. The motion of that magnitude is accompanied by a gallop motion of nearly 10meters peak-peak.

Negative detuning is studied also. This is a case where the twist natural frequency is not higher than the gallop natural frequency. The negative detuning equal to -5% corresponds to a frequency ratio equal to 0.95. For that case, the galloping motion is only slightly reduced. However, the twist motion is only 40 degrees peak-peak.

Anti-gallop remedies

From the previous illustrative examples, it is clear that the Den-Hartog type of galloping is sensitive to damping, natural frequency, and a type of aerodynamic lift. A remedy that acts on one or more of these factors would be expected to influence the gallop amplitude. Devices that are available commercially that act on one or more of those factors include : (1) T-2 conductors, (2) air flow spoilers, (3) Windamper^{R} devices, (4) AR twister devices, (5) drag and cylinder dampers, (6) Tanztilger type devices (Germany). The first five are from the U.S.
For the coupled twisting type of gallop, all the above are available, and, in addition, (7) a tuned damper - gallop control damper - (Japan) plus (8) phase spacers, (9) rotating clamp spacers (Germany) and (10) detuning pendulums (Canada) . The last three items contribute no damping, while all the former devices do. Finally, (11) unbundling is a viable concept for bundled conductors.

Thus there are eleven remedies to choose from if one wishes to limit gallop amplitudes.

The foregoing analyses have not included two other parameters : (i) inertia offset, and (ii) torsion mode damping. The effect of inertia offset was examined previously [12] but further analysis is needed. The effect of torsion damping was also examined previously [20] but further analysis is needed. Results will be included in a future paper.

Conclusions :

(1) Galloping loads on both suspension and strain towers can be rather high causing low frequency (0.15 to 1 Hz) variations up to 50% and more of the static equilibrium value. These loads can cause severe damage on the towers by fatigue oscillations (torsional and longitudinal).
(2) There is also a risk of fatigue if the length of the section permits resonance between longitudinal waves and first tower frequency (in torsion or longitudinal)
(3) It is a very complex phenomenon, and the same amplitude of galloping can give a wide range of tension oscillation due to mode mixture, especially for Den-Hartog galloping.
(4) Up to now the most common way to estimate the amplitude of galloping is to record tension. According to point (3) this method seems to be inaccurate.
(5) At a first glance pendulums could appear as a good solution as long as Den-Hartog galloping is not concerned. But we must keep in mind that twisting frequency is not a true structural parameter but may exhibit sensible variations related to wind. In some case pendulums could have a bad effect.
(6) The Den-Hartog galloping appears with very thin ice coating.
(7) For other ice coating the galloping mechanism is a coupled action between torsion and vertical motion if both torsional and vertical frequencies are close together, as in bundled conductors.
(8) For Den-Hartog galloping, the windamper^{R}seems to be a true solution.
(9) For other galloping a torsional damper would probably help to solve the problem.

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Notations

$y_{s,k}$ magnitude of mode k on span s

$$y_s = \sum_{k=1}^{3} y_{s,k} \sin \frac{k\pi z}{L_s} \quad \text{(z the abscissa } [0, L_s])$$

$y_{s,ko} = y_{s,k}$ for static equilibrium (zero for k even)

T Instantaneous tension in one phase (N)
To = initial static value

m total mass of one phase per unit of length.(kg/m)

ΔT tension variation in one phase (N)

Δl length variation of one phase (m) :

$$\Delta l = \int_0^{L_s} \sqrt{1 + \left(\frac{\partial y}{\partial z}\right)^2}\, dz = \int_0^{L_s} \left[1 + \frac{1}{2}\left(\frac{\partial y}{\partial z}\right)^2\right] dz$$

EA/L extensional stiffness of one phase (N/m)

K anchoring tower longitudinal stiffness [N/m]

L total length of the section (N_s spans) [m] :

$$L = \sum_{i=1}^{N_s} L_i$$

K_{ev} section equivalent stiffness [N/m]

$$\frac{1}{K_{ev}} = \frac{L}{EA} + \frac{2}{K}$$