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OVERHEAD LINES GALLOPING - MODELISATION

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A novel simple model with 3 degrees of freedom describes the phenomenon of galloping (one loop) and shows its necessary and sufficient conditions of appearance.

1. INTRODUCTION

Despite the important literature on the phenomenon of galloping, it is still far from being explained thoroughly. Witness the relative efficiency of most preventive devices used, whose effects are sometimes opposite to expected results. We endeavoured to tackle the problem in a simple and thorough way. Our model is simple due to the use of an equation with three degrees of freedom which allows having a physical interpretation of starting and obtaining an approximate value close enough to the magnitude of limit cycles. It is complete to the extent that horizontal and vertical movements and cable torsion are included in our model.

2. MODEL SELECTION

Our model with three degrees of freedom is halfway between partial derivatives model [3, 13] and models with one or two degrees of freedom [2, 5], which have sometimes proved satisfactory. Some rare models with 3 degrees of freedom [14, 8] have already been proposed but, unlike ours, they did not take into account important effects such as modification of torsion rigidity, reaction of anchoring points, tension variation in conductor during movement and aerodynamic pitching moment.

It goes without saying that our intention is not at all to provide any qualitatively accurate prediction of phenomena because the parameters of the system - at least aerodynamic ones - are subject to statistical uncertainties depending on ice sleeve shape.
Our purpose is to highlight the main physical mechanisms of the phenomenon, which can hardly be detected with a model with finite elements.

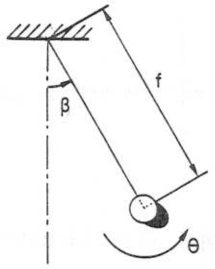


Fig. 1 a 3 dof simple model for galloping

We shall limit our study on oneloop galloping, assimilating the span to a curve whose geometry is determined by a single parameter (sag). This is our first degree of freedom (f). Then we shall assume that, at a given time, the span is completely included in a plane rotating about the axis which joins the two anchoring points of the cable on insulator chains.

The angle made by this plane and the vertical is our second degree of freedom (β). Finally, the conductor's torsion will be determined as a function of a vertical axis; this torsion angle is our third and last degree of freedom (θ) [Fig. 1].

We shall assume a linear variation of the torsion angle between anchoring point and half span.

With single-phase conductors, the characteristics are clear. With bundles of "n" conductors, aerodynamic forces are multiplied by the number of conductors. A single equivalent conductor is chosen (section, tension, mass multiplied by "n") but its torsional stiffness and inertia moment are calculated from the characteristics of the bundle. Particularly, its torsion stiffness is not a constant but is expressed by : [4]

$$(GJ)_n = \frac{nTd^2}{4} \circ \mathrm{Cos}\,(\frac{2\theta}{k}) + n.(GJ)_{1\,cond.} \qquad (1)$$

Order of magnitude of $(GJ)_1$: about 8% of the stiffness of the equivalent beam of same cross-section.

3. STARTING GALLOPING

Under determined static conditions (weather temperature, wind speed, characteristics of snow or ice sleeve), the equation system makes it possible to obtain the corresponding state of static equilibrium, i.e. β^*, f^*, θ^*. Instability will be proved by the linearization of the equations around this state of equilibrium : it suffices to apply the theory of linear systems to these equations.
Given the preceding remarks, the 3 criteria of instability are :

1) Swing instability

Figure 2 shows the areas of instability with respect to β^* and angle of attack for different excentricities of ice sleeve. This curve can easily be drawn from linearized equation in case of determined aerodynamic coefficient curve.

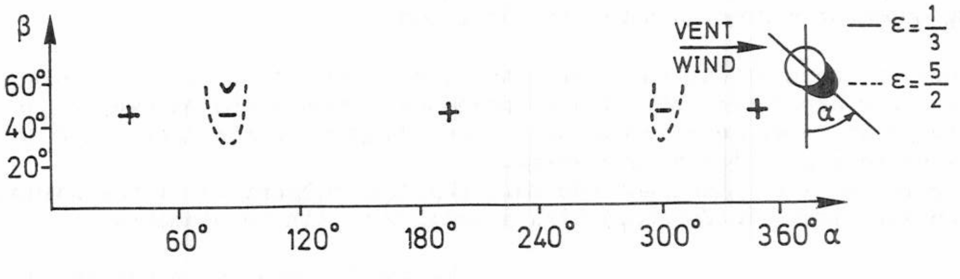


Fig. 2 Swing instability in negative zones

This criterion is thus seldom met except in case of fierce wind and strong excentricity.

2) Sag Instability

Figure 3 shows these same areas of instability determined from linearized equation.

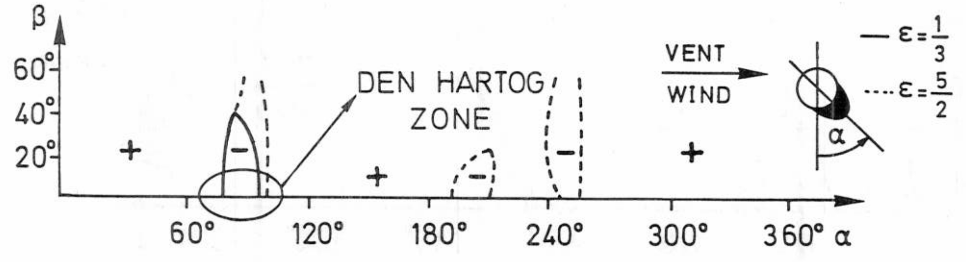


Fig. 3 Sag instability in negative zones

Limited areas of instability around 90° and 270° of angle of attack can be noticed. These areas depend on chosen aerodynamic curves (Annexe 1). As we know, main effect of more important turbulence is to decrease C_D significantly, which in turn increases the number of unstable areas. With $\beta = 0$, Den Hartog criterion is met

$$\frac{\partial C_L}{\partial \alpha} + C_D < 0 \qquad (2)$$

Therefore we propose a generalization of this criterion.

With a low excentricity, this type of instability disappears in case of fierce wind.

The physical justification of this criterion confirms Den Hartog's approach, namely that the energy supplied to the cable when lift has a negative derivative with respect to α whose effect outdoes that of drag (damping effect).

This type of instability only exists with a very limited range of angles of attack whatever the excentricity. Therefore this criterion will only come true for a particularly unfavourable position of the line to prevailing wind and only in case of important phase torsion rigidity (bundle conductors with spacer or wide-section conductors). Otherwise the angle of attack on the span is too dispersed about values causing instability which makes galloping unlikely.

3) Torsion Instability

This criterion cannot be clearly expressed without a further hypothesis. We shall see that there are three types of galloping. One of them makes two out of degrees of freedom intervene in a determining fashion. The third one remains present but does not influence galloping frequency nor orientation nor amplitude.

If internal torsion damping is disregarded, then as a first approximation, the instability criterion reduces to :

$$a_{13} \cdot b_{31} \cdot (a_{33} - a_{11}) > 0 \qquad (3)$$

where the sign of $a_{13}b_{31}$ is only determined by aerodynamic coefficients and their derivatives (sign on Fig. 4).

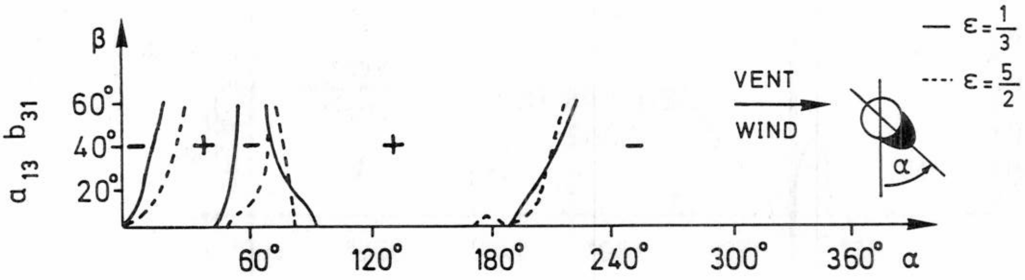


Fig. 4 Sign of a factor related to torsional instability

On the other hand, the criterion is linked to the difference between swing (a_{11}) and torsion (a_{33}) frequencies. Under such conditions, the criterion can be met or not for given angle of attack and wind speed according to whether torsion frequency is smaller or greater than swing frequency. Let us recall here that both frequencies depend on the wind and ice distribution. Torsion frequency is certainly the more sensitive one. Swing frequency increases together with wind speed since there is an increase in tension. By contrast, following the aspect of ice to the wind, torsion frequency may either increase or decrease from its resting values. This effect has already been reported several times in the literature under the name of "inverse pendulum" effect. It can have frequency change by more than 50%. A similar reasoning can be made in the event of sag-torsion galloping, in which case swing should be replaced by sag in reasoning. Because of their construction, bundles of conductors with spacers have a torsion frequency close to that of swing (see conclusions). Therefore, whether the criterion will be met depends very much on wind speed. This criterion also strongly depends on the presence of a pendulum-type device which modifies torsion behaviour. However, the way in which the criterion is modified is far from obvious, and we must be careful not to introduce instability where there would be none naturally. But the usefulness of some pendulums of desyntonisation is that they reduce the amplitude of oscillation by departing from natural resonance (see below).

As far as single conductors are concerned, we think that the use of pendulums is not advisable for narrow-section conductors. It does not seem reasonable to bring closer frequencies which are naturally different, and we must be careful to prevent any rotation hinder which would favour excentricity of the ice deposit.

Finally, even if the initial equilibrium is stable, a gust of wind can cause a modification of torsion frequency which can destroy the equilibrium. The reverse phenomenon can also occur.

4. SELF-EXCITATION MECHANISM

Instability does not necessarily cause great amplitude variation unless the following two additional conditions are met :

1) Sufficient wind, otherwise internal dissipation strongly restricts the phenomenon.

2) Proximity of 2 of the three eigenfrequencies, each of them being asso-

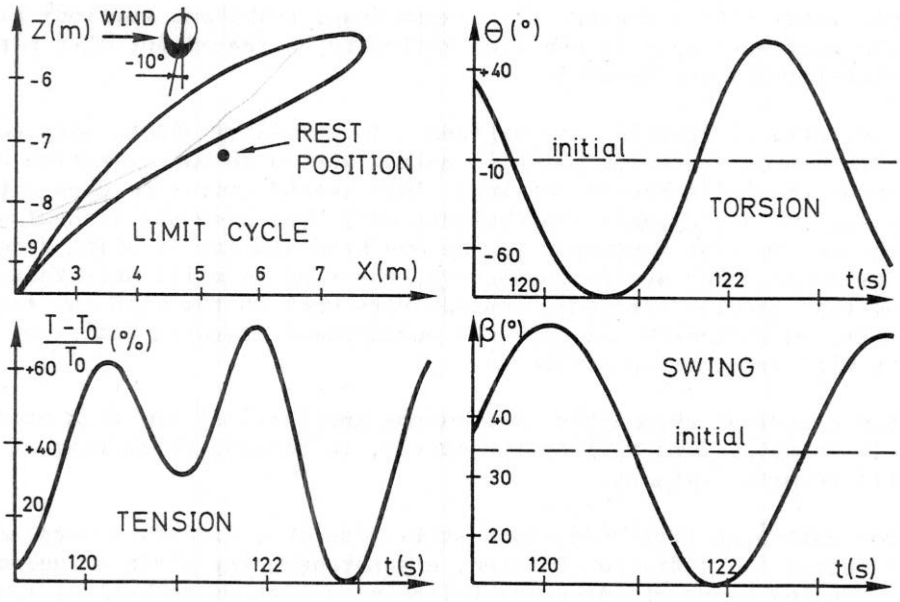
ciated to a particular type of galloping. These 3 modes correspond to possible coupling between the 3 degrees of freedom of the system (the first resonance between swing and sag takes place in case of a ratio 2 between frequencies which can never be identical). This resonance makes aerodynamic coupling particularly strong.

Indeed, as a first approximation, we can consider that instability on one of the degree of freedom (which is thus self excited) makes the other, which is coupled , in forced oscillation. The amplitude of this forced oscillation is inverse function of the variation between the frequencies at stake. It is finally limited by dissipation. The system being unstable, only non-linearity limits this amplitude. This amplitude is not due to the elastic return force but to modification of aerodynamic coefficients as a function of the angle of attack, which can very a lot.

5. APPLICATIONS

Two applications on a AAC conductors 620 mm^2 in a 361 m span length (deadended) will be described.

The first one is a twin bundle (0,45 m between subconductors), with an initial 7.8 m sag. Ice : deposit of 5 mm, density 300 kg/m^3. Wind speed of 20 m/s.
Initial torsional stiffness of the bundle was about 3880 Nxm^2.
Fig. 5 to 8 give the results of numerical simulation. It's a swing-torsion galloping (third criterion). There is a 90° shift between swing and torsion time evolution. Mechanical tension variations looks like the experimental oscillograms observed in february 1986 in Belgium.
Peak to peak amplitude (8m) and limit cycle pulsation (1,5 rad/s) give a reduced amplitude [18] of 8x1.5/20 = 0.6
Another simulation of the same case but including torsional damping of 3% from critical damping (which is a normal situation for classical cable) reduces the peak to peak amplitude to 3 m.



The second application is the same case but with only one conductor in the phase (or a decoupled bundle). Other spray angle of ice had been taken into account and wind speed reduced to 10 m/s to obtain instability. Torsional stiffness of the phase is reduced to 190Nxm^2.
Fig. 9 and 10 give the results of numerical simulation for the limit cycle and torsional evolution (this last shows a forced vibration at sag frequence and a superposition of the first natural torsional frequence). This case is a quasi-pure one direction galloping. It's a sag torsion galloping (second criterion). The peak to peak amplitude (2.6m) and limit cycle pulsation (2,4 rad/s) give a reduced amplitude of 2.6x2.4/10 = 0.62, a similar value as for the first application.
In this case the effect of torsional damping it much more limited (2.3m instead of 2.6m) because instability is marked on the sag. For a decoupled bundle there is surely a high vertical damping effect induced by the coupling between both conductors in the yoke plate. This has not been included in the presented simulation.

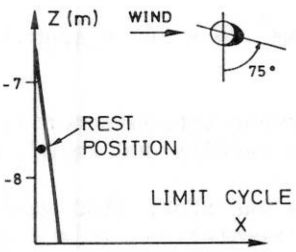


Fig. 9 Single conductor limit cycle at 10 m/s

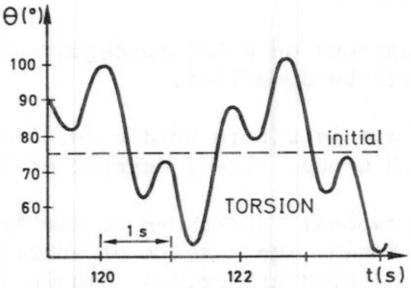


Fig. 10 Single conductor mid span torsion evolution during one loop galloping

6. CONCLUSIONS

1. A simple model with 3 degrees of freedom (sag, swing and torsion) allows simulating every type of one loop galloping to the extent that aerodynamic coefficients are defined.

2. Three criteria of starting are defined. In the first place, they generalize Den Hartog criterion which is paired with a second criterion which clearly shows the influence of torsion. This second criterion does not take into account aerodynamic coefficients only, but also the sign of variation between torsion frequency on the one hand and sag or swing frequencies on the other. For bundle conductors, the sign is still uncertain. So much so that torsion frequency depends very much on the wind and ice excentricity, which modify not only the aerodynamic characteristics of the bundle but also its torsion stiffness.

3. The two classical approaches (Den Hartog and torsion) are thus complementary. It is still very difficult, however, to foresee which type of galloping will be most frequent.

4. Maximum galloping amplitude, when still possible, increases together with wind speed; the variation between, eigenfrequencies plays a fundamental part. In the event of sag-swing galloping a beat of mechanical tension

is generally observed, which corresponds to variation of galloping mode from pure sag oscillation to 8 oscillation or double loop, related to ratio 2 between swing and sag frequencies. This phenomenon was observed in experiments carried out in Japan and Belgium.

5. If cable internal oscillation damping for oscillations in its plane is negligible for classical cables, torsion damping is not. Any increase in the latter by means of adequate devices or through different cable design constitues a preventive means particularly efficient against galloping involving torsion.

6. Single conductor's behaviour is very different from that of bundle conductors coupled by means of classical spacers. The latter have a much higher torsion rigidity (about 20 times higher) which depends on tension in the conductor and on bundle geometry (bundle diameter and number of sub spans). Besides, the inertia moment is far higher (about 500 times higher) as it depends more on the conductor's mass than on the diameter.
Disregarding aerodynamic effect, we can use the following equations for torsion frequency.

Single conductor : $$\sqrt{\frac{12\,GJ}{I\,l_o^2}} \simeq \frac{2}{l_o}\sqrt{\frac{E}{\rho}} \quad (4)$$

Bundle conductor : $$\sqrt{\frac{3nTd^2}{I\,l_o^2}} \simeq 0.55.\sqrt{\frac{T}{Ml_o}} \quad (5)$$

we find the expression of swing frequency in (5). A greater natural sensitiveness of galloping bundles (mainly in swing-torsion) could be inferred from it. This is the case in Europe but not in the US. In fact, the cross sections of the conductors used in the US are often much wider than those of conductors used in Europe. As a result, they have a greater torsion rigidity ($\propto$ to the fourth power of cross section) and therefore rotate less under the effect of ice. Aspect to the wind is thus more constant in case of spans favouring aerodynamic instabilities.

NOMENCLATURE

f : half-span sag (m)
M : total cable mass (ice included)
T : mechanical tension
lo : span length
GJ : phase torsion stiffness
d : diameter of the bundle
k : number of sub-spans
CD, CL, CM : aerodynamic coefficients of drag, lift and moment
n : number of subconductors per phase
α : angle of attack of relative wind
β : swing angle of the span
Θ : angle of torsion of the phase
ε : excentricity of iee deposit
a_{13}, b_{31}, a_{33}, a_{11} : terms of linearized equation around statical equilibrium

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ANNEXE 1 : AERODYNAMIC COEFFICIENTS

One of the curves used in this paper's calculations are printed below

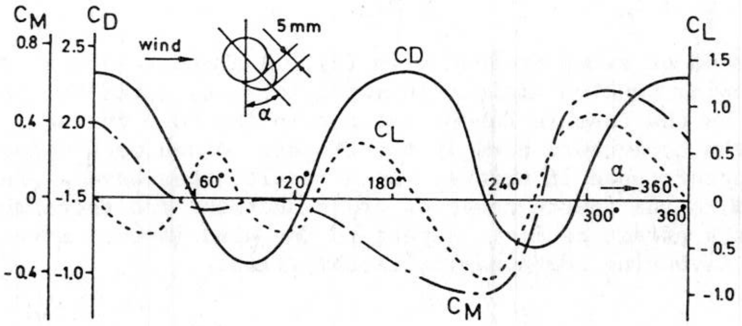

Fig. 11 Aerodynamic coefficients for ice excentricity of $\frac{1}{3}$ (deposit of $\frac{0.5}{3}\phi$)

The curves determined during wind tunnel tests, source O. NIGOL, enable us to raise several points.

$C_D = a + b \cos 2\alpha$ (for the given curve; a = 1.79; b = 0.63)

$C_M = a\cos\alpha - b \sin 2\alpha$ (for the given curve; a = 0.4; b = 0.27)

In conclusion, aerodynamic curves must always be interpreted with great care. Conclusions based on tests on non natural shapes cannot be generalized. Nevertheless, all curves have the same general aspect. No model can be strictly based on a particular case.
An interesting approach would be to examine the effect of a modification of the terms of Fourier's development in series of these curves from a representative sample, especially as far as lift and drag are concerned. This will be the subject of a forthcoming paper.