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HIGH VOLTAGE OVERHEAD LINES. THREE MECHANISMS TO AVOID BUNDLE GALLOPING

J.L. Lilien and O. Chabart
University of Liège, Institut d'Electricité Montefiore
Sart Tilman (B28) Belgium

Abstract

Overhead lines in electrical network cannot be installed without frequency tuning between torsion and vertical movement. That intrinsic structural property is at the origin of numerous large vibration observed in many countries in winter during windy time (Japan, Canada, U.S.A., Germany, etc...) .
Some actual way to avoid that kind of flutter is to add on the line some so-called anti-galloping devices which are based on different principles.

We will compare three families of these devices :
- the family increasing the torsional stiffness
- the family increasing the moment of inertia
- the family with one of these two first effect + torsional damping

The mechanism of action will be investigated and it will be proved that devices based on a combination of torsional damping and increased torsional stiffness is most effective because of energy transfer from wind to the line is affected directly via the angle of attack and not only by the detuning effect obtained in the two first cases.
That is because instability is affected both by torsional amplitude and phase shift with vertical movement. This last being hardly influenced by wind speed and the derivative of aerodynamic pitching moment.

A practical device has been manufactured and tested to fulfil the third family efficiency and some results will be shown in the paper.

I. THE GALLOPING PHENOMENON ON BUNDLE CONDUCTOR LINES

I.1. Hypothesis

The galloping phenomenon on bundle conductors is mainly governed by vertical and torsional degree of freedom. In fact complete set of equations include horizontal movement, but this degree of freedom doesn't contribute significantly to the instability in most of the case. In fact such participation would force galloping ellipse to be more horizontal (or 8 shape) which very seldom occur in practice.

Nevertheless, not to loose any of seldom galloping possible occurrence, we developed a full 3 degree of freedom galloping modelling. This modelling includes up to 20 spans (limitation is of course due to practical section line data and is not a numerical one), up to 3 loops galloping (more than 3 loops galloping also very seldom occurs and is generally of small amplitude, thus of no interest for design), includes the movement of suspension insulators, tension oscillations both in each span of the section and in suspension insulators, includes also appropriate modelling of torsional behaviour of the fixation of the bundle on anchoring insulators, and last but not least the tower stiffness. Anti-galloping devices like pendulums (any position, any orientation) can be simulated either by local effect or distributed one.

In our modelling we have included horizontal, vertical and torsional damping by equivalent modal viscous damping, inertial and pendulum effects of ice are taken into account. We can used about 15 different kind of ice accretion shape, from very thin (like freezing rain) to very thick (like wet snow), from very light (200 kg/m3) to very heavy (900 kg/m3) density. Quasi-steady aerodynamic curves have been taken from literature ([2], [13], [14], [17], [20]) and from our own wind tunnel tests (for TV cable).
The atmospheric turbulence is not taken into account and thus the wind is assumed to be constant all along a span (even though this is not an intrinsic limitation of the modelling).
Ice accretion is supposed to be received instantaneously on the conductor all along the span at no-wind condition (means the same ice shape all along the span) but equilibrium position with conductor and bundle stiffness is afterwards evaluated, taking into account wind effects. So that ice accretion is defined by one angle (which is in fact the angle at anchoring or suspension point, independently of wind condition). The ice position varies finally all along the span due to bundle stiffness, ice pendulum effect and aerodynamic pitching moment, which is a function of ice shape and wind speed.
We supposed that suspension insulator can only move in longitudinal way (means V suspension insulator), that torsion, vertical and horizontal movement are zero at all fixation point (anchor and suspension) but the relative movement between subconductors is free at suspension insulator and restricted to actual design at anchoring level. The anchoring fixation in torsion is thus defined by a flexibility matrix which is easily managed automatically for the most of practical cases by the knowledge of yoke plate design.

I.2. Simple modelling

For the sake of simplicity, in relation with our aim in this paper, we reproduce here under only the two degrees of freedom equations, let's say for one mode of galloping and for one particular span of the section :

$$\ddot{y}_k + 2\,\xi_v\,\omega_v\,\dot{y}_k + \left(\frac{k\pi}{L_s}\right)^2 \frac{T}{m} y_k = \frac{2}{L_s} \int_0^{L_s} \left[\frac{f_v}{m} - g + \frac{m_i d_i}{m}\left(\ddot{\theta}\cos\theta - \dot{\theta}^2 \sin\theta\right)\right] \sin\left(\frac{k\pi}{L_s} z\right) dz \quad (1)$$

$$\ddot{\theta}_k + 2\,\xi_\theta \omega_\theta \dot{\theta}_k + \left(\frac{k\pi}{L_s}\right)^2 \frac{GJ}{I} \theta_k = \frac{2}{L_s} \int_0^{L_s} \left[\frac{f_\theta}{I} + \frac{m_i g d_i}{I}\cos\theta + \frac{m_i d_i}{I}\left(\ddot{y}\cos\theta - 2\dot{\theta}\dot{y}\sin\theta\right)\right] \sin\left(\frac{k\pi}{L_s} z\right) dz \quad (2)$$

where, y = global vertical displacement (m)
y_k = k th modal component of the vertical displacement (m)
L_s = span length (m)
ξ_v = vertical damping
f_v = vertical aerodynamic force per unit length (N/m)
m = bundle mass per unit length (Kg/m)
m_i = ice accretion mass on the bundle per unit length (Kg/m)
d_i = distance between the ice accretion centre of gravity and the subconductor centre (m)
θ = global torsional movement (radian)
θ_k = k th modal component of the torsional movement (radian)
ξ_θ = torsional damping
GJ = torsional stiffness of the bundle ($N.m^2$/radian)
I = bundle inertia per unit length (Kg.m)
f_θ = aerodynamic pitching moment per unit length (N)

ω_v and ω_θ are the frequencies (rad/s) of the studied mode (coupled with the others, but not represented here for the discussion), for example the up and down one loop mode. The other spans interact through the tension which is evaluated by an integration on all the section length.

To better understand physically the instability, let's do a linearisation around an equilibrium position (equilibrium position is the "virtual static equilibrium" position of the cable during wind event and in the presence of ice accretion, means that the former equation are solved by neglecting inertial and damping terms) :

$$\Delta\ddot{y}_k + \left[2\,\xi_v\,\omega_v + \frac{k_D U_0}{m}\left(C_D - \partial C_L\right)\right]\Delta\dot{y}_k + \omega_v^2\,\Delta y_k = \frac{k_D U_0^2}{m}\,\partial C_L\,\Delta\theta_k \qquad (3)$$

$$\Delta\ddot{\theta}_k + 2\,\xi_\theta\omega_\theta\Delta\dot{\theta}_k + \omega_\theta^2\left(1 + \frac{m_i g d_i}{I\,\omega_\theta^2}\sin\theta_0 - \frac{k_M U_0^2}{I\,\omega_\theta^2}\partial C_M\right)\Delta\theta_k = \frac{m_i\,d_i}{m}\cos\theta_0\,\Delta\ddot{y}_k + \frac{k_M U_0}{I}\partial C_M\,\Delta\dot{y}_k \qquad (4)$$

where, U_0 = horizontal wind speed (m/s)

$k_D = 0.5\ nsc\ \rho\ \phi$

$k_M = k_D\ \phi$

ρ = air density (Kg/m^3)

nsc = number of subconductor

ϕ = subconductor diameter (m)

$\Delta y_k = y_k - y_{0,k}$ and $\Delta\theta_k = \theta_k - \theta_{0,k}$

$y_{0,k} = y_k$ in the virtual static equilibrium

$\theta_{0,k} = \theta_k$ in the virtual static equilibrium

C_D = drag coefficient (weighted value along the span length)

∂C_L = derivative of the lift coefficient (weighted value along the span length)

∂C_M = derivative of the pitching moment coefficient (weighted value along the span length)

For the sake of simplicity of the discussion we didn't take into account some terms which are negligible in most of the practical cases (like coupling between vertical and torsional movement due to the ice eccentricity for the vertical equation, limit to one mode neglecting intermodal coupling). This system is similar to the system obtained by Rawlins [15], Richardson [17] and Yu [21] but used in their cases with constant θ along the span.

The system will develop a galloping if the "virtual static equilibrium" (VSE) is not stable. The problem is fully non-linear so that it could be doubtful to apply linear stability approach to obtain the stability of VSE. Nevertheless it could be applied for a very small perturbation around the VSE. Amplitude could even be evaluated by describing function analysis for example. The best would be to evaluate Lyapounov coefficient, but this need cumbersome time analysis.
A program based on the simplified linearised equations has been developed. Even if the results are less accurate than time analysis, the influence of different structural parameters can be easily put into evidence. Confirmation is obtained afterwards by time analysis.

I.3. Amplitudes

Simplified formula for amplitudes can easily be obtained by describing function analysis.

For vertical :

$$\bar{y}_k = \frac{\omega \Delta y_k}{U_0} = \frac{\zeta \, \partial C_L}{\omega_r\left[\left(\frac{P_1}{\omega_r}\right)^2 - 1\right] + \left(2\xi_v P_1 + \zeta C_D\right)j}\Delta\varphi \quad (5)$$

where, P_1 = vertical / torsional frequencies ratio with wind and ice

ω = pulsation of the galloping limit cycle

$\omega_r = \omega / \omega_\theta$

$\zeta = \frac{k_D \, U_0}{m \, \omega_\theta}$

For torsion :

$$\Delta\theta_k = \frac{-\frac{P_5 \, P_6}{\zeta}\omega_r \cos\theta_0 + P_2 \, \partial C_M j}{-\omega_r^2 + 1 - P_2 \, \partial C_M + P_5 \sin\theta_0 + 2\xi_\theta \omega_r j}\bar{y}_k \quad (6)$$

where, $P_2 = \frac{k_M \, U_0^2 \, L_s^2}{k^2 \pi^2 \, GJ}$

$P_5 = \frac{m_i \, g \, d_i \, L_s^2}{k^2 \pi^2 \, GJ}$

$P_6 = \frac{k_D \, U_0^2 \, L_s^2}{m \, g}$

$\Delta\varphi$ is the angle of attack variation for limit cycle analysis (this is mainly connected to aerodynamic curves). The first formula shows that the galloping amplitude strongly depends on the aerodynamic coefficients and thus on the ice deposit angle. But amplitude is also dependent on structural parameters and angle of attack. This last being influenced by torsion.

I.4. A case study

For this study we used a section of two same spans length (350 m), with twin horizontal bundle (2 x AMS 620^2, Aluminium-Alloy). The diameter of one subconductor is equal to 32.31 mm and the space between subconductors is equal to 0.45 m. The torsional stiffness of one cable is equal to 400 Nm^2/radian and its mass per unit length is equal to 1.791 Kg/m. The sagging tension in one subconductor is equal to 35000 N. We considered also that the wind speed is equal to 15 m/s with the Nigol curve and a very heavy ice density (900 Kg/m^3). The ice thickness is equal to 11.31 mm. Rigid spacers are used every 60 m. The vertical and torsional frequencies (without wind nor ice) for up and down oscillation are respectively equal to 0.2 and 0.221 Hz. The structural damping in vertical is equal to 2 % of critical value and the torsional damping is equal to 4 %. The structural parameters don't change excepted when it is notified explicitly.

II. ANTI-GALLOPING DEVICES

II.1. Torsional stiffness

If we increase the torsional stiffness, the only effect is on torsional frequency which will increase, thus the tuning factor (ratio vertical/torsional frequency without ice nor wind) will be shifted. 20% shift is a practical good estimate which is available with pendulums of limited extra-weight.
There are some problems in relation with torsional stiffness increase. Torsional frequency is also a function of wind speed and anchoring fixation. The free oscillation torsional frequency can be higher (twin horizontal) or lower (quad) than vertical frequency and this is also influenced by spacer type (rotating clamp spacer, spacer with some pendulum effects). The increase of the torsional frequency must be done with enough detuning effect to avoid the tuning for some wind speed and some aerodynamic pitching moment. But a too large detuning is difficult to obtain (for weight problem) and also of some danger for tuning with other frequencies (other modes). Moreover local eccentric masses to obtain such a detuning can cause aeolian vibration damage (no more damper between two eccentric masses), depending on conductor type and every day stress used.

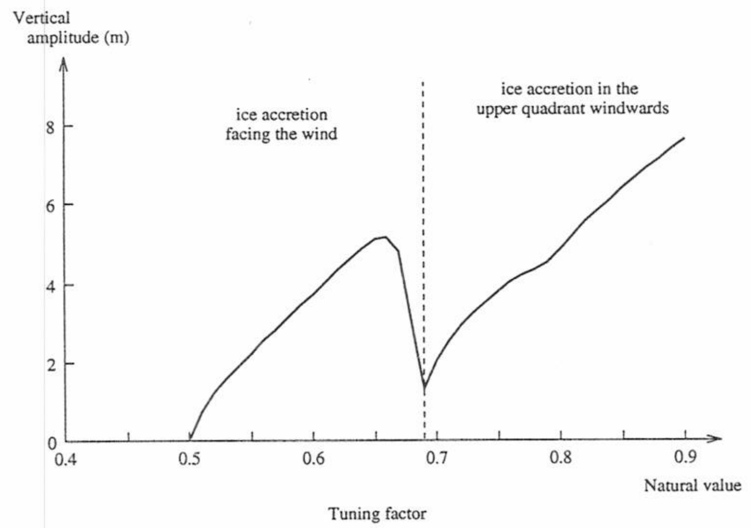

Fig. 1. Maximal peak-to-peak vertical amplitude of the galloping as a function of the tuning factor (vertical frequency / torsional frequency without ice nor wind) for an increase of the torsional stiffness.

The figure illustrates the detuning effect on the maximum amplitude of galloping, by the torsional stiffness increase. It shows that the detuning must be executed carefully. The part between 0.5 and 0.7 corresponds to a different zone of ice deposit angles.

This idea of pendulums has been first developed by Ontario Hydro (Canada) by Nigol and Havard and is widely used in USA and Canada with some success [7].

II.2. Moment of inertia

The increase of the moment of inertia also changes the torsional frequency (to decrease it) and has also the advantage to influence some coupling terms between vertical and torsional motion. These coupling terms are fundamental to guide the transfer of energy from wind to vertical movement through the angle of attack and cause the so called "flutter" galloping.

But this method has some disadvantages. As torsional frequency is higher than vertical frequency for twin bundle (the widely used geometry), the detuning must first overlap the vertical frequency before starting the efficient detuning. But unfortunately the maximal amplitude is obtained for a tuning factor greater than 1, thus the detuning must be more important than in the case of an increase of torsional

rigidity. Due to the fact that moment of inertia increase needs much more mass, compared to the same frequency shift obtained by torsional stiffness increase (that is because the arm length of the mass must remain short - about 0.5 m -), this could force to reinforce tower legs , crossarms and fitting in some cases. We have also the same disadvantages as for pendulum what concerns torsional frequency dependence with wind speed.
One could argue that a simple way to increase moment of inertia would be to simply design with a larger bundle diameter. In such a case the moment of inertia is well increased but this has no effect on detuning because the torsional stiffness is increased in the same way, nevertheless the coupling terms remains affected in the appropriate way. This point will be presented below.

The following figure details the detuning effect on the amplitude, caused by the artificial increase of the moment of inertia (means using appropriate device with two symmetric eccentric masses) :

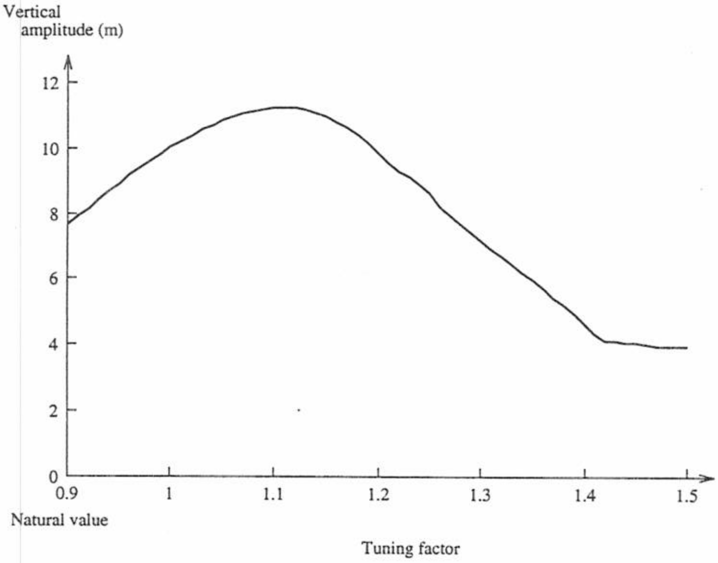

Fig. 2. Maximal peak-to-peak vertical amplitude of the galloping as a function of the tuning factor (vertical frequency / torsional frequency without ice nor wind) for an increase of the torsional inertia.

As explained before the curve present a maximum for a value of tuning factor about 1.1. And in this case even for a detuning of 1.5, the maximal amplitude is decreased of only the half.

The following figure details the effect of bundle diameter on the galloping amplitude :

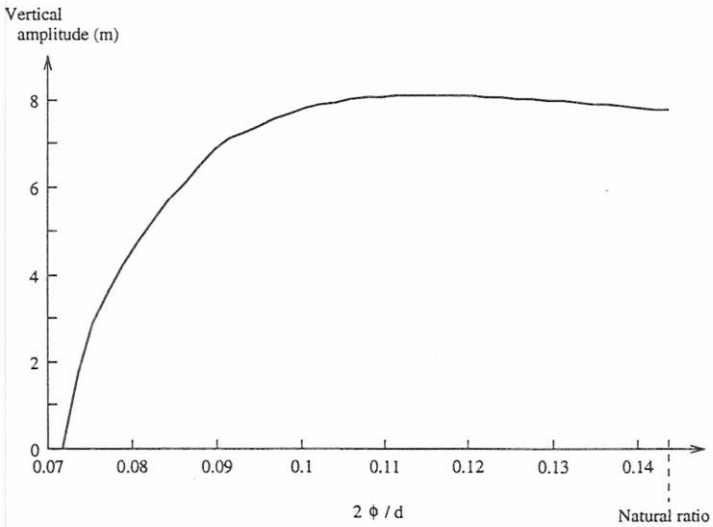

Fig. 3. Maximal peak-to-peak vertical amplitude of the galloping as a function of the ratio between the the subconductor diameter and the bundle diameter (ratio multiplied by 2).

The basic case correspond to the value 0.1436 and if the diameter of the subconductor is constant, the bundle diameter must be doubled to eliminate the risk of galloping. This would probably be the best way in our case study.

This method has been developed by some Japanese manufacturers (Sumitomo Electric and Furukawa Electric) and used on bundle up to quad configuration with some success [18].

3. The increase of torsional stiffness together with the increase of torsional damping.

To better understand this proposal , we need some more explanations on the physical mechanism of galloping , we are speaking about flutter galloping, not Den-Hartog galloping (this last can be induced only by very specific aerodynamic curves, very rare for our point of view).

The flutter instability is caused by the coupling between torsional and vertical movement. Energy cannot be directly inputted into vertical movement because Den-Hartog condition is not fulfilled (means roughly that the drag coefficient is not lower than lift derivative of appropriate sign). Energy from the wind is transfer to vertical movement owing to the angle of attack, which is directly connected to torsion of the bundle. So that both torsional amplitude and phase shift with vertical movement is of prime importance for instability, growth of amplitude and limit cycle amplitude.

If the vertical equation (3) of the movement is used to make the difference between the energy transmitted by the wind to the vertical movement and the energy dissipated by this one, a simple condition of instability can be obtained :

$$(C_D - \partial C_L)\Delta\alpha < \partial C_L \Delta\theta \sin\Phi \qquad (7)$$

where Φ is the phase shift between the torsion and the vertical displacement which can be deduced directly from the equation of the torsional amplitude (6). $\Delta\alpha$ is the part of the angle of attack due to the vertical displacement. Thus to get instability for the ice angle studied, $\partial C_L \sin\Phi$ must be at least positive. And the more Φ will be close to 90°, the higher the instability will be.

The following figure indicates a typical galloping ellipse and all along its trajectory, the position of ice and the direction of the aerodynamic force (of course this picture is deduced from 3 dof modelling) :

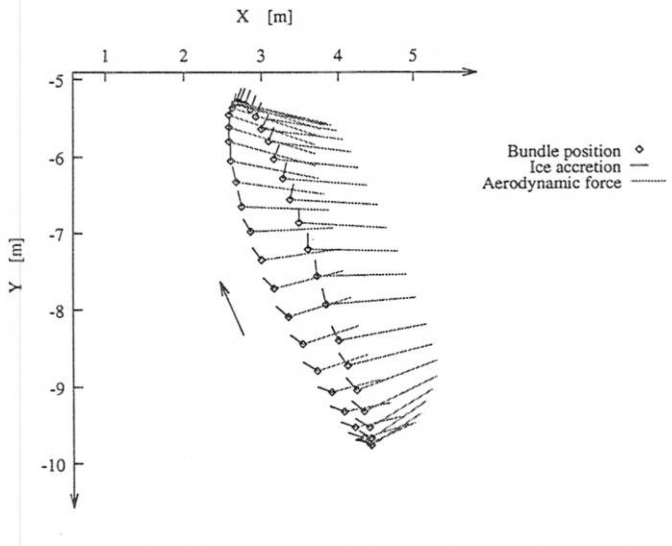

Fig. 4. View of the position of the bundle at mid span every 0.1 second. The directions of the ice accretion (straight short line) and aerodynamic forces (dotted line) are also represented. (this curve is obtained by full 3-DOF modelling in time analysis)

So that it is clear that, if detuning is important to decrease the amplitude, the increase of torsional (and vertical) damping is a leading factor to limit amplitude or even to avoid instability.

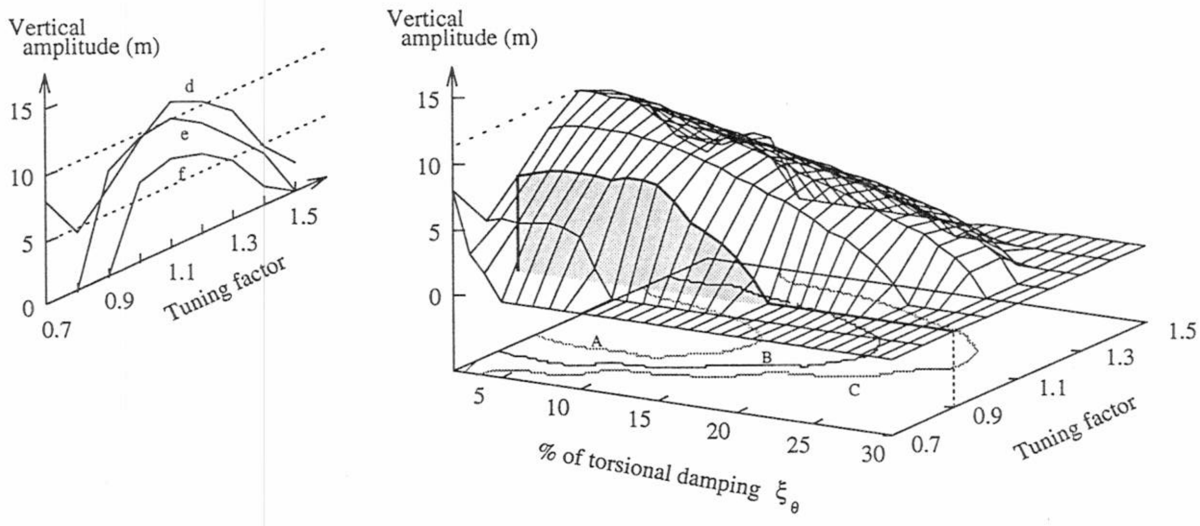

Fig. 5. Maximal peak-to-peak vertical amplitude of the galloping as a function of the tuning factor the torsional damping. The shadowed area corresponds to the natural tuning factor. The 3 curves in the parameters plan are the level curves corresponding to a vertical amplitude of 2.8 m (C), 5.7 m (B) and 8.5 m (A). The curves d, e and f show the influence of the tuning ratio for respectively 2, 10, 18 % of torsional damping.

This figure summarises the influence of the combination of detuning and torsional damping on the maximal vertical amplitude of galloping. The part of the graphic (shadowed area) corresponding to the natural tuning shows that the maximal amplitude got a maximum with the torsional damping. It can be explained by the vertical equation (5) where the amplitude is proportional to $\Delta\varphi$ and to the average on the limit cycle of the lift coefficient derivative. The first factor decrease with torsional damping but the second can increase, it depend on the aerodynamic curves and the angle attack variation. *We can see easily than the more efficient solution is to decrease the tuning factor and increase the torsional damping.*

III. A PRACTICAL DEVICE

The question coming now is how to increase the torsional damping? This has been done recently by the design of a new kind of anti-galloping device : the TDD (torsional damper and detuner), which mixes the increase of torsional frequency by a pendulum effect and increase the torsional damping by high dissipative synthetic rubber. The damping increase with the square of the torsional amplitude of the TDD rotating parts, without changing the torsional stiffness increase. Moreover appropriate design can easily also managed protection against aeolian vibration.
Moreover, nowadays it appears some new kind of conductors, so called "smooth conductors" , which have been proved to have a sensible increase of both vertical and torsional damping at low frequency. It is an evidence that such conductors will be very valuable to decrease galloping sensitivity, if used in bundle configuration.

The effectiveness of TDD is in connection with the tuning on some galloping frequency, TDD is a dynamic active device. TDD has to be tuned on vertical galloping frequencies which are not very much influenced by wind speed nor ice accretion. Due to its design TDD can acts in quite a large range of frequency which largely encapsulated dangerous ones. Even if galloping starts, TDD enter in resonance and its rotating amplitude will grow up and avoid energy transfer owing to phase shift modification between vertical and torsional frequency.

This has been proved recently by chance on an experimental line in Belgium on which TDD have been installed for only 3 years. This line has reference phase (without TDD) and one phase with 3 TDD installed following our recommendations (position, detuning factor, global mass), each of them were 13 kg only.
The following observations (under natural icing conditions) has been made :

Date	Meteorological conditions	Tension vibrations		
		Vibrating phase	Frequency	Max. peak-peak tension amplitude
17/11/1992 duration: 10 min.	wind speed : 18 to 40 km/h direction : 70° to line some gusts temperature : + 0.6 °C light snow	without TDD with TDD	0.39 Hz 0.38 and 0.55 Hz	10 kN 1.3 kN

This is of course not a definite prove of the efficiency, we need more observations and for that we need more tests span.

CONCLUSION

Galloping on bundle conductor lines is very dangerous and needs appropriate actions. We have proved that if detuning is a key point to avoid galloping, the additional damping in torsion is of some help. Torsional damping is manageable, as has been proved by recent observation, and optimum anti-galloping device characteristics (combining detuning effect and increasing damping) can be evaluated by simulation.
In the computed case, a detuning vertical / torsion of 0.8 (by increasing torsional frequency) coupled with 10 % of torsional damping (structural basic damping is around 4 %) will suppress galloping for wind speed up to 15 m/s. Without extra damping, amplitude would be 5 m. Without detuning nor extra damping, amplitude would be about 8 m.
Recent observation clearly point out a reduction by a factor 8 of tension variation during natural icing galloping event in Belgium. More experimental observations could qualify this new approach.

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