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OVERHEAD TRANSMISSION LINES DESIGN
SOME MECHANICAL ASPECTS

J.L. Lilien J. Wang O. Chabart P. Pirotte

Montefiore Electrical Institute
University of Liège, B-4000 Liège, Belgium

Abstract - The importance of mechanical effects on long distance power transmission lines, especially galloping is detailed in this paper. A new three-degree-of-freedom (3-DOF) iced-transmission line system is described. The specific galloping parameters are given as a simplified approach. Some simulations are also detailed as a help for overhead transmission lines design.

INTRODUCTION

With long distance power transmission lines of HVAC and HVDC, there are not only electrical aspects to be considered. If a general collapse occurs due to mechanical aspects, there will be no way to refit all the power system.

This paper deals with galloping. Galloping is a large amplitude, low frequency and wind-induced oscillation on both single and bundle overhead transmission lines. Even though galloping is sometimes weak and fugitive, in some other cases it may cause lots of troubles. The effects of galloping on a line are dependent on the severity and the duration of the event and on the type of line construction. The typical problems that galloping causes are:

The electrical damage: Because galloping amplitudes may approach or even exceed the sag of the span, the conductors may get too close so that it may cause phase-to-phase flashovers, which make circuit breakers operation and the arcing damage to conductors. After a few time, the galloping lines must be tripped out with many problems for network operation.

The mechanical damage: When galloping occurs, the strings and towers are subjected to great dynamic stress leading to damage to strings and towers, such as loosering and ejection of tower bolts, wearing on landing bolts, ovalling of hole and distortion of tower swivels as well as associated hardware. Galloping also causes the fatigue of conductor at semi-tension strings, jumpers and tower steelwork during sustained events. In addition, damages to spacers and stock-bridge dampers, to subconductor strands at suspension clamps and spacer clamps from fault current can also occur.

Of course, the cost of repair and the lost of revenue are also two important factors to define the risk. In several instances the losses of revenue due to gallop-induced outages have exceeded $500,000 for a utility in one year [14].

Although this problem has been recognized for about 60 years [1,2,3,4], because of the complexity of galloping mechanism, there is no definite way to avoid it.

Before any special investigation on anti-galloping device, it is always necessary to perform an appropriate structural analysis to point out the effects of some basic choices on galloping phenomena. Important parameters of transmission lines are: type of conductor, span length, subconductor diameter, bundle geometry, type and number of spacers, sag-span ratio, yoke plate dimension, bundle orientation, etc.

This paper describes some analyses including the theoretical modeling and specific approach on the transmission line system with its important parameters. Various simulations on real cases are given as a help for overhead transmission lines design.

BASIC MECHANISM

Galloping is nearly always caused by moderately strong, steady cross-winds acting upon an asymmetrically iced conductor surface. This asymmetry generally appears when the meteorological conditions are favorable to formation of ice coating around the conductors which grows preferentially on the side facing the wind or the precipitation. The origin of galloping is caused by two aerodynamic forces due to the wind action on an asymmetrical conductor profile. Because of boundary conditions, cable can rotate only around its shear center. So that the aerodynamic drag and lift (acting in the aerodynamic center) are replaced by three loads acting in the shear center of the cable: the same drag f_D and lift f_L, and an additional pitching moment M_W. The drag and lift forces are respectively oriented parallelly and perpendicularly to the relative wind speed which refers to conductor in movement. The reference directions are defined in Figure 1.

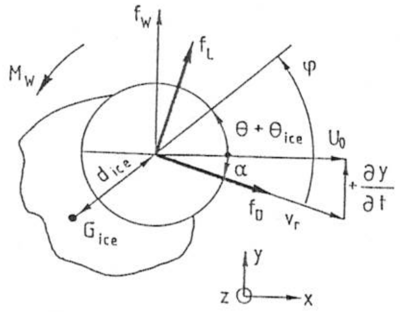


Figure 1: Definition for angles and forces

According to aerodynamics, the drag force f_D, lift force f_L and moment M_W are given by

$$f_D = K_D V_r^2 C_D(\varphi), \quad f_L = K_D V_r^2 C_L(\varphi), \quad M_w = K_M V_r^2 C_M(\varphi)$$

$$\text{with } K_D = \tfrac{1}{2}\rho_{air}\phi \text{ and } K_M = \tfrac{1}{2}\rho_{air}\phi^2$$

where ρ_{air} is mass density of air, V_r is relative wind speed, ϕ is diameter of conductor, C_D, C_L and C_M represent aerodynamic coefficients of drag, lift and moment. The eccentricity of ice shape is defined by $\varepsilon = 2(\frac{d_{ice}}{0.5\phi} - 1)$, where d_{ice} is the distance between the shear center of conductor and the center of the ice gravity. For a 3/2 eccentricity ice shape, the general shapes of aerodynamic coefficients are shown in Figure 2.

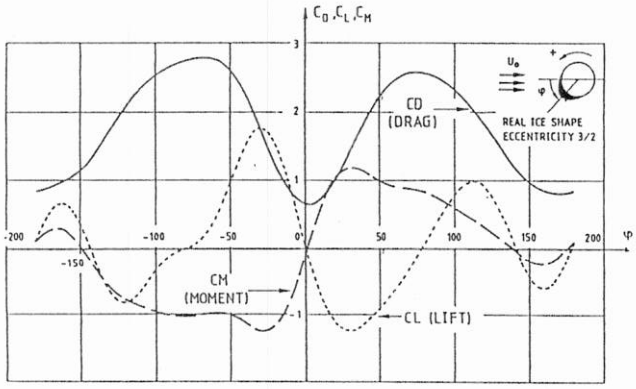


Figure 2: Aerodynamic coefficients of drag, lift and moment [5]

For some appropriate ice accretion angle θ_{ice}, the aerodynamic coefficients behave that upwards velocity increases the vertical force and inversely for a downwards velocity. The drag damping effect can be so compensated that a self-sustained oscillation appears. This oscillation is so called galloping.

A NEW 3-DOF TRANSMISSION LINE SYSTEM

The early theory of galloping was formalized by Den Hartog [1], without taking into account the dynamic effect of torsion. Early in the eighties, Rawlins [12] already presented the linearized stability equations in 3-DOF for galloping on single conductor. Today very few developments on both stability and time response analysis have been performed on bundle conductors. Yu *et al* [7] recently published some interesting developments in the field, limited to single conductor, but including some new insights in stability analysis and time analysis.

We developed a full 3-DOF analysis on both single and bundle conductors including stability analysis, parameter analysis and time response. This development includes the appropriate modelization of bundle torsional stiffness and tension oscillation including multi-span sections. All mixing between 1, 2 and 3 loops galloping are included in our theory, together with all so called "second order" coupling terms which sometimes were neglected [3,6]. This part describes a generalization on some former developments [8,9] based on 2-DOF model after our comparison between 2-DOF and 3-DOF models [10].

The basic second-order partial derivatives equations for vertical, horizontal and torsional motion can be found in the literature for cable structures [11] as the following form

$$m\ddot{y} + C_y\dot{y} + K_y y = -mg + F_v \quad (1)$$

$$m\ddot{x} + C_x\dot{x} + K_x x = F_h \quad (2)$$

$$I\ddot{\theta} + C_\theta\dot{\theta} + K_\theta\theta = M_w \quad (3)$$

where y and x are the displacements in vertical and horizontal, respectively, θ is the torsional angle. The definition for angles and forces in this 3-DOF system is shown in Figure 1. The coefficient C_y, C_x and C_θ represent the damping, and K_y, K_x and K_θ represent the stiffness in these 3 degrees of freedom, The F_v, F_h and M_w are corresponding the external excitations on the conductor system. They are combined by the aerodynamic drag, lift and moment due to the asymmetrical profile, which are written in part 2. Furthermore, m and I are the mass and the moment of inertia of the iced conductor's cross-section per unit length.

Model decomposition of the function $y(z,t)$ (vertical), $x(z,t)$ (horizontal) and $\theta(z,t)$ (torsion) are given by

$$y(z,t) = \sum_{k=1}^{\infty} y_k(t)\sin k\delta \quad (4)$$

$$x(z,t) = \sum_{k=1}^{\infty} x_k(t)\sin k\delta \quad (5)$$

$$\theta(z,t) = \sum_{k=1}^{\infty} \theta_k(t)\sin k\delta \quad (6)$$

$$\text{with} \quad \delta = \frac{\pi z}{L}$$

where t represents time, L and z are span length and the distance from the beginning of the span to the point where to be studied. k is model number.

The 3-DOF conductor system with each mode k are described by

$$m\ddot{y}_k + C_y\dot{y}_k + T\left(\frac{k\pi}{L}\right)^2 y_k = \frac{2}{\pi}\int_0^\pi [-mg + F_v]\sin k\delta d\delta \quad (7)$$

$$m\ddot{x}_k + C_x\dot{x}_k + T\left(\frac{k\pi}{L}\right)^2 x_k = \frac{2}{\pi}\int_0^\pi [F_h]\sin k\delta d\delta \quad (8)$$

$$I\ddot{\theta}_k + C_\theta\dot{\theta}_k + GJ\left(\frac{k\pi}{L}\right)^2 \theta_k = \frac{2}{\pi}\int_0^\pi [M_w]\sin k\delta d\delta \quad (9)$$

where T, the tension on the cable is given by the constitutive law which needs to consider appropriate evaluation of deformed length of the cable from tension to tension tower (including all suspensions and spans in one section). GJ represents the torsional stiffness, which is linear for the single conductor but highly non-linear for bundle. Bundle stiffness depends on many parameters such as tension, spacer, number of subspan and yoke plate, etc.

The angle of attack

In this line system, one of the most active factor is the angle of attack. It is defined as φ in Figure 1.

The source of the external excitations is wind. The wind velocity relative to the conductor is described by

$$v_x = V_{0x} - R\dot{\theta}\sin(\theta_0 + \theta) - \dot{x}$$

$$v_y = V_{0y} + R\dot{\theta}\cos(\theta_0 + \theta) - \dot{y}$$

Therefore the relative wind velocity is given by

$$V_r = \sqrt{[V_{0x} - R\dot{\theta}\sin(\theta_0 + \theta) - \dot{x}]^2 + [V_{0y} + R\dot{\theta}\cos(\theta_0 + \theta) - \dot{y}]^2} \quad (10)$$

where θ_0 is the angle in the original equilibrium position, generally it is the ice accretion angle θ_{ice}. V_{0x} and V_{0y} are the components of wind velocity. R is the radius of subconductor.

The angle of attack is described by

$$\varphi = \theta_0 + \theta - \frac{r_i}{V_0}\dot{\theta} - \alpha \quad (11)$$

where r_i, called characteristic radius, is the distance between the shear center of conductor and the center of the ice gravity (d_{ice}). V_0 is the true wind speed.

The angle α is given by

$$\alpha = \frac{V_{0y} + R\dot{\theta}\cos(\theta_0 + \theta) - \dot{y}}{V_{0x} - R\dot{\theta}\sin(\theta_0 + \theta) - \dot{x}} \quad (12)$$

The linearized line system

Under the basic approximation and after some analytical steps, the linearized external aerodynamic excitations on the line system are described by

$$\begin{pmatrix} \Delta F_v \\ \Delta F_h \\ \Delta M_w \end{pmatrix} = V_0 \begin{pmatrix} K_D(C_{L\alpha} - C_D) & -2K_D C_L & -K_D C_{L\alpha} r_i \\ K_D(C_{D\alpha} + C_L) & -2K_D C_D & -K_D C_{D\alpha} r_i \\ K_M C_{M\alpha} & -2K_M C_M & -K_M C_{M\alpha} r_i \end{pmatrix} \begin{pmatrix} \Delta\dot{y} \\ \Delta\dot{x} \\ \Delta\dot{\theta} \end{pmatrix}$$

$$+ V_0^2 \begin{pmatrix} 0 & 0 & K_D C_{L\alpha} \\ 0 & 0 & K_D C_{D\alpha} \\ 0 & 0 & K_M C_{M\alpha} \end{pmatrix} \begin{pmatrix} \Delta y \\ \Delta x \\ \Delta\theta \end{pmatrix} \tag{13}$$

where $C_{D\alpha}$, $C_{L\alpha}$ and $C_{M\alpha}$ are the first order derivatives of aerodynamic coefficients of the drag, lift and moment to φ respectively.

The modified aerodynamic coefficients are given by

$$\overline{\Psi} = \frac{2}{\pi}\int_0^{\pi} \Psi \sin^2 k\delta d\delta \tag{14}$$

where Ψ represents C_D, C_L, C_M, $C_{D\alpha}$, $C_{L\alpha}$, $C_{M\alpha}$, $\sin\theta_0$ and $\cos\theta_0$, respectively.

Therefore, the 3-DOF linearized conductor system with each mode k is obtained in matrix form by

$$\begin{pmatrix} 1 & 0 & -\frac{m_i r_i}{m}\overline{\cos\theta_0} \\ 0 & 1 & -\frac{m_i r_i}{m}\overline{\sin\theta_0} \\ -\frac{m_i r_i}{I}\overline{\cos\theta_0} & -\frac{m_i r_i}{I}\overline{\sin\theta_0} & 1 \end{pmatrix} \begin{pmatrix} \Delta\ddot{y}_k \\ \Delta\ddot{x}_k \\ \Delta\ddot{\theta}_k \end{pmatrix}$$

$$+ \begin{pmatrix} \frac{C_y}{m} + \frac{K_D V_0}{m}\left(\overline{C}_D - \overline{C}_{L\alpha}\right) & \frac{2K_D V_0}{m}\overline{C}_L & \frac{K_D r_i V_0}{m}\overline{C}_{L\alpha} \\ -\frac{K_D V_0}{m}\left(\overline{C}_{D\alpha} + \overline{C}_L\right) & \frac{C_x}{m} + \frac{2K_D V_0}{m}\overline{C}_D & \frac{K_D r_i V_0}{m}\overline{C}_{D\alpha} \\ -\frac{K_M V_0}{I}\overline{C}_{M\alpha} & \frac{2K_M V_0}{I}\overline{C}_M & \frac{C_\theta}{I} + \frac{K_M r_i V_0}{I}\overline{C}_{M\alpha} \end{pmatrix} \begin{pmatrix} \Delta\dot{y}_k \\ \Delta\dot{x}_k \\ \Delta\dot{\theta}_k \end{pmatrix}$$

$$+ \begin{pmatrix} \omega_v^2 & 0 & -\frac{K_D V_0^2}{m}\overline{C}_{L\alpha} \\ 0 & \omega_h^2 & -\frac{K_D V_0^2}{m}\overline{C}_{D\alpha} \\ 0 & 0 & \frac{GJ}{I}\left(\frac{k\pi}{L}\right)^2 - \frac{K_M V_0^2}{I}\overline{C}_{M\alpha} + \frac{m_i g r_i}{I}\overline{\sin\theta_0} \end{pmatrix} \begin{pmatrix} \Delta y_k \\ \Delta x_k \\ \Delta\theta_k \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \tag{15}$$

It is very similar to the system obtained by [12] but including a full non-liner description of GJ, the torsional stiffness, ω_v and ω_h by taking into account tension variation (not explained in detail here), which are linearized around the equilibrium position. Moreover Eq.(14) takes into account the non-uniform distribution of ice position along the span, this is also very different from former theories. From this line system, it is clearly to see the coupling terms including the second order ones between vertical, horizontal and torsional modes. The aerodynamic damping terms are also obvious in this system.

PARAMETER ANALYSIS

The basic important parameters of transmission lines are: type of cable, span length, subconductor diameter, bundle geometry, type and number of spacers, sag-span ratio, yoke plate dimension, bundle orientation, etc. In order to discover the most important physical parameters which influence galloping, a specific parameter analysis should be done.

The best way to define galloping parameters is to be able to write down the the instability criteria of linearized system with dimensionless values. Generally it has to be done in different steps. The easiest way is to simply get back all coefficients from Eq.(15) (3-DOF system). But by this way, there will be so many parameters and some of them have no significant physical meaning. In order to get parameters with significant physical meaning while as simple as possible, the basic parameters and coefficients of equations should be reduced from manipulation, generally according to the aspects of wind effect, structural effect and ice effect.

Based on some analysis from the literature [12] about single conductor, which is based on experimental results, the specific relations necessarily connecting the structural parameters of transmission line, wind and ice to galloping are found by the following galloping parameters:

- Synchronizing $Q_1 = \frac{\omega_v}{\omega_\theta}$
- Diameter ratio $Q_2 = \frac{2\phi}{d}$
- Reduced wind speed $Q_3 = \frac{V_0}{\phi f_v}$
- Reduced ice density $Q_4 = \frac{\rho_{ice}}{\rho_c}$
- Cable span parameter $Q_5 = \frac{\phi T_0}{L^2 mg}$

where d is the subconductor separation, f_v is vertical frequency without ice nor wind, ρ_{ice} and ρ_c represent the mass density of ice and conductor, respectively. L is the span length. The other basic physical parameters are introduced in the former parts. This is the first time that Q_2 and Q_5 are presented in the literature. In fact Q_5, obtained from the theory, mixed two parameters obtained by experimental observations by [12].

An example on the reduced wind speed

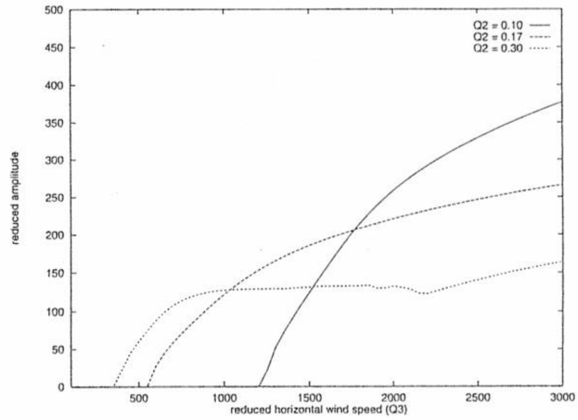


Figure 3: Parameter analysis

This example is based on the Norway case (in next part, case 2). The diameter ratio value $Q2$ in this case is 0.17. The Figure 3 shows the influence of the reduced wind speed $Q3$ on the reduced vertical amplitude $\frac{A_v}{\phi}$ with different diameter ratio values.

The aim of this approach is just to find the most important physical parameters which influence galloping by a simplified method.

SOME SIMULATIONS

Case 1

By observation in Europe, single conductor are less sensitive to galloping than bundles. The main reason is because the torsional stiffness of single conductor is low (a few hundred Nm^2 for diameters below $35mm$) than that of spacered bundle. Torsional stiffness of bundle conductors can be 20 times larger than that of single. Therefore the static analysis for torsional stiffness is very useful for transmission line design. The following example is about bundle stiffness.

We chose a dead-end span from a $380kV$ transmission line in Belgium, the span length is $234m$. Its basic data are: AMS $2 \times 620mm^2$ horizontal bundle, subconductor cross section $A = 620mm^2$, Young modulus $E = 5.3 \times 10^{10} N/m^2$, mass of subconductor $m = 1.8kg/m$, subconductor diameter $\phi = 32.4mm$, subconductor separation $d = 0.45m$, sagging tension per subconductor $T = 30000N$, intrinsic torsional stiffness $\tau = 460Nm^2$, four identical subspans in this span.

In order to evaluate the torsional stiffness, we apply a static torque at the mid-span. Torsional stiffness can be then got from the rotation angle. The simulation and the experiment results are shown in Figure 4.

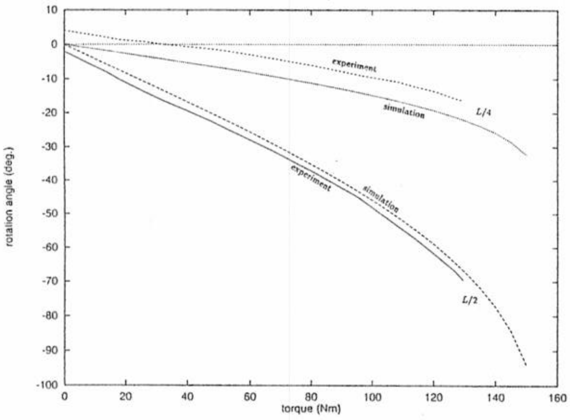


Figure 4: Bundle rotation angles

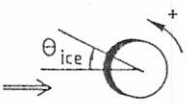
The experiment is performed by Laborelec (the Belgian laboratory for power plants and networks). Because this model takes nto account the tension variations between subconductors which has not been considered by the existing theory [13], and these tension variations may increase bundle stiffness more than 50% in some cases, the results of rotation angles at both mid-span and a quarter agree very much with the experiment. It is also clearly to see that the torsional stiffness will not be linear when the rotation is large.

Case 2

For galloping mechanism study and special investigation on anti-galloping device, it is always necessary to perform some simulations under appropriate meteorological conditions to see the galloping behavior and point out the effects of some basic choices on galloping phenomena. There is an important $420kV$ transmission line in Norway, where galloping occurred before. With this line there is a section of two spans between the anchoring towers. The span length is 292m and 196m respectively. Its basic data are: Horizontal twin bundle, subconductor cross section $A = 863.10mm^2$, Young modulus $E = 7.0\times10^{10}N/m^2$, mass of subconductor $m = 2.879kg/m$, subconductor diameter $\phi = 38.25mm$, subconductor separation $d = 0.45m$, sagging tension per subconductor $T = 50802.07N$, intrinsic torsional stiffness $\tau = 530Nm^2$, 15 spacers per span are chosen in this case.

Galloping will occur after a short time under the following external conditions:

$V_0 = 15m/s$



$\theta_{ice} = 50°$

$\varepsilon = \frac{1}{3}$ (ice thickness = $6mm$)

The view of galloping, its time evolution during limit cycle and some relative results are simulated as Figure 5 - 12.

Figure 5 gives the view of galloping in vertical from rising galloping to getting into the limit cycle, i.e. steady galloping. Figure 6 to 8 detail time evaluation at mid-span during steady galloping, by which we can find galloping amplitudes in vertical and horizontal, and torsional angle. It is also important to see the limit cycle shape at mid-span, i.e. galloping ellipse which is shown in Figure 9. This is very useful in establishing phase clearances. By analysis these results we can find this galloping is "up-down" type, and galloping frequencies can be also found from Fourier analyses.

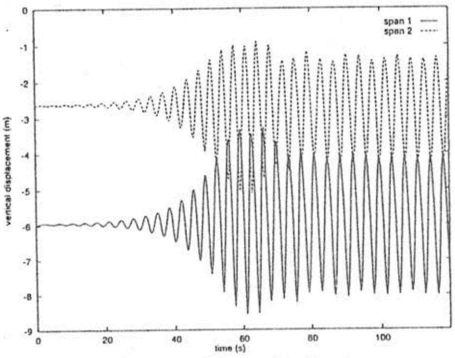


Figure 5: View of galloping

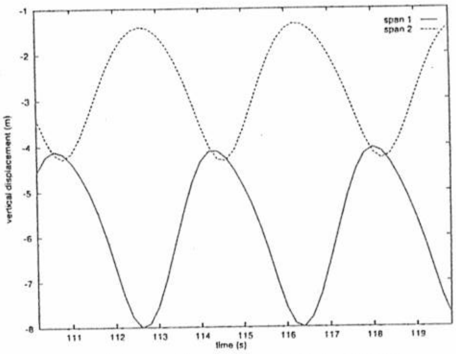


Figure 6: Vertical displacement

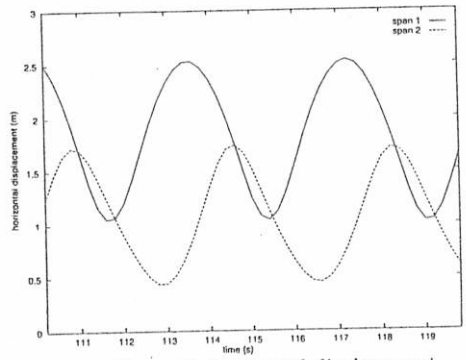


Figure 7: Horizontal displacement

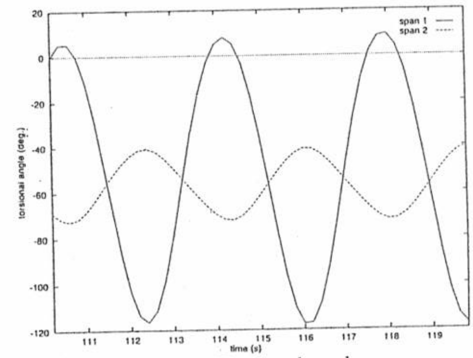


Figure 8: Torsional angle

CONCLUSIONS

Mechanical aspects are also very important to be considered for long distance power transmission lines of HVAC and HVDC. The phenomena of galloping can cause a lot of problems by both its electrical consequences (flashover between phases at each cycle of oscillation, i.e. once every 5 seconds) causing generally a definitive tripping out of the line for a long period of time, and mechanical damage. Anti-galloping devices are widely used as a method to avoid galloping. The comprehensive mathematical model is the foundation for performing structural

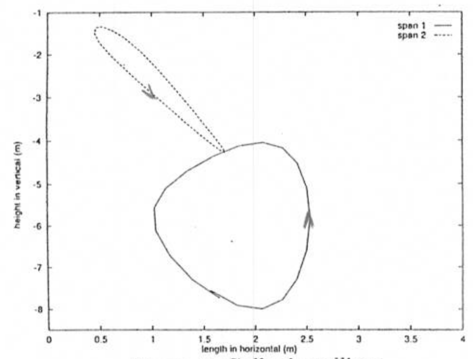


Figure 9: Galloping ellipse

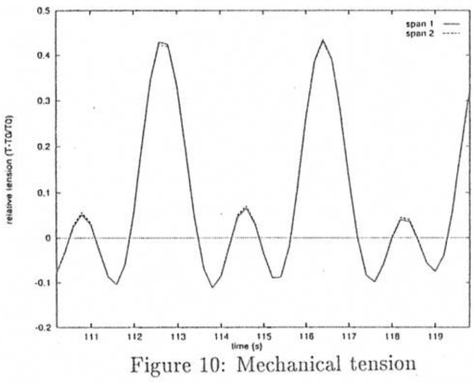


Figure 10: Mechanical tension

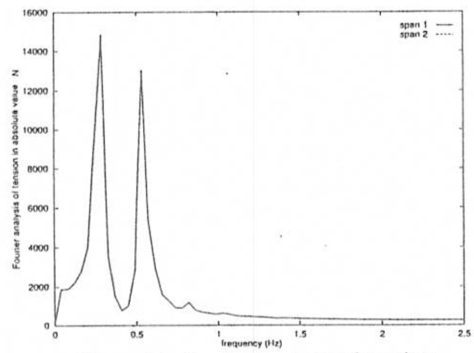


Figure 11: Fourier analysis of tension

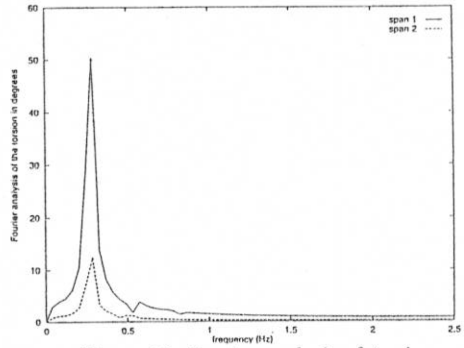


Figure 12: Fourier analysis of torsion

analysis for investigations on anti-galloping devices . A new 3-DOF mathematical model is detailed in this paper. This model takes into account the second order coupling factors between vertical, horizontal and torsional modes. It can effectively explain some behaviors for both single and bundle conductors, such as bundle stiffness, tension distribution, etc. Indeed, it can be then used for modelization of galloping by simple approach. The specific galloping parameters are also defined by which the most important physical parameters which influence galloping can be found by a simplified method. Several simulations with two real cases are performed. The results of the simulation on torsional stiffness perfectly agree with the experiment. General behaviors of galloping are simulated in a multi-span transmission line. The galloping amplitude in every DOF, tension oscillation, galloping ellipse and so on are also important informations for overhead transmission lines design.

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Jean-Louis Lilien was born in Liège, Belgium, on May 24, 1953. He received his degree in electrical and mechanical engineering in 1976 and his Ph.D degree in 1984 from the University of Liège. He is presently a *Chef de Travaux* in the Department of Transmission and Distribution of Electrical Energy at the same University and a consulting engineer for SAMTECH, a Belgian consultant firm. His main activity is based on the non-linear behavior of cable structures in power systems.

He was an expert of the CIGRE working group 23-02 (high current in substations) for ten years. He is now an expert of the task force on galloping, a part of the CIGRE working group 22-11. He participated to more than 20 international symposiums or congress and has published over forty technical papers. He received the international prize *George Montefiore* in 1986.

Jianwei Wang was born in Henan, China, on January 21, 1963. He received the B.S. degree from Zhengzhou Institute of Technology and the M.S. grade diploma from Southeast University, China, in 1985 and 1991 respectively, both in electrical engineering.

From 1985 to 1991 he worked as a teaching assistant and a lecturer in the Electrical Engineering Division at Nanjing Institute of Chemical Technology, China. In 1992 he joined the Department of Transmission and Distribution of Electrical Energy at the University of Liège as a researcher. He is presently working toward the Ph.D degree in the field of Overhead Lines Galloping at the same University.

Olivier Chabart was born in Seoul, Korea, on December 10, 1970. He received his degree in electrical and mechanical engineering from the University of Liège in 1993. He is presently a research engineer in the Department of Transmission and Distribution of Electrical Energy at the same University.

Pol Pirotte was born in Saint Georges, Belgium, on December 27,1936. He received his degree in electrical engineering from the University of Liège in 1960. After one year in Canada he received the M.S. degree from Laval University and his Ph.D degree from the University of Liège in 1972.

He is presently full professor in charge of the Transmission and Distribution of Electrical Energy branch.

He is convener of the 36-01 CIGRE Working Group (corona and fields).

He is involved in the organization of the CIGRE Conferences in England and Belgium every two years since 1971.

He has published over eighty technical papers in T and D fields.

He is Senior Member in IEEE.