# GALLOPING OF ELECTRICAL LINES IN WIND TUNNEL FACILITIES

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**ABSTRACT**. Galloping is a large amplitude, low frequency, wind-induced oscillation of overhead electrical lines. In the vast majority of cases, an ice accretion is present on the conductor : this has the effect of modifying the conductor's cross-sectional shape such that it becomes aerodynamically and/or aeroelastically unstable. [1-18]

This paper deals with galloping generated during wind tunnel testing. A typical eccentric ice shape has been reproduced on a classical stranded overhead line conductor. In the first part, the quasi-static aerodynamic coefficients have been measured for different wind speeds in the range of galloping observations. In the second part the same sample has been suspended in the wind tunnel by springs in order to obtain a system as close as possible of an overhead line (the vertical, horizontal and rotational movements are allowed). For appropriate angles of attack, galloping has been obtained. For electrical engineer, there are two kinds of galloping : Den-Hartog galloping and flutter galloping. The first one is an aerodynamic instability because the main factor at the origin of this problem is the aerodynamic properties of the ice deposit. The flutter galloping is an aeroelastic problem. For this type of instability, the structural properties of the line are also important and there is a coupling between at least two degrees of freedom. Both of them were recorded

These tests make available a full set of data and recordings of limit cycles during galloping events. Such measurements can be used for numerical model validation and for efficiency evaluation of some anti-galloping means (detuning, increase of damping in vertical, torsion, modification of rotational inertia, etc.). [11, 15]

## INTRODUCTION

Overhead lines galloping may bring flashover between phases and cause damage to the conductors, the fittings or the towers. It results that the reliability of energy transmission is affected; moreover construction costs must be increased to reduce the flashover probability. Numerous practical observations have been summarized in the literature [9, 10], mainly on single conductors.

Despite some nice papers on wind tunnel approach [2,6,13], there are no published, known by the authors, full experimental set of data of galloping, except one case on single conductor with partial results [14]. On the field there are many videos, but no access on the data of the lines and/or the wind speed and/or the ice shape, ... and of course (but obviously) no aerodynamic properties of the ice coating during observed event! Some recent tests on a full-scale site will give access in the next future to some extraordinary attractive results [17].

In fact in the past some field tests have been performed with artificial D shape which easily caused Den-Hartog galloping. For our point of view such tests do not reproduce actual galloping on overhead line, or only exceptionally. None of the wet snow, rime or glaze ice on overhead line conductors could reproduce a D shape [15]. Only very thin eccentric layer could induce Den-Hartog galloping for natural position of the ice eccentricity facing the wind [2,5,13]. But most of the deposits would not be like that.

A simple and cheap way to get a full data set is a laboratory test. As it is impossible to put an overhead lines in a wind tunnel and as reduced scale model will not reproduce the true phenomenon, we decided to experiment a string suspended model of a small section of the line. The conductor, the artificial ice and the wind remain as in the field but the span and interaction between spans in a line is replaced by giving to the model the appropriate frequencies of oscillations. As we were convinced with others [4, 6, 8] of the fundamental influence of the three frequencies (horizontal, vertical and torsion), appropriate test arrangements were installed. We have not the feedback related to tension changes in the cable, but this phenomena is very easily reproduced by simulation, and is not a fundamental parameter to evaluate galloping instabilities and influences of some parameters (like detuning, damping, etc.).

Our wind tunnel tests will give access to a full complete set of data for the validation of a numerical model. Moreover a nice experimental set is available to tests many parameters, like different frequencies for each degree of freedom (including the effect of detuning), the wake effect on galloping for bundle conductor (2 conductors will be putted in the tunnel), damping effects (appropriate dampers will be inserted in the test arrangement), etc.

After validation of a numerical model [12,17], the same model can then be used for full-scale simulations, including tension variation, full inter-spans effects, spacers effects, inter-phase spacers effects, etc.

## TEST SAMPLE

This paper will be restricted to one kind of ice shape, very eccentric (Figure 1). Other slightly eccentric shape has also been studied during our tests.

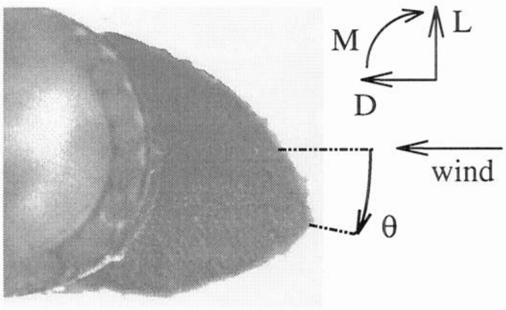

Figure 1. Ice shape and sign convention.

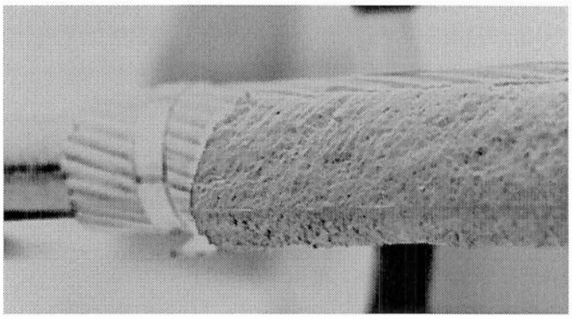

Figure 2. View of the ice sample.

The overhead line conductor is the one used in Belgium for 400 kV network : AMS (all aluminum alloy conductor) 620 $10^{-6}$ $m^2$ (diameter 32.5 $10^{-3}$ m). The outside layer of a conductor has been putted on an aluminum tube of appropriate diameter in order to maintain a straight line of the sample on approximately one-meter. Artificial ice has been chosen close to Mike Tunstall shape # 1 [13] and adapted to our outside diameter. The 'ice' in silicone (density 1.13) has been modeled on the cable with a wooden mold on which the roughness pattern has been printed (figure 2). This pattern has been copied from the original sample (itself obtained from a sample of real ice accretion). The length of the artificial ice is 0.8 meter and its eccentricity, the ratio between the ice thickness and the radius of the conductor, is 1.32. The distance between the center of gravity of the ice and the center of the cable is 2.17 $10^{-2}$ m.

## WIND TUNNEL FACILITIES

The wind tunnel of our university is small and originally designed and used by the aeronautical department. The 46 kW electrical engine allows a wind speed of 60 m/s, but the minimum wind speed is about 8 m/s. It is a close loop with an open section for the testing area. The diameter of the useful circular cross-section is 0.8 meter. The turbulence intensity is about 1 %.

The sample is suspended by a rigid rod to a frame and 3 dynamometers (10 kg maximal load, 0.1 % of deviation on full-scale measurement) are used to measure the aerodynamic coefficients. Two vertical dynamometers (set at 1 and 2 on the figure 5) measure the vertical force (L) and the moment (M). The last one (set at 3) measures the drag (D). The average of the forces over one minute is taken 3 times for each angle of attack and this for five different wind speeds (between 8 and 20 m/s). The 360 degrees range of angle of attack has been covered with an increment of 5°. The figure 3 shows the experimental measurements for a specific wind speed.

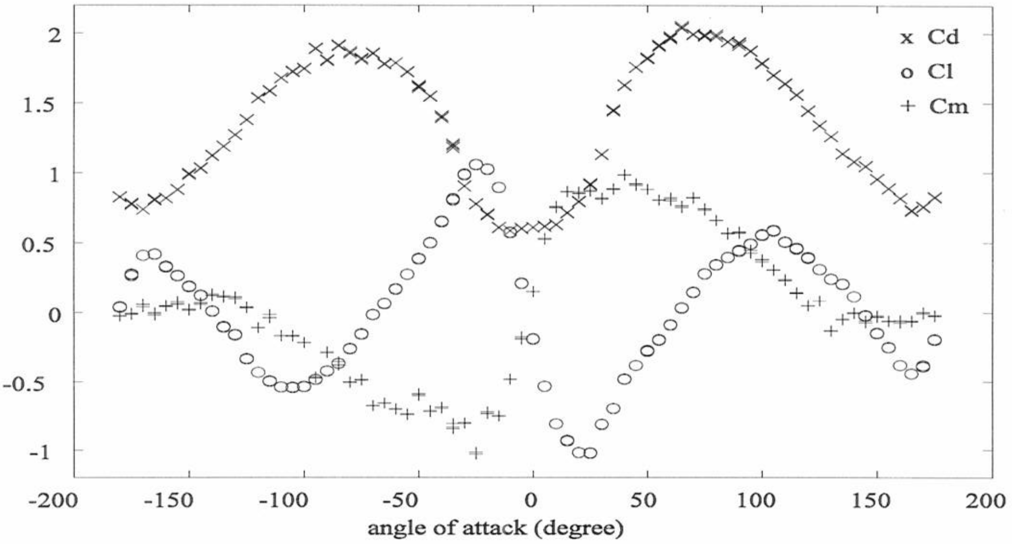

Figure 3. Measured values of the coefficients for 15 m/s.

In order to obtain usable curves, we apply different data processings (average, spline or Fourier interpolation). The figure 4 is an illustration of the final result.

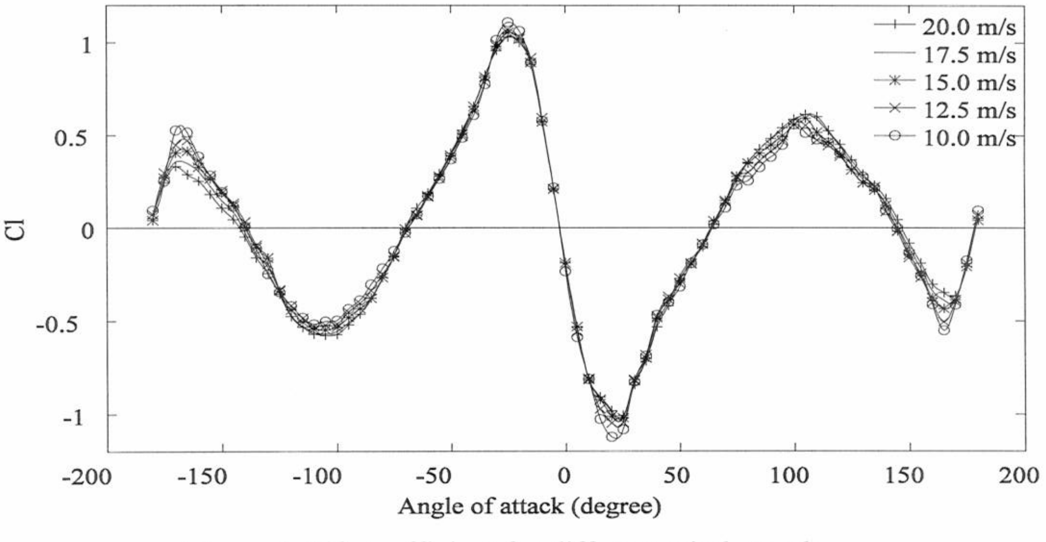

Figure 4. Lift coefficient for different wind speeds.

This figure shows that the effect of the wind speed on the lift coefficient is limited for the majority of the angles of attack. It is also true for the other coefficients. The evolution of the coefficients in function of the wind speed is in fact different for each angle of attack.

## GALLOPING IN WIND TUNNEL

The sample is suspended by 4 vertical springs in the wind tunnel (Figure 5). The 4 horizontal springs allow the horizontal oscillation of the system. All the springs have the same stiffness (14 N/m) but the vertical ones are prestressed in order to limit the static deformation due to the weight of the structure (2.99 Kg). To prevent that the wind blows on the springs and the part of the structure without ice, two vertical plates (not drawn on the figure) are placed just at the extremities of the ice sample. The convergent and the divergent of the wind tunnel have been slightly modified to join these plates. Two circular (diameter 0.2 m) openings allow the movement of the sample but limit the maximum amplitude. The damping in the structure is very low, about 0.08 % of critical damping for the vertical and horizontal movement and about 0.3 % for the rotation (measured by logarithmic decrement). The ratio between vertical and torsional frequencies is a factor often used to avoid the galloping, either by increasing the inertia or by increasing the torsional stiffness (addition of pendulums on the overhead line). In this case, it is easier to change the torsional stiffness, simply by modifying the distance between the vertical springs. The frame anchoring points can be moved in the spring direction to keep the sample in the center of the plates openings when the wind blows (if no instabilities are considered). The vertical and horizontal displacements of the sample and its rotation are recorded by means of a CCD camera working at 50 Hz and with a resolution of 520 pixels. A row of LEDs is placed at the end of the tube to make easier the processing (in real time) of the signal by a PC.

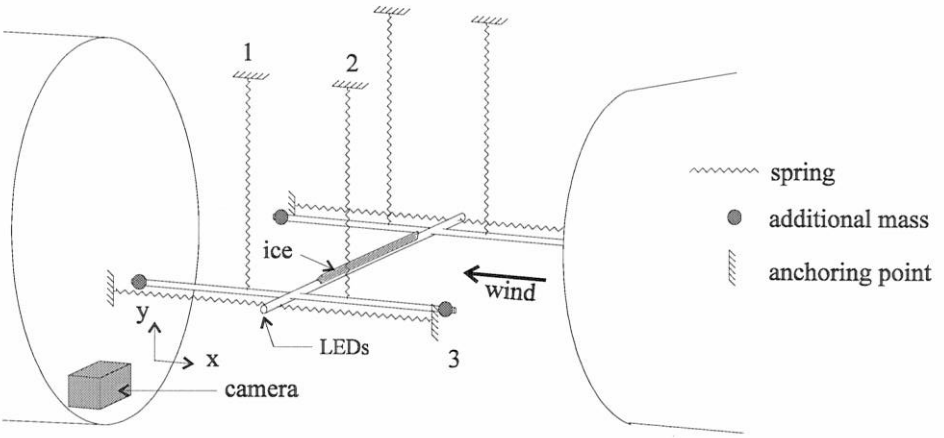

Figure 5. Diagram of the dynamic system in the wind tunnel.

The angular position of the ice with regard to the horizontal is noted θ (figure 1). The ice accretion angle ($\theta_0$) is the angle θ when the structure is horizontal. Different ice accretion angles and frequencies ratios have been tested, and this for different wind speeds. First the vertical springs have been placed at 0.12 m from the center of the sample. For this configuration and without wind, the measured vertical ( $f_V$ ), rotational ( $f_\theta$ ) and horizontal frequencies are respectively 0.845 Hz, 0.865 Hz and 0.995 Hz. So the ratio between the vertical and the rotational frequencies is about 1, as for a real overhead line with bundle conductors. Different ice accretion angles have been tested : classical upper quadrant windward (0° to -90°) and the following quadrant (-90° to -180°) in case of reverse wind [9]. The galloping amplitudes observed during our tests exceeded very often the limit of 0.2 m imposed by the openings in the vertical plates, even for the minimum wind speed allowed by the wind tunnel. The figures 6 to 9 show the results for a case where the amplitude remains limited. The reduced wind speed is defined by the ratio $U_0/(fd)$ where $U_0$ is the wind speed, f the galloping frequency and d the diameter of the conductor.

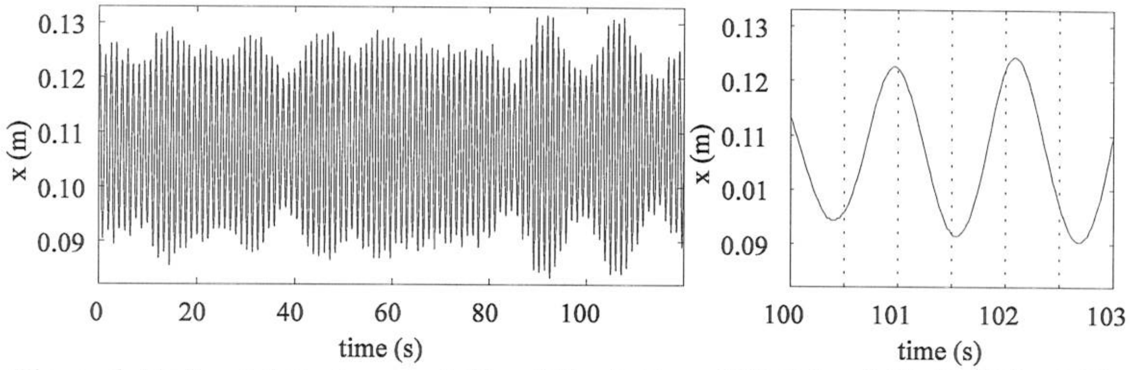

Figure 6. Horizontal displacement, $U_0 = 9.7$ m/s, $\theta_0 = -30°$, $f_v/f_\theta = 0.98$, $U_0/(fd) = 335$.

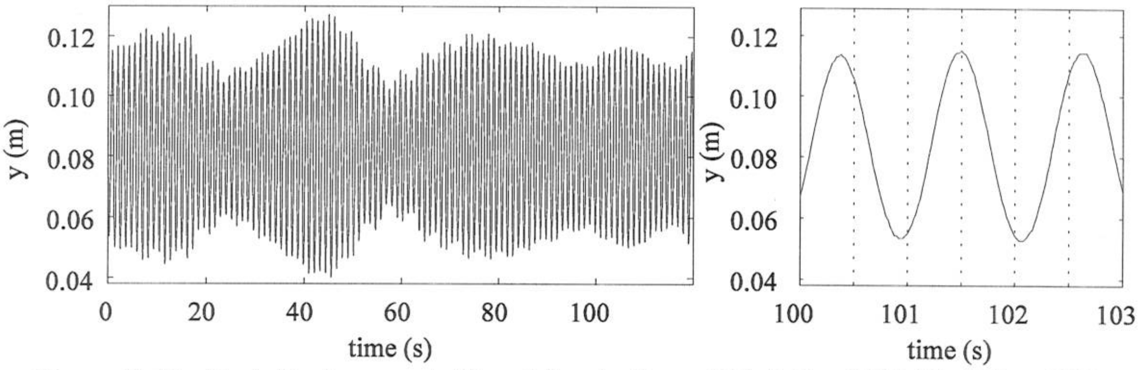

Figure 7. Vertical displacement, $U_0 = 9.7$ m/s, $\theta_0 = -30°$, $f_v/f_\theta = 0.98$, $U_0/(fd) = 335$.

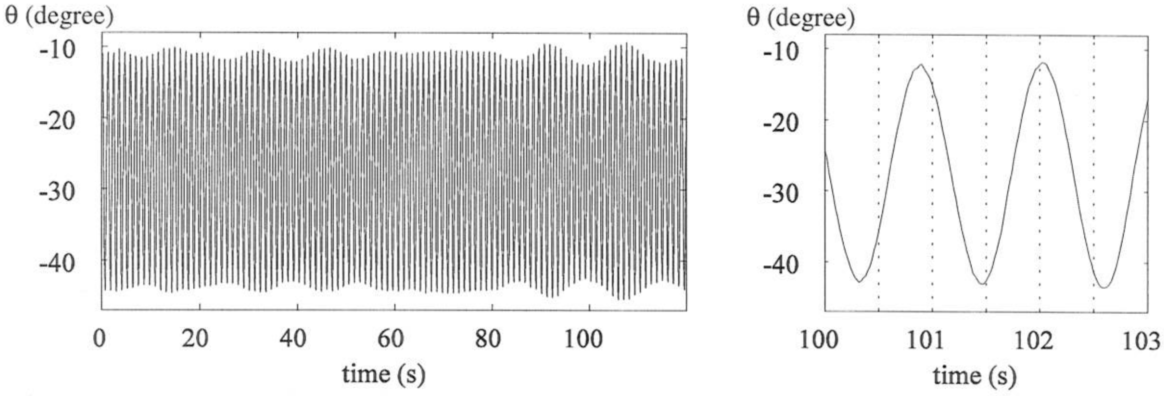

Figure 8. Angular position of the ice, $U_0 = 9.7$ m/s, $\theta_0 = -30°$, $f_v/f_\theta = 0.98$, $U_0/(fd) = 335$.

For this ice accretion angle ($\theta_0 = -30°$), the instability is too high to obtain the limit cycle (actually, a more or less stabilized response) when the wind speed is below 9 m/s and above 12.5 m/s. For the wind speeds between these two limits the following remarks can be made. The angular position variation remains constant (figure 8), but the maximal peak to peak rotational oscillation increases with the wind speed (from 36.1° to 52.8°). The vertical and horizontal oscillation amplitudes change with the time (figure 6 and 7). The frequencies of the three movements are the same, 0.89 Hz, this is the galloping frequency (means a reduced wind speed of 335). The trajectory of one point of the sample in the x-y plan is called the galloping 'ellipse'. Both the shape and the size of this ellipse are important for preventing the effect of galloping. It can be used by the designers of the towers as a passive countermeasure. For this ice accretion angle, the aspect of the galloping 'ellipse' varries highly in relation with the wind speed, even if the wind variation is weak (figure 9).

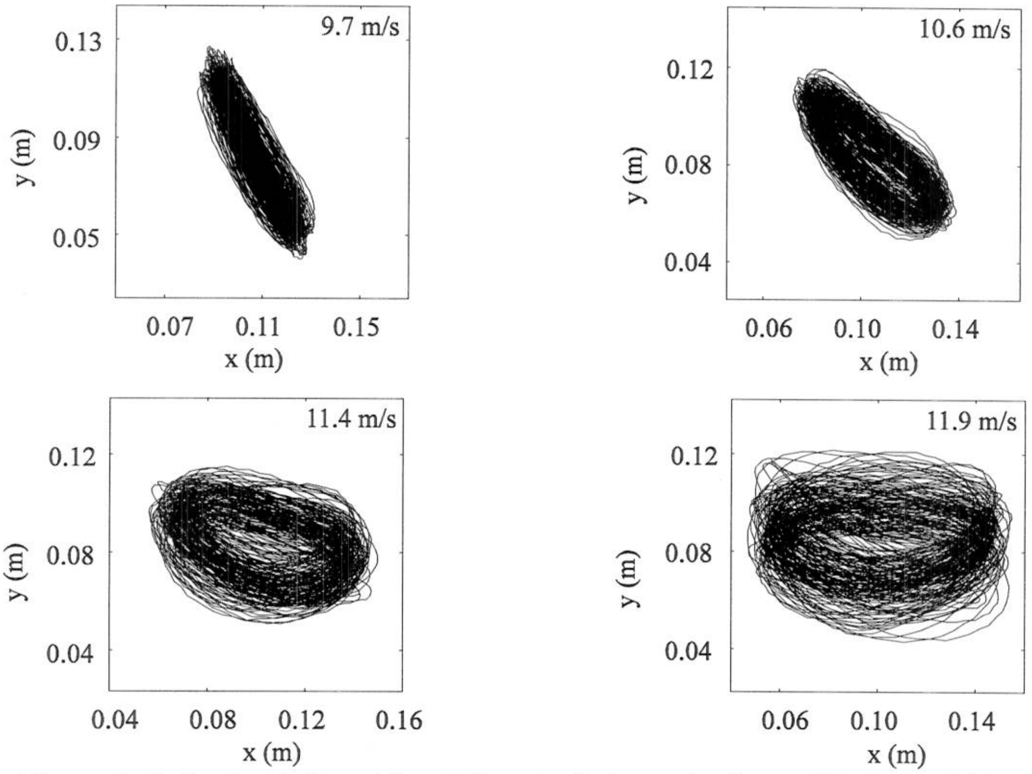

Figure 9. Galloping 'ellipse' for different wind speeds, $\theta_0 = -30°$, $f_v/f_\theta = 0.98$.

In this case, the rotation has a reducing effect on the vertical amplitude, but it is due to the changing slope of the galloping ellipse. In other cases it could be the opposite effect. In fact, the variation the variation of the angle of attack is more important. And the phase shift between the variation of angle of attack and the vertical movement could also influence the vertical amplitude.

The figure 10 shows the results for an ice accretion angle of -165° (corresponding to a reverse wind). For this angle, the galloping had a behavior different from the previous angle. The amplitudes remained below the limit for all wind speed below 20m/s and the 3 movements were stable in amplitude. The galloping 'ellipse' kept the same aspect for the different wind speeds. For 12 m/s the peak to peak rotational amplitude was about 13° and the galloping frequency is 0.86 Hz.

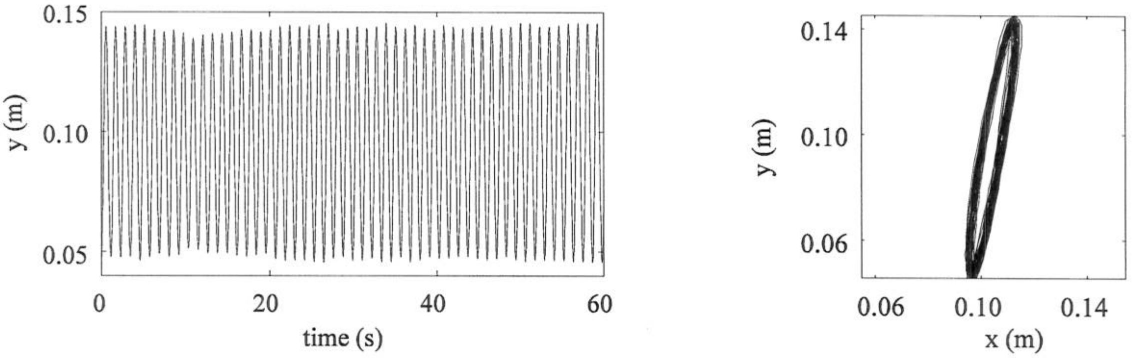

Figure 10. Vertical displacement and galloping 'ellipse',
$U_0 = 12$ m/s, $\theta_0 = -165°$, $f_v/f_\theta = 0.98$, $U_0/(fd) = 429$.

The system is strongly unstable for this frequency ratio ($f_v/f_\theta = 0.98$) except between -20° and 0° where it is stable. But between -180° and -20° the system is so unstable that galloping begins for a wind speed below the minimum one allowed by the wind tunnel. So the critical wind speed can not be measured. Sometimes the system is naturally unstable, sometimes a perturbation must be introduce, either a small rotation or a vertical displacement. For some ice accretion angles a special instability has been observed. It is a rotation in the horizontal plan around the center of the ice sample as the yaw movement for an airplane.

Den-Hartog galloping is characterized by a vertical movement and the absence of significant torsional movement. But for a frequency ratio around 1 it is possible to have an ice accretion angle for which the Den-Hartog criterion is respected and which is also sensitive to the flutter galloping. The Den-Hartog criterion applied to the aerodynamic curves of our ice shape shows 2 unstable areas (between -180° and 0°), one is located around -180° (classical for a realistic ice shape) and the other around -35°. So in a second time the system has been configured to have the maximum available detuning of the vertical and rotational frequencies. The vertical springs have been placed at 0.36 m from the center of the sample. For this configuration and without wind, the measured vertical, rotational and horizontal frequencies are respectively 0.85 Hz, 1.54 Hz and 0.96 Hz ( $f_v/f_\theta = 0.55$). It allows also to verify the effect of detuning on the flutter galloping. Two areas of ice accretion angles corresponding to Den-Hartog instability were observed. The figure 11 shows the galloping for an ice accretion angle of -180°. This is not the limit cycle (the amplitude became too high and the sample shocked the plates), but it is clear that the galloping ellipse was vertical and very thin. The rotational amplitude at the end of the recording was less than 3° peak to peak. The frequencies were different for each movement, 0.85 Hz for the vertical displacement, 1.27 for the horizontal displacement and 1.71 for the rotation.

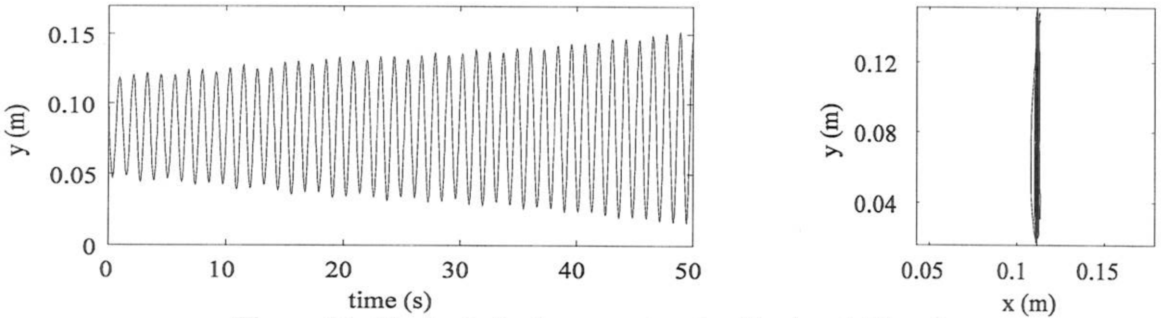

Figure 11. Vertical displacement and galloping 'ellipse',
$U_0 = 8.5$ m/s, $\theta_0 = -180°$, $f_v/f_\theta = 0.55$, $U_0/(fd) = 308$.

## CONCLUSIONS

This experience shows that the system used to simulate galloping on a suspended string model is appropriate. The observations made during these tests are in good agreement with the tendencies (effect of wind, detuning ratio, galloping ellipse, perturbation effect) noticed with the numerical simulations of a real overhead line. This is a splendid tool to validate numerical model, both for instabilities and limit cycles in 3-D.

In the next future, tests will be performed to evaluate the wake effect in bundle conductor on aerodynamic coefficients, this will give access to more appropriate modeling of bundle conductors by equivalent single conductor. Other tests will be performed to better define the influence of damping (in the three degrees of freedom) on galloping instabilities and amplitudes. Tests will be executed with different detuning ratios to cover single and bundle conductors. Unfortunately our wind tunnel is not convenient to evaluate the effect of turbulence, which would also be of biggest interest.

## ACKNOWLEDGMENTS

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