Wind induced motion on bundled conductors (Excluding ice galloping) Part B – Subspan oscillations

Study Committee B2

resp.Working Group B2.46

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1. Introduction

Subspan oscillations is a well-known phenomenon in High Voltage and Ultra High Voltage Overhead Transmission Lines (HV and UHV OHTL) [1]. It occurs on conductor bundles and it is due to the effect of the wake produced by the windward conductor on the leeward one. For this reason the phenomenon is also classified as wake induced oscillations, this phenomenon is a flutter type instability due to the coupling of vertical, horizontal modes in a frequency range between 0.5 – 2 Hz.

Recently, problems associated with this phenomenon has become more recurrent, attracting the attention of transmission line operators, hence WG B2.46 decided to dedicate an effort to evaluate the present developments in such a field.

As for the analytical models developed for studying such a problem, the first ones are those of Simpson [2], Ikegami [3], Diana [4], Ko [5] and Tsui [6]. These are two degrees of freedom models: the motion of the leeward cylinder is studied along two orthogonal directions, the windward cylinder being still. The linearized Quasi Steady Theory (in the following QST) is employed and the drag and lift coefficients on the leeward cylinder are deduced from static measurements in wind tunnel, as a function of the relative position of the leeward cylinder with respect to the windward one. Such models are linear and clearly simplify the structural behaviour of the bundle sub-conductors, taking it back to a two degrees of freedom system in which the leeward conductor is the only one moving. Rawlins in [16][17][18] expresses bundle dynamics in terms of normal propagation modes using the transfer matrix method. The bundle stability is analyzed reproducing the aerodynamic forces through the QST with a linear approach. Nowadays the Finite Element Model (in the following FEM) analysis allows for the reproduction of the bundle dynamics and for the application of the aerodynamic forces to each subconductor using the QST with a non linear approach.

However, FEM analyses in the time domain are not always a practical tool for subspan oscillation simulation also because of the computation time required to obtain results.

All the models developed up to now rely on the Quasi Steady Theory (QST): according to this, the field of forces acting on the conductors in the wake is identified using the static aerodynamic coefficients measured in the wind tunnel and the effect of relative motion between sub-conductors is accounted for introducing a relative velocity with respect to the approaching flow [7][10]. This approach generally holds for very high "reduced velocities" V_r, being V_r defined as the ratio between the wind speed V and the product of oscillation frequency f and cylinder separation I: $V_r=V/(f\,I)$. Moreover, being the problem highly nonlinear, the validity of this theory needs to be confirmed. Another important issue is the Reynolds number (Re) effect.

In fact for stranded conductors, i.e. rough cylinders, with the typical values of conductor diameter and wind speed involved by subspan oscillations, Re may be close to the critical zone: hence the Re number could significantly affect the phenomenon, due to the non-negligible variations of the drag coefficient with Re itself [2][8]. As a matter of fact, recent researches made at Polimi [9] have shown that the QST maintains its validity for these values of "reduced velocity".

However, the same research put in evidence that the Reynolds number is very important because the conductors during subspan oscillations can operate around the critical range of the drag coefficient (see figure B.1 [8], where the drag coefficient of a 40.7 mm

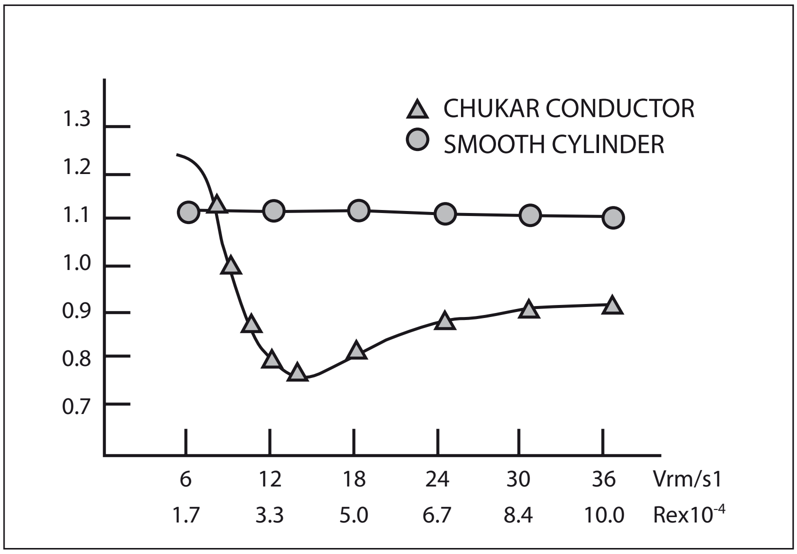

Figure B.1: Drag coefficient on windward rough cylinder as function of speed/ Reynolds number from Wind tunnel experimental tests [8]

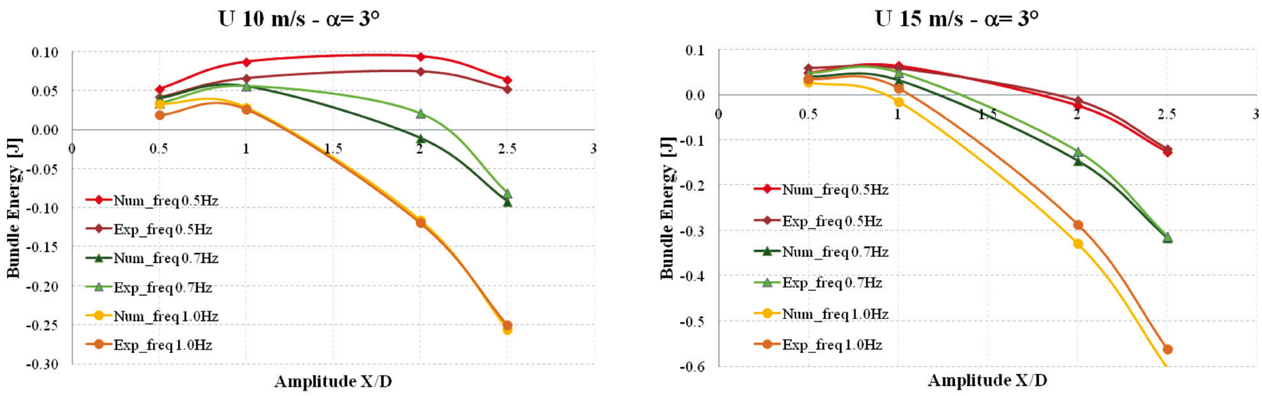

Figure B.2: Rough cylinders energy with respect to x/D amplitude for the three considered frequencies: experimental – numerical comparison. Due to the model scale, f = 0.5 Hz corresponds to f = 1 Hz full scale
∝ is both the static and dynamic bundle rotation angle with respect to the wind.

diameter Chukar conductor is reported, compared to that of a smooth cylinder with the same diameter). For this reason the static tests in wind tunnel to identify the aerodynamic coefficients on the leeward conductor must be made on rough cylinders, covering the critical and supercritical range of the drag coefficient. Such an aspect has a direct impact on the evaluation of the bundle stability as demonstrated in Figure B.2, where the measured and computed energy on a couple of cylinders with one in the wake of the other is reported for different wind speeds, when the cylinders are moving along elliptical orbits [9]. The energy input from the wind reported in Figure B.2 is a function of the subspan elliptical motion amplitude, represented on the horizontal axis in non-dimensional terms, as ratio x/D between the amplitude and the conductor diameter.

As can be seen, increasing the vibration amplitude, the wind energy input is decreasing, becoming negative, so the subspan phenomenon is self-controlled. The Reynolds effect makes the bundle less stable at low speed, as can be seen comparing the energy input at 10 m/s to that at 15 m/s in Figure B.2 (please note that, to held readability, the vertical scales are different in the two figures).

Additionally, it can be observed that the higher the frequency of the motion, the more stable the bundle appears, hence it is confirmed that a benefic effect on subspan oscillation can be obtained by decreasing the subspan length.

In the present work a benchmark within the different type of models at disposal for subspan oscillation studies is carried out comparing numerical results with measurements on the IREQ Varennes test span equipped with a quad bundle of ACSR Bersimis conductors and spacer-dampers.

2. Analytical methods and assumptions used in the study

In this section a brief description of the analytical methods adopted in the study is provided, together with the assumptions introduced in the analysis.

2.1.Diana Model:

The Diana Model is an energy based method that firstly evaluates the natural frequencies and vibration modes of the bundles, then identifies the modes showing a predominant horizontal and vertical component and selects those in the frequency range 0.5 – 3 Hz, frequency range typical of subspan. Subsequently within the selected modes, the ones which could be coupled by the aerodynamic forces to give rise to subspan oscillations are chosen.

For each possible pair of horizontal and vertical modes, the possibility of having instability is evaluated by a Quasi Steady Theory (QST) linear approach and the range of wind speeds for which subspan oscillation may be excited together with an instability index are computed. This preliminary analysis provides also the maximum difference between the vertical mode frequency and the horizontal mode frequency allowing for the coupling between the two modes.

Once the types of modes that can be coupled are defined, two independent modal coordinates $q_o(t)$ for the horizontal mode and $q_v(t)$ for the vertical mode of the bundle are chosen. Harmonic laws are imposed to the two coordinates $q_o(t)$ and $q_v(t)$, in such a way to reproduce the elliptical motion of the conductors typical of flutter instability. Being the maximum instability index found for a phase shift between the two modes of ± π/2 the imposed law is:

$$q_o(t) = S_{am} * e^{i\omega t}$$
$$q_v(t) = S_{im} * e^{i(\omega t \pm \frac{\pi}{2})} \quad (1)$$

where S_{am} and S_{im} represent the maximum amplitudes for the horizontal and vertical modes, being the modes normalized in such a way that the maximum amplitude of the cylinder motion along the whole span is equal to unit, and ω is the chosen as the circular frequency of the horizontal mode. Finally, the conductors motion all along the span is obtained multiplying $q_o(t)$ and $q_v(t)$ by the modal shapes.

Using the QST, the forces acting on the conductors in the different positions occupied along the elliptical trajectories are computed, taking into account the velocity of each conductor [7][10].

Once the aerodynamic forces on the conductors are known, it is possible to compute, in each section of the bundle, the energy introduced by the forces themselves in one complete elliptical cycle.

The method gives the energy introduced by the wind in all the bundle, summing up the energies computed in each section: the evaluation is performed both for + π/2 and – π/2 phase shift (see equation (1)), obviously choosing the situation for which the aerodynamic forces can introduce maximum energy into the bundle system.

Finally, the steady state amplitudes of oscillation are defined through the balance between the energy introduced by the aerodynamic forces and the energy dissipated by the bundle, equipped with the spacer-dampers.

The Reynolds effect plays an important role in the drag and lift aerodynamic coefficients of the conductors, both for the windward and the leeward ones. This effect is introduced in the model thanks to the results of a recent research conducted in the Wind Tunnel of Polimi [9].

2.2.1. I.Sergey / Vinogradov Model:

The I.Sergey/Vinogradov method [14, 15] relies on the direct numerical simulations of the conductors and spacer-dampers movement in the process of subspan vibrations. It is fully based on the finite differences method and the explicit scheme of system equations solution. The equations of movement initially compiled in 3D form, for the sake of simplicity are reduced to 2D problem taking into account negligible longitudinal displacements of Spacer-Dampers along the span length. The calculation of the bending stresses in the conductors is performed assuming that the Spacer-Damper clamp divides conductors bending angles uniformly. The aerodynamic coefficients are taken after G.Diana [4], S.Price [11]. The assumption that Poffenberger-Swart formula is valid while subspan oscillation process is taking place is made. Moreover the model has been demonstrated to be valid for quad bundle span, where in order to replicate properly the subspan oscillation an initial condition in terms of force field is applied on the bundle: two short startup impulses of the forces acting in opposite directions are applied on a pair of interacting conductors. In case of even number (e.g. four) of conductors in the bundle, it turned out most effective to take into interaction only one pair of conductors. The solutions taken prevent the model to find only the snaking motion and allow to detect subspan

Spacer-damper data	
Quad spacer-damper interaxis	457mm
Torsional stiffness of the hinge	125 Nm/rad
Radial stiffness of the hinge	50000 N/m
Ratio between torsional damping and torsional stiffness	0.35
Ratio between radial damping and radial stiffness:	0.35
Arm mass	0.71 kg
Arm mass moment of inertia with respect to the centre ofmass	2.74E-3 kg m2
Central body mass	3.44 kg
Central body mass moment of inertia with respect to the centre ofmass:	38.5E-3 kg m2
Mass of spacer damper	6.28 kg
Span data	
Conductor:	ACSR Bersimis
diameter	35.1mm
mass	2.185 kg/m
Tensile load	34420 N
Span length	450m
Sub-Span arrangement [m]	40-53-57-50-55-49-58-52-36

Table B.1: Subspan oscillation test case data

oscillations. But lack of wind energy influx provided lower sensitivity of the model to weak and moderate winds; this disadvantage was corrected by a coefficient found with the help of the benchmark test itself.

2.3. Snegovskiy / Lilien Model :

The corresponding model relies on the use of finite-element nonlinear formulation. Within this approach, the interaction of subconductors due to the wake is represented using Simpson's aeroelastic model [2]. A special force element is created to introduce the aerodynamic loads due to the wake which are computed according to the QST. Moreover the aeroelastic properties of the wake force field are tuned to meet the wake-induced instability properties, as measured by Price [11]. Extension of the wake interaction sample onto the full line span (including spacer-damper, any bundle configuration) is done taking into account the inertia-stiffness properties of the line fittings (spacer dampers). More details on [12], [13].

2.4 Kurmann Model :

The idea of the model approach is a finite element implicit transient analysis with an update of the aerodynamic forces after each time step. The geometry model consists of linear beam elements for the conductor, the frame and the arms of the spacer damper. The stiffness and damping properties of the spacer-damper hinges are considered as spring-damper elements. The self-damping of the conductor is implemented with the Rayleigh damping model.

The first two load steps for the pretension of the conductor and the dead load are executed without time integration. Afterwards a do-loop with time integration and update of the aerodynamic forces is performed. For the numerical solution the HHT (Hilber-Hughes-Taylor) algorithm is applied.

The Quasi Steady Theory (QST) is used for the computation of the aerodynamic forces. The resultant polynomials of the wind tunnel test according [7] are the input for the model approach. The latest wind tunnel test results [9] are also included, which quantify the influence of the Reynolds number onto the aerodynamic coefficients.

3. Experimental and analytical benchmark : description and results

It must be pointed out from the first beginning that the models using FEM can give rise, at wind velocities between 10 – 20 m/s, as reported in detail in [12], to an instability motion of the whole span at very low frequency also called galloping or snaking motion. This instability motion is predominant and this approach is generally not able to reproduce subspan oscillation. However a full description of the results obtained by FEM model is reported in [12].

The I.Sergey-Vinogradov model, on the other hand, in order to excite subspan uses as initial condition an external excitation to move the subconductors out of phase.

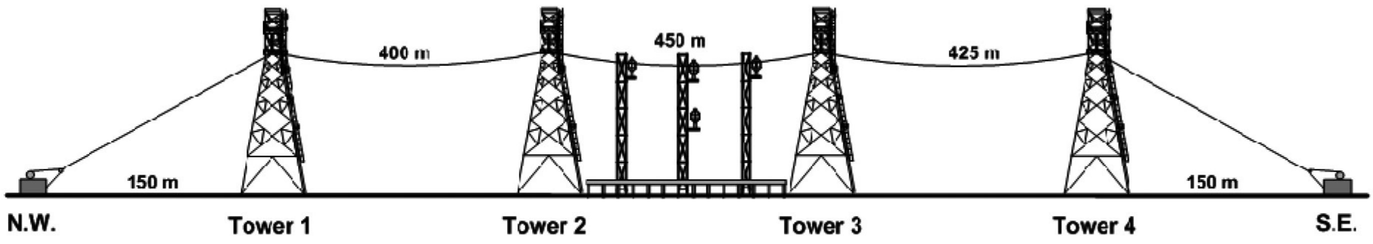

Figure B.3: Test set-up showing towers, conductors and anemometers of the test line

By means of this approach the model is able to reproduce subspan oscillation in a reasonably short time (after 30s of real time process development).

In order to compare the models accuracy and reliability an experimental-numerical benchmark has been carried out, considering as a reference case the one tested in Varennes by IREQ, which is described in table B.1.

The compared quantities are the maximum peak to peak oscillations of the subconductors in the most critical sections of the span, during subspan oscillations.

The experimental benchmark was obtained on the Hydro-Quebec full scale test line which has two dead-end spans and three suspension spans. The length of the spans is successively 150, 400, 450, 425, and 150 m. The subspan oscillations were measured on the middle span (450-m span).

The subspan oscillations were measured in the middle of each subspan on the bottom North-East conductor to obtain the horizontal component of the first subspan mode antinode amplitude. The data was measured during four weeks every ten minutes at a rate of 32.3 pts/s for a duration of 145.5 s. The time signal was then processed to determine the peak-to-peak amplitude of the most severe vibration cycle during the recording period and the vibration frequency. Only the recordings with an apparent frequency corresponding to the first subspan mode of the subspan considered and its adjacent subspan were selected. The purpose here was to distinguish between subspan oscillations appearing in the above-mentioned frequency range from snaking oscillations, which usually occur at lower frequencies, and also from rain vibrations or aeolian vibrations, which have higher frequencies.

Figure B.4 reports the maximum peak to peak conductor amplitudes measured in the different subspans.

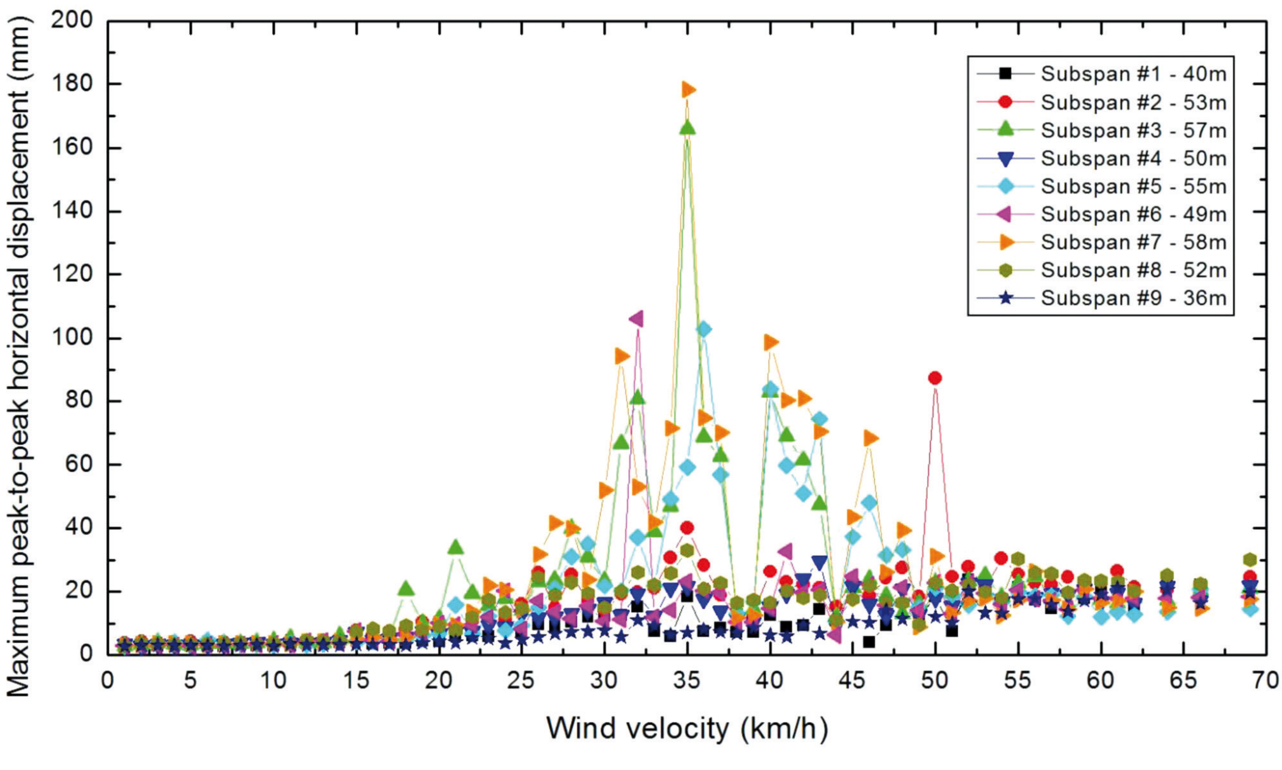

Figure B.4: IREQ Measurements: Maximum peak to peak horizontal oscillations as function of mean wind speed.

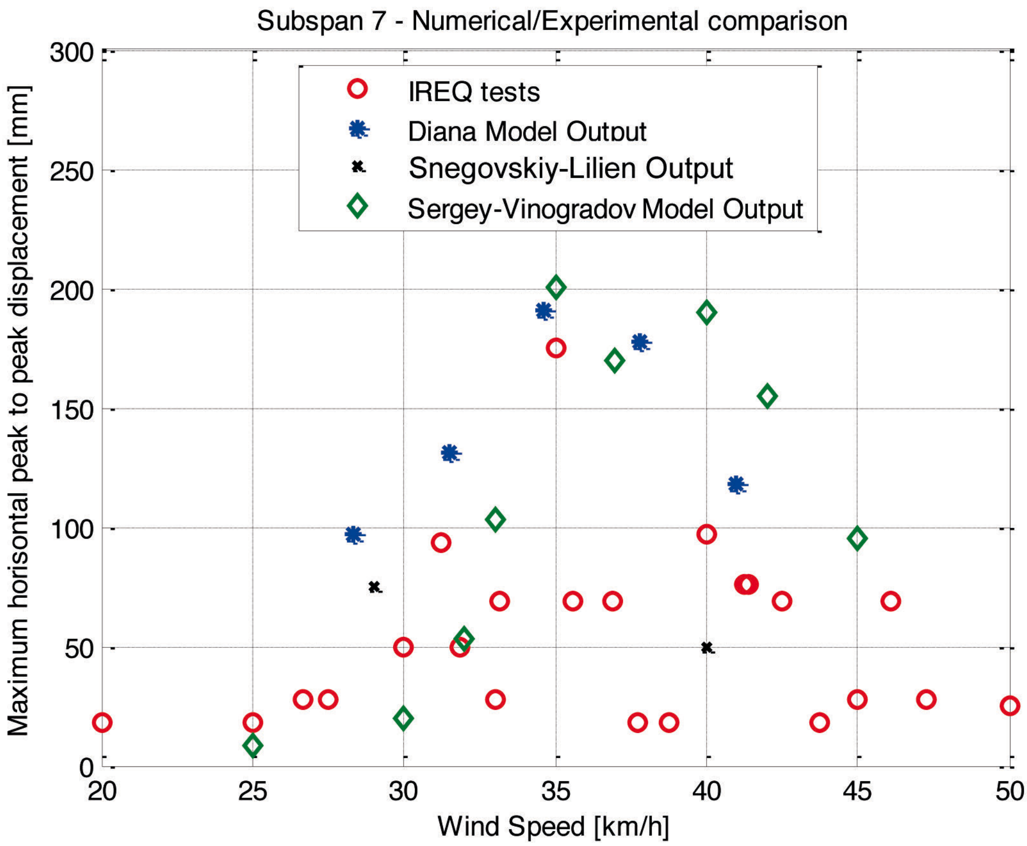

Figure B.5: Benchmark results: Maximum peak to peak horizontal oscillations as a function of mean wind speed.

The numerical simulations have been carried out in the speed range 20 – 60 km/h.

Figure B.5 shows, as a function of mean wind speed, the peak to peak horizontal oscillation amplitude registered in the subspan 7, which is found to be the most critical one.

In blue the results from the Diana model are reported, in green the results from the I.Sergey-Vinogradov model and in black the results from the [12.] Snegovskiy / Lilien model, while in red the experimental points are represented.

It is possible to observe that the Diana and I.Sergey-Vinogradov numerical models correctly replicate the trend of the oscillation peak to peak values, which increase with the increase of mean wind speed up to reach a maximum in correspondence of a mean wind speed of 35 km/h, then the oscillation amplitude starts to decrease.

The numerically computed amplitudes are also in good agreement with the ones experimentally registered.

4. Conclusions

The study presented several approaches to the evaluation of the subspan phenomenon, ranging from approaches based on the EBP to approaches relying on FEM modelling.

Subspan Oscillations is a complex vibration on bundle conductors. It needs relatively high winds. Important parameters are :

- Bundle tilt
- Ratio vertical to horizontal frequency in each subspan Tensile load
- Ratio between bundle separation I and conductor diameter D (I/D)
- Subspan length

Simple and advanced methods can be used nowadays. Complex FEM model have been applied with success but they need a very cumbersome analysis which is very much depending on some details.

Methods based on modal analysis and energy approach seem a more useful tool for practical applications.

Moreover the presented results, even if applied to one only test case, allow to state that:

- The quasi-steady theory seems able to well reproduce the aerodynamic forces produced during subspan oscillations;
- The Reynolds number affects in a large amount the energy introduced by the wind. In fact the flow on the conductors can vary from sub-critical – critical and super-critical region of Reynolds number depending on the conductor diameter, surface roughness

and, finally, wind speed. In the critical region the energy introduced is greater due to the decrease of aerodynamic damping on the upstream cylinder associated to the negative slope of the drag coefficient. It can be observed that, considering two conductors with the same diameter but different surface roughness, the critical region moves towards higher wind speeds for smoother conductors, like those with trapezoidal wires - with respect to the standard conductors with circular strands. This aspect of the problem is for sure worth of further investigation through suitable wind tunnel tests.

- The numerical model based on EBP approach and on sophisticated Wind Tunnel tests to identify the aerodynamic parameters seems a useful tool for analyzing the subspan oscillations phenomenon, as shown by the comparison between its results and the measurements on a full scale transmission line structure subjected to the real wind.
- The numerical model based on the finite differences method and the explicit scheme of system equations solution, even if it had to be calibrated with the help of the benchmark test itself, also seems in condition to well reproduce the phenomenon. However more results and analyses are required to confirm its validity.

From the analyses performed in this research and, more precisely, from the results shown in figure B.2, it is possible to conclude that one way of controlling subspan oscillations is to increase the subspan oscillation frequency decreasing the subspan length.

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