30th International Conference
ENGINEERING MECHANICS 2024
Milovy, Czech Republic, May 14 – 16, 2024

GALLOPING OF INSULATED BUNDLED OVERHEAD LINE - NONLINEAR NUMERICAL ANALYSIS IN TIME DOMAIN

Macháček M.*, Hračov S.**

Abstract: *Our contribution focuses on a 3D numerical nonlinear analysis of galloping in a specific bundled overhead line with ice accretion. We studied the susceptibility to this self-excited oscillation, critical onset wind speeds, and global dynamic response of a very low-tensioned line with simulated icing observed on similar real conductors. Due to the highly nonlinear mechanical behavior of such a flexible cable, we employed the Newmark integration method combined with the iterative Newton-Raphson method. We analyzed two numerical models of the overhead line loaded by the wind: one assuming nonlinearity only in the wind load, while retaining the linearity of the mechanical system itself, and the other representing a fully nonlinear system including geometrical nonlinearity. Our analysis revealed that the determined critical wind speeds for the onset of galloping are in relatively close ranges for both models. However, numerical simulations with the fully nonlinear system indicated significantly lower amplitudes of limit cycle oscillations, especially at higher wind speeds, compared to the linear model of the line. This underscores the necessity of using fully nonlinear models during the design stage of such low-tensioned aerial conductors.*

Keywords: Aerial bundled conductors, wind effects, galloping, limit cycle oscillation.

1. Introduction

Wind action on the electrical conductors can cause a loss of their aeroelastic stability called galloping. Galloping is a low frequency, self-excited vibration, usually in a plane perpendicular to the wind direction, see Holmes (2018) with large amplitudes. The most often observed vibration mode shapes has one to three loops; higher modes have been detected only sporadically, see EPRI (2006). A necessary condition for the emergence of galloping is a rotationally asymmetric cross-section of the line. Power lines are generally rotationally symmetrical, but ice accretion can cause the significant changes in their shapes. The amplitudes of galloping oscillations can reach, in some cases, more than ten times the diameter of the cable. Such deformations lead to substantial axial stresses in the lines, which can be crucial not only for the safe design of supporting structures, but also for fatigue life of the lines. This article presents outcomes from a fully nonlinear 3D numerical analysis of galloping of a very low-tensioned bundled overhead line with ice accretion. The power line consists of four conductors covered by polyethylene insulation see Fig. 1.

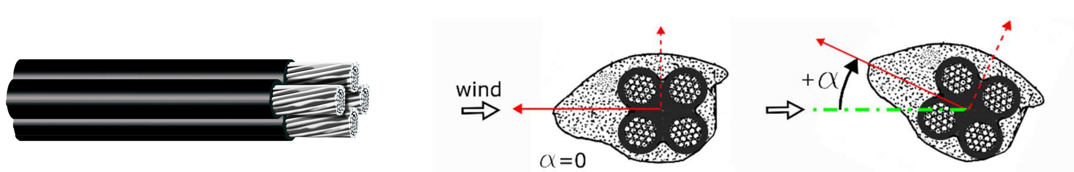

Fig. 1: Bundled overhead line – axonometric view and ice-covered cross-section.

* Ing. Michael Macháček, PhD.: Institute of Theoretical and Applied Mechanics of the Czech Academy of Sciences, Prosecká 809/76; 190 00, Prague; CZ, machacek@itam.cas.cz

** Ing. Stanislav Hračov, PhD.: Institute of Theoretical and Applied Mechanics of the Czech Academy of Sciences, Prosecká 809/76; 190 00, Prague; CZ, hracov@itam.cas.cz

doi: 10.21495/em2024-190

In all cases the wind direction is perpendicular to the sag plane and α is the angle of ice accretion with respect to the wind. By varying the angle of ice accretion it is possible to find the lowest critical wind speed for loss stability at galloping, see Fig. 1. The simulated icing observed on similar real conductors was adopted from Desai et al. (1995). Both cable ends are supported against torsion and all three directions of linear movements. The geometrical and mechanical properties of the electrical cable are shown in Tab. 1. The elastic polyethylene makes it difficult to define the stress transfer between the aluminium cores. For this paper, torsional stiffness was calculated as the arithmetic mean between minimum and maximum torsional hypothetical stiffness. Minimum torsional stiffness was calculated as four single acting aluminium circular rods and maximum torsional stiffness was calculated as a group of four circular rods using Steiner's theorem.

Parameter	Value	Parameter	Value
Horizontal distance of suspension points	21.1 m	Vertical distance of suspension points	1.55 m
Length of line	21.588 m	Cross-sectional are of line	0.00046528 m^2
Young's modulus	57 GPa	Shear modulus	25.5 GPa
Diameter circumscribed circle of power-line	0.038 m	Mass moment of rotational inertia unit length of line (with ice accretion)	4.6504e $\cdot 10^{-4}$ kg$\cdot$m^3
Viscous damping ratio of dynamic system	0.5 %	Polar moment of inertia of the cross section	2.7502 10^{-8} m^4
Mass per unit length of line (with ice accretion)	2.09 kg/m	Horizontal component of tension force for: -5 °C with ice accretion	1 149.5 N

Tab. 1: Geometrical and mechanical properties of electric line (AES 4 x 120).

2. Proneness of ice-coated cable to galloping

The susceptibility to galloping can be assessed using the Den Hartog criterion, which is based on the quasi-steady theory. This criterion can be expressed as:

$$C_D(\alpha) + \frac{dC_L}{d\alpha}(\alpha) < 0 \tag{1}$$

where C_D a C_L are drag and lift coefficients and α is the angle of wind attack. Aerodynamic coefficients for analysed ice-covered line adopted from Desai et al. (1995) are depicted as functions of α in Fig. 2. The drag coefficient is represented by the red line, the lift coefficient by the blue line and the torsion (moment) coefficient by the green line. The Den Hartog criterion is also expressed for all α in Fig. 2 by the black line. The negative values of this black curve indicate the angles of wind attack α for which the instability can occur. The angles α = 40.0 ° and 179.3 ° were determined as critical angles from the point of view of the onset of galloping and the character of the response.

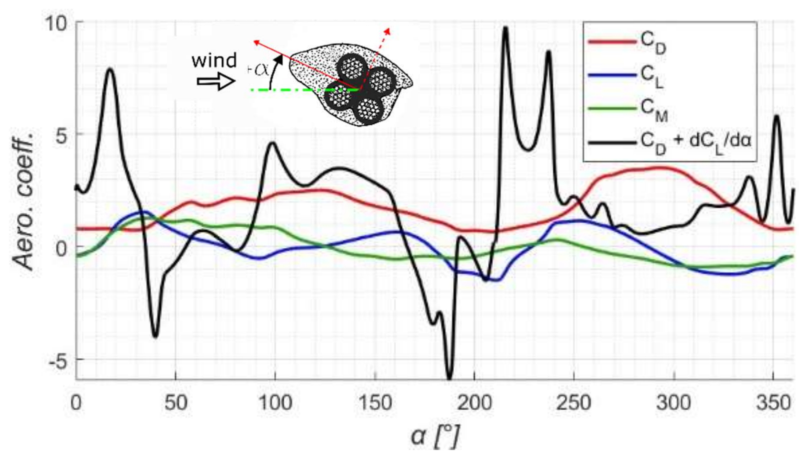

Fig. 2: Aerodynamic drag, lift and moment coefficients, C_D, C_L, C_M, and Den Hartog criterion of line.

3. Description of used numerical methods and computational model

CALFEM, finite element toolbox for Matlab was used for the analysis of the effects of wind on the bundled overhead line. The necessary modifications of this toolbox consist of an adaptation of the geometrical nonlinearity to achieve a better approximation of the real cable behavior. Because of the geometrical nonlinearity and the nonlinearity in the wind load, which depends on the velocity of the cable motion, we used the Direct Integration Time-history analysis in combination with the incremental iterative Newton-Raphson method to solve the differential equations of motion.

The finite element model of the overhead line was built using the modified bar element in 3D space. This adjustment involves adding torsional stiffness to the previously completely flexible joint (connection) between every two elements. Therefore, it is a finite element that can be loaded by and carry only normal forces and torsional moments. This modification ensures a more realistic numerical simulation of a perfectly flexible cable with the required torsional stiffness. The entire finite element model consisted of 100 modified bar elements.

The correctness of the used 3D FEM model was initially verified by comparing the results of the static nonlinear numerical analyses with the simplified analytical solutions. Subsequently, the results from modal analysis of this linearized 3D model were successfully compared with analytical solutions in Madugula (2001), which are valid for tensioned cables with a sag-to-span ratio of 1:8 or less. In our case, this ratio is approximately 1:17. The lowest in-plane natural mode, crucial for galloping susceptibility, was determined from modal analysis and is shown in Fig. 3. The corresponding frequency for this mode is 1.105 Hz.

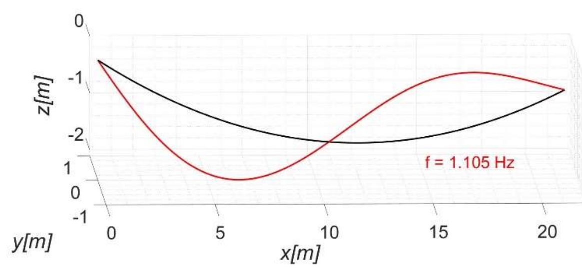

Fig. 3: Sag of the cable (black curve) and the lowest natural in-plane mode (red curve).

4. Time-Domain numerical analysis of galloping

The amplitude of the limit cycle oscillation and the global dynamic response for selected wind speeds ranging from 0 to 6 m/s were evaluated using the Newmark integration method with a constant time step of 0.001 s and the iterative Newton-Raphson method performed at each time step. The responses of three modifications of a fully nonlinear computational model of the power line were analyzed and compared.

The first simplest model, FEM - 1D model, allows vibrations only in the perpendicular plane to the wind direction, i.e., only the aerodynamic nonlinear forces in this plane are considered. The linearity of the cable is assumed, i.e., its structural matrices remain constant during the numerical calculations. An extended version of this model, the second model, FEM - 3D model, differs from the first model only by allowing the line to move in three-dimensional space and by incorporating all three components of aerodynamic wind load. The third model, FEM - 3D – nonlinear model, represents the fully nonlinear model in 3D, with the structural matrices being reassembled at each time step according to the actual deformed state.

The calculated amplitudes of the limit cycle oscillation are shown in Fig. 4 as functions of the wind velocity for each model and for two critical angles of wind attack. From the graphs in this figure, it is evident that the numerical simulations with all the models described above provide almost similar and accurate estimations of the critical galloping onset wind velocity. The graphs in Fig. 4 also demonstrate good agreement between the outcomes from the simplified galloping analysis of the same overhead line represented by the black line, and the results of numerical simulations with the simplified model, FEM - 1D, indicated in this figure by the red diamonds. This fact confirms the equivalence of both models when considering identical model assumptions. The amplitudes of limit cycle oscillations related to the FEM - 3D model, marked in Fig. 4 by blue squares, reach higher values than for the FEM - 1D model. This effect is especially pronounced for the angle of wind attack equal to 40 °. It is caused by the torsional load introduced into the 3D model, which significantly contributes to the increase in the galloping effect.

The fully nonlinear solution of the response of the bundled line is shown in Fig. 4, marked by green dots. Nonlinear numerical simulations indicate that the amplitudes cannot increase beyond a certain level. In our case, a maximum amplitude of 35 mm was identified. The inclusion of geometric nonlinearity into the model causes significant oscillations of the normal forces, especially for higher wind speeds and amplitudes, leading to substantial changes in the stiffness matrix during a vibration period. This phenomenon results in amplitude limitation and changes in the dominant vibration frequency and the shape of the forced oscillation mode.

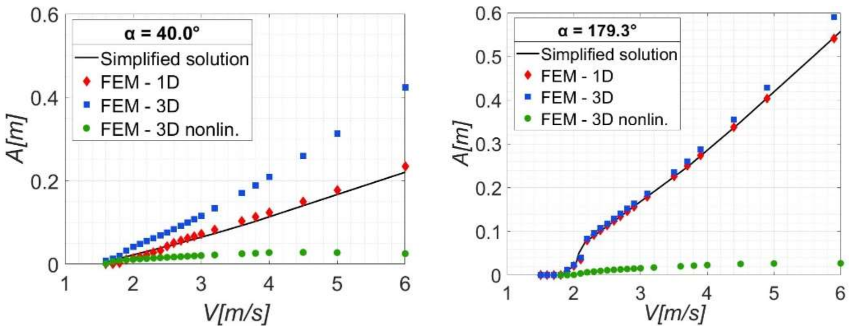

Fig. 4: Amplitude of limit cycle oscillation as function of wind speed.

The selected calculated trajectories of the antinode of the cable during one period of limit cycle oscillation related to various wind speeds are shown in Fig. 5. The elliptical trajectory at the onset of galloping instability is very similar for the geometrically linear and nonlinear approaches see Fig. 5a. However, the trajectory at higher wind speeds for the nonlinear model is no longer elliptical see Fig. 5b. The substantial flattening of the trajectory at the lower edge demonstrates the increase in stiffness when the cable moves downwards and the tensile forces increase. The inclination of the elliptic oscillation depends on the slope of all aerodynamic coefficients, especially the drag coefficient. This is demonstrated on trajectories related to angles of wind attack α = 40.0 ° and 179.3 ° in Fig. 5, which have oppositely inclined elliptical shapes due to their reversed slope of the drag coefficient.

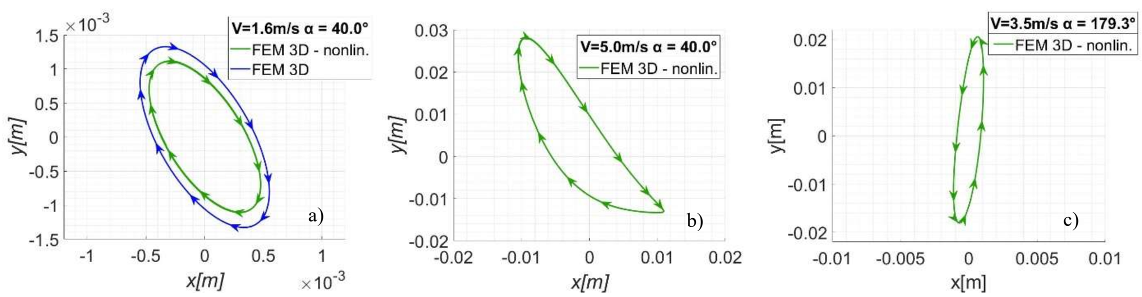

Fig. 5: Trajectory of amplitude of limit cycle oscillation.

5. Conclusions

The presented numerical analysis has proved the necessity of adopting a fully nonlinear model for predicting the dynamic response in the case of such low-prestressed electric lines. This approach will ensure a more realistic estimate of the maximal stress in the line and supporting structures, resulting in a safer and, in some cases, more economical design.

Acknowledgement

The kind support of Czech Scientific Foundation project No. 24-13061S is gratefully acknowledged.

References

Desai, Y. M., Yu, P., Popplewell, N. and Shah, A. H. (1995) Finite element modelling of transmission line galloping, *Computers & Structures*, 57, 3, pp. 407–420.

EPRI (2006) Transmission Line Reference Book - Wind Induced Conductor Motion.

Holmes, J. D. (2018) *Wind Loading Structures*, CRC Press, 3rd edition.

Madugula, M. K. S. (2001) *Dynamic Response of Lattice Towers and Guyed Masts*, ASCE.