Nonlinear passive control of galloping of overhead transmission lines: design and numerical verifications

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Abstract

In the field of power delivery, the vibration of overhead conductors affects the sustainability of transmission lines. The passive control of galloping of conductors is the subject of this study. Galloping oscillations are caused by ice accretion on a cable that creates an aerodynamic instability. The consequences of galloping on transmission lines are electrical outages, fatigue failure of cables, and the impacts between cables. The study focuses on the nonlinear passive control of a single conductor. The use of a nonlinear absorber called as nonlinear energy sink (NES) with a piecewise linear restoring forcing function for galloping mitigation on a single span of a suspended cable is proposed. An analytical model of a single conductor span coupled to a NES is developed. The fluid-structure interaction, i.e. the interactions of the wind and the ice-accreted cable, is modeled by a parametric excitation supposing the quasi-steady theory. A complexification technique accompanied by the time multiple scale method is used to determine the slow and fast dynamics of the system. The bifurcation diagrams are analytically determined and compared with results obtained from the numerical integration of the governing equations of the system. The system with harmonic excitation is modeled using the finite element (FE) method with the software Code_Aster. An equivalence between harmonic and parametric excitation is addressed to compare the results from the FE model and the analytical developments. The influence of the parameters of the nonlinear absorber: clearance, stiffness, and damping coefficient on galloping mitigation is studied.

1 Introduction

Control problems in civil and mechanical engineering systems covered large spectrum ranging from active to passive control [1], [2], [3]. Active control solutions need external energies for the activations while passive control strategies rely on interactions between coupled oscillators or systems for energy reductions. Passive controllers are divided into two categories: linear and nonlinear systems. In the early 21st century a new type of nonlinear absorber has been developed which contained pure cubic term reading as $\mathscr{F}(\alpha) = k_{NL}\alpha^3$ [4], [5], [6], it was the NES. The NES has no special frequency and can enter in resonance at any frequency. Galloping oscillations on overhead power lines are a major issue, as they correspond to large amplitudes at low-frequencies. They are caused by ice and snow accretion on conductor cables [7]. The galloping instability was first studied by Den Hartog that gave his theory on its vertical mechanism [8]. A lack of control solutions remains even if there are some widely used techniques to deal with galloping oscillations as interphase spacer [7] and torsional pendulum [9]. In this work, we propose the control strategy of a nonlinear cable by considering a non-smooth nonlinearity for the restoring forcing function of the NES.

2 Formulation of the problem

An analytic model of cable coupled to a NES is considered. Fig. 1 shows a schema of this model where the static equilibrium of the cable is represented by a dashed line and the dynamic shape of the cable at the moment t is represented by a continuous line. The NES is coupled to the cable at the position L_n. The equations of motion of the system can be written as :

$$\begin{cases} C_R EAe + (N_R + EAe)w'' + f_{an} - c\dot{w} = \rho_R \ddot{w} \\ e(t) = -\frac{C_R}{L_R}\int_0^{L_R} w\mathrm{d}S + \frac{1}{2L_R}\int_0^{L_R} w'^2 \mathrm{d}S \\ w(0) = w(L_R) = 0 \end{cases} \quad (1)$$

And,

$$m_{NES}\ddot{u} - \mathscr{F}(w(S_n,t) - u(t))\delta(S - S_n) - c_{NES}(\dot{w}(S_n,t) - \dot{u}(t))\delta(S - S_n) + m_{NES}g = 0 \quad (2)$$

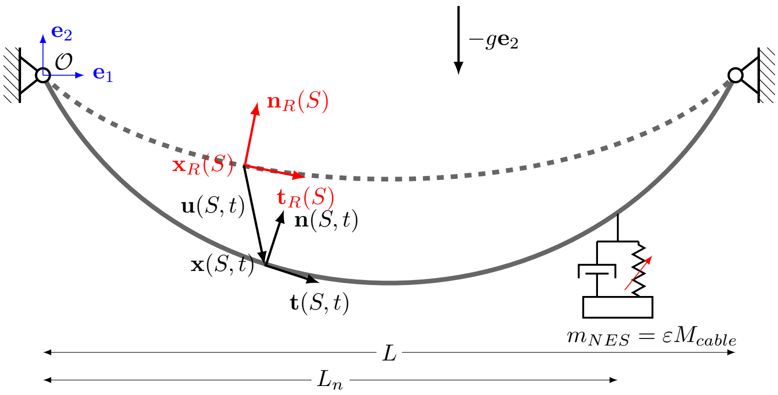

Figure 1: The considered model of a span of cable coupled to a NES.

Where w and u are the dynamic displacement of the cable and the NES. E, A and ρ_R are the Young modulus of the cable, the cross section area of the cable and the mass density of the cable. C_R, N_R and L_R are the curvature, the axial tension and the length of the cable all in the static equilibrium. The NES is characterized by its nonlinear restoring forcing function $\mathscr{F}$, its mass m_{NES} and its viscous damping c_{NES}. The restoring forcing function is piece wise linear with zero stiffness when the displacement is lower than δ_{NES} and a stiffness of k_{NES} when the displacement is larger than the clearance.

3 Behavior of the system under galloping instability

The dynamics of the system under galloping instability is investigated. The case of study is a cable with a span of 100 meters length and a horizontal tension of 36 kN. The linear mass of the cable is 1.368 $Kg.m^{-1}$, the cross section area is 4.085×10^{-4} m^2 and its Young modulus is 67.6 GPa. The system is projected on one mode, here the first mode. The dynamics are studied using Manevitch variables [11] and a multiple time scales study. The ice shape which leads to a aerodynamic instability has been taken from an study by Chabart et. al. [10]. The first result is the bifurcation diagram of the system without the coupling of the NES. Then, a NES with a mass of 2.74 Kg, a clearance of 20 cm and a stiffness after the clearance of 232 $N.m^{-1}$ is coupled to the cable. The equilibrium points of the cable with the coupling of the NES can also be investigated. Fig. 2 shows both equilibrium points without and with the NES. It can be seen that the NES reduce the amplitude of oscillations of the cable but the control is not the same for all wind speeds.

Conclusion

This work shows the study of the dynamics of a cable coupled to a non smooth nonlinear energy sink. The bifurcation diagram of the system under galloping instability with and without the NES have been investigated. The parametric study on the parameters of the NES shows the possibilities and the limitations of a such device for controlling galloping oscillations on overhead transmission lines.

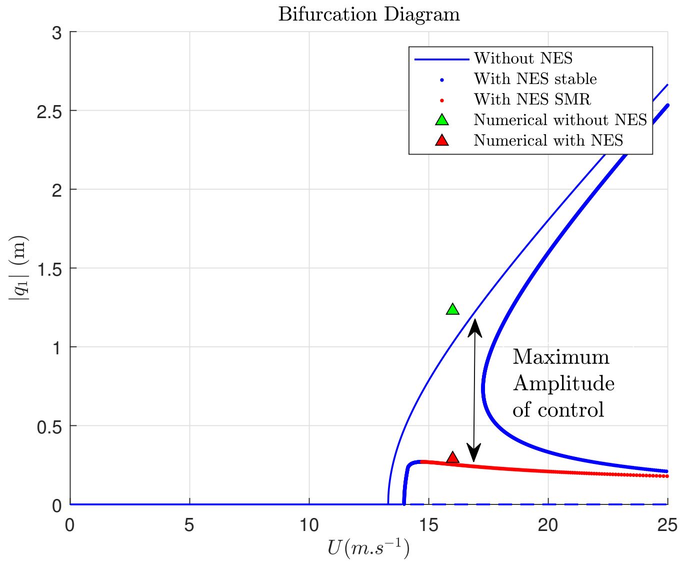

Figure 2: Bifurcation diagram of cable under aerodynamic excitation with and without the NES.

Acknowledgments

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