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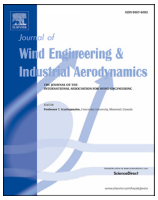

An enhanced unified model for the self-damping of stranded cables under aeolian vibrations

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A B S T R A C T

A new formulation for cable self-damping, based on a mechanical model for the hysteretic bending of metallic strands, is derived by extending a previous model by the authors. It accounts for the possible occurrence of micro-slip phenomena at the wire contact surfaces and distinguishes between the different dissipation mechanisms that can take place before and after the activation of the gross-sliding between the wires. The dissipated energy per unit of length is shown to depend on the cube of the bending curvature in the no-sliding regime, and on the square of the curvature when gross-sliding takes place. A specific value of the bending curvature is proposed to switch between the two dissipation mechanisms. The resulting unified dissipation model can be used to compute the dissipated power in the mono-modal steady-state vibrations characteristic of the Energy Balance Principle. The proposed model allows to recover, as limit cases, the exponents controlling the dissipated power evaluated with different theoretical models under both assumptions of micro-slip and gross-sliding. Moreover, it gives very good predictions of the experimentally measured vibration amplitude on a field-line. The results obtained make mechanical models for the prediction of cable self-damping viable tools that can be adopted in the practice.

1. Introduction

Overhead power lines comprise suspended cables, which are very prone to vortex-induced vibrations. These flexural vibrations, also known as “aeolian vibrations”, take mainly place in the vertical plane under the action of light to moderate winds (up to about 10 m/s), and are characterized by having low amplitude (less than about one diameter) but high frequency of oscillations (in the range of 3–200 Hz, depending on the size and axial load of the cable (EPRI, 2006)). Aeolian vibrations of the conductors, or the guard-wires, are a significant source of damage for overhead power lines since they lead to alternate bending stresses; these can induce wear damages and fatigue failures of the cables or of other equipment (insulators, vibration dampers, structural components of the suspension towers) (see e.g.: Fricke and Rawlins, 1968; EPRI, 2006; Azevedo et al., 2009). The assessment of the severity of aeolian vibrations is hence a crucial issue, both in the design of new electrical transmission lines and in the upgrade or retrofitting of existing ones.

The maximum expected amplitude of aeolian vibrations is commonly estimated, through the simplified procedure of the Energy Balance Principle (EBP), i.e. by imposing a balance between the energy provided over a vibration cycle by the wind to the cable and the energy dissipated within the structure.

When no additional passive vibration control devices (e.g. Stockbridge dampers) are added to the line, the energy dissipation term is mainly due to the so called “self-damping” of the conductors (Ervik et al., 1986). Within this context, the cable structural damping is usually characterized by using empirical expressions for the power dissipated per unit of length as a non-linear function of the axial load, as well as of the amplitude and frequency of vibration. The parameters entering these expressions, however, require expensive and time consuming experimental tests in order to be defined, while remaining nevertheless characterized by quite relevant uncertainties.

Starting from a mechanical model of the hysteretic bending behavior of metallic strands, the authors have recently proposed a unified closed-form expression for the energy dissipated during the cyclic bending of the conductor cross sections, which served as the basis of a new formulation of the cable self damping in mono-modal steady state vibrations (Foti and Martinelli, 2018). That proposal had the advantage of avoiding experimentally calibrated model parameters, while leading to an expression for the dissipated power of the same form (a power law) of the empirical equations of the literature and with exponents well within the range of those obtained from experimental tests on laboratory spans. While

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showing an encouraging agreement with the results of both experimental measurements and well-established empirical models of the literature, that proposal tended to overestimate the measured self-damping of conductors. This was recognized to come from the assumption of a rigid contact model (only gross-sliding possible) to describe the interactions between the wires over the whole range of curvatures characteristic of aeolian vibrations.

In this work, the previous authors' formulation for the cable self-damping will be extended by enhancing, in the low-curvature regime, the model of the interwire sticking/sliding dissipative mechanism, accounting also for the possible occurrence of micro-slip phenomena at the contact surfaces. This additional/alternative dissipation mechanism leads to lower values of the dissipated energy in the low-curvature regime. The results that are presented largely reconcile the predictions of the model with the experimental measurements.

The paper is organized as it follows. Section 2 presents the technical approach currently adopted to assess the amplitude of aeolian vibration, pointing out the significant effect of the uncertainties coming from the adoption of empirical self-damping models. Section 3 briefly reviews the available theoretical damping models for cables. Section 4 describe the mechanical formulation from which the new damping model, presented in Section 5, is derived. Finally, Section 6 compares the prediction coming from the novel damping model to the aeolian vibrations data recorded on of a full scale experimental test span.

2. The energy balance principle

Conductors can be characterized aerodynamically as bluff bodies for which the airflow in proximity of their surfaces can separate and form vortices that are shed downstream. The shedding of vortices in the wake of the conductor generates pressure fluctuations that are able to activate the motion of the conductor.

Initially, the frequency f of vortex shedding is related to the velocity V of the oncoming flow and to the diameter D of the conductor, through the well-known Strouhal equation:

$$f = V\,\frac{St}{D} \tag{1}$$

where St is Strouhal number. When the wind speed V is such that the vortex shedding frequency reaches one of the natural frequencies of the cable, relatively large oscillations can occur, especially in the transverse direction with respect to the flow. Typical vibration amplitudes are less than about one diameter, depending on the structural and aerodynamic damping available. Due to synchronization (or "lock-in") effects, the range of speed velocities that will activate such large vibrations covers a range from 80-90% to 120–130% of the value related to a specific natural frequency by Eq. (1) (see e.g. EPRI, 2006; CIGRE, 2007; Van Dyke et al., 2008).

Light to moderate winds have the potential to excite a very large spectrum of vibration frequencies. Indeed, assuming that the possible diameter of the conductors is in the range $D = 1.0 - 5.0$ cm (the smaller value for small guard wires) and that the value of the Strouhual number is in the range $St = 0.18 - 0.22$ (EPRI, 2006), wind velocities in the range $V = 1 - 10$ m/s would induce vibrations in all the rather large frequency range of approximately $f = 3 - 260$ Hz.

Notwithstanding the complexity of the related aeroelastic phenomena (see also Foti and Martinelli, 2018), and that several modes can be simultaneously excited due to the wind variation in time and along the cable span (e.g. Diana et al., 1993; Cigada et al., 1997; Muggiasca et al., 2018), it is assumed, for design purposes, that the cable vibrates according to one vibration mode only. For each of the excited natural frequencies, the maximum steady-state amplitude is customarily computed by imposing the energy balance over one oscillation cycle between the average input power P_w, imparted by the wind, and the average power P_d dissipated by the system:

$$P_w(y_{\max}, f) - P_d(y_{\max}, f) = 0, \ \forall f \tag{2}$$

The non-linear algebraic equation (2) can be solved, for any frequency f, to evaluate the amplitude of vibration $y_{\max}$ that allows to satisfy the Energy Balance Principle (EBP).

2.1. Wind input power

The shedding of vortices in the wake of the conductor (see e.g. Brika and Laneville, 1993, 1996; Rawlins, 1983; Williamson and Govardhan, 2004) is responsible for the power imparted by the wind to the structure. The power input on the cable has been recognized through experiments to be a function of the motion amplitude $y_{\max}$, the motion frequency f and the wind velocity V (EPRI, 2006).

A general form to express the experimentally measured wind power input data (see Lilien, 2013), valid for most of the experimental cases, is:

$$P_w(y_{\max}, f) = B_w(I_v) D^4 f^3 \,\mathrm{fnc}\left(\frac{y_{\max}}{D}\right) \tag{3}$$

where: $I_v = \sigma_v / V_m$ is the turbulence intensity, σ_v is the standard deviation of the wind velocity fluctuation, V_m the average value of the wind velocity, $B_w(I_v)$ is a correction factor to account for the turbulence, fnc() is a non-linear function of the dimensionless antinode vibration amplitude $y_{\max}/D$.

Several fitting curves of the wind power input have been obtained by the experimenters (see e.g. EPRI, 2006; CIGRE, 2018). Consistently with Foti and Martinelli (2018), in the following the well-accepted model recommended by CIGRE (Diana et al., 1998) will be adopted, along with the modification proposed by Lu (2003) and Lu and Chopra (2008) to account for the effects of wind turbulence intensity:

$$P_w(y_{\max}, f) = B_w(I_v) D^4 f^3 \left(-99.73\left(\frac{y_{\max}}{D}\right)^3 + 101.62\left(\frac{y_{\max}}{D}\right)^2 + 0.1627\,\frac{y_{\max}}{D} + 0.2256 \right) \tag{4}$$

$$B_w(I_v) = \left(1 + \left(\frac{I_v}{I_L}\right)^2\right)^{-\frac{1}{2}} \tag{5}$$

In Eq. (5) I_L is the "lock-in" index (Lu, 2003) which takes the value of 0.09. Typical values of turbulence intensity reported in test settings and in in-situ measurements are in the range $I_v = 0 - 15\%$ (see e.g. Noiseux et al., 1988; Rawlins, 1998; Hardy and Van Dyke, 1995).

2.2. Empirical damping models

The current engineering practice for the evaluation of the cable self-damping is based on an empirical approach. Forced vibration tests are typically performed on laboratory test spans, with length in the order of 30–90 m, according to two widely accepted international standards (CIGRE, 1979; IEEE, 1979). The power, P_d, dissipated during steady-state mono-modal vibrations of the cable is measured for different values of: vibration frequency f (Hz), antinode vibration amplitude $y_{\max}$ (m), and axial force T (kN). The experimental data, then, are usually fitted through the following power law:

$$P_d = k\,\frac{y_{\max}^l f^m}{T^n} \tag{6}$$

Different sets of exponents (l, m, n) for Eq. (6) have been estimated by different research groups over a period of more than three decades and compared in (Diana et al., 1998; EPRI, 2006; CIGRE, 2018). The values of the exponents measured from these laboratory tests are in the range of: $l = 2 - 2.5$; $m = 4 - 6$; $n = 2 - 2.8$. The scatter in the values of the exponents can be due to both the differences related to the adopted experimental set-up and measurement technique, as well as to the