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A parametric study on the structural damping of suspended cables

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Abstract

The maximum expected amplitude of aeolian vibration is commonly evaluated, in overhead power lines, by the Energy Balance Principle. Within this approach empirical power laws are used to express energy dissipation, and usually require experimental tests to define their coefficients. Starting from a previous formulation for the hysteretic bending of overhead electrical lines, the authors propose first a unified non-dimensional expression for the dissipated energy per unit of length of ACSR conductors, and, second, a closed form expression of the upper-bound estimate of the cable self damping. The proposed self-damping model is applied to the aeolian vibrations of a full-scale experimental test span comparing the predictions with application of the empirical power laws and with experimental data. The results highlight the paramount role played by the self damping model.

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Keywords: Structural damping; cable dynamics; hysteretic bending; aeolian vibration

1. Introduction

Suspended cables employed in overhead power lines are prone to aeolian vibration, triggered by the alternate shedding of Von Karman's vortices. Aeolian vibration is characterized by low-amplitude, high-frequency oscillations mainly in the vertical plane of the cable, which can induce wear damage and fatigue failures of both the conductor and the support equipments [1]. The assessment of aeolian vibration severity, hence, is one of the major concerns in both the design of new lines and in the upgrade or retrofit of existing ones.

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The maximum expected amplitude of aeolian vibration is commonly evaluated through a simplified procedure, which assumes a mono-modal vibration of the cable, imposing the balance between the energy provided by the wind to the vibrating conductor and the energy dissipated within the structure (Energy Balance Principle) [1]. The reliability of the results hence, is strongly affected by the criteria adopted to define the internal damping, also called *self damping*, of the cable.

The technical approach usually adopted to define the cable self-damping relies on expensive and time consuming experimental tests, performed on laboratory test spans according to international standards [2, 3]. The power per unit of length, P_d, dissipated by the cable during mono-modal, steady-state, forced vibrations is measured and the experimental data are usually fitted through the following power law:

$$P_d = k\frac{y_{\max}^{l} f^{m}}{T^{n}} \tag{1}$$

where: $y_{\max}$ (m) and f (Hz) are the single-peak vibration amplitude and frequency of the excited mode, respectively; T (kN) is the axial force of the cable, which is assumed constant along the length of the cable; k is a proportionality factor.

Different sets of exponents (l, m, n) have been measured by different research groups, and results are typically in the ranges: $l = 2 \div 2.5$, $m = 4 \div 6$, $n = 2 \div 2.8$ (see e.g. [1]). The scattering in the values of the exponents can be related to the different experimental set-ups, measurement techniques, measurement errors.

Table 1 lists two sets of exponents, which will be considered in this paper for comparison purposes, since they are often adopted in the literature as reference for computations. The two sets of exponent differ mainly in the values of n. These represent values typically at the opposite ends of the range reported in the literature. The proportionality coefficient, which depends on the geometric and material properties of the cable, should be evaluated for each particular case through experimental tests. However, since experimental data are often missing, the following empirical rule [4] is commonly adopted for stranded Aluminum Conductors Steel Reinforced (ACSR):

$$k = \frac{D}{\sqrt{RTS \times m}} \tag{2}$$

where: D (mm), RTS (kN) and m (kg/m) denote respectively the diameter, the Rated Tensile Strength and the mass per unit of length of the cable.

Table 1. Exponents of the empirical power law (Eq. (1)) measured by different researchers.

Reference	l	m	n
Noiseux [7]	2.44	5.63	2.76
Mechanical Laboratory, Politecnico di Milano [1]	2.43	5.50	2.00

Even if the application of the technical approach, through Eqs. (1) and (2) is straightforward, its results are affected by relevant uncertainties. In fact, a small scatter in the experimental determination of the exponents (l, m, n) leads to large differences in the values of dissipated power predicted by (1), as it has been extensively discussed e.g. in [1, 5-6]. To circumvent the drawbacks of the technical approach and trying to reduce the need for expensive laboratory tests, several mechanical models have been proposed in the last decades to characterize the cable self-damping starting from the knowledge of the physical properties of the cable, see e.g. [7-11]. However, the predictions of these models have shown only limited agreement with the experimental results and should be still considered at a research state, as it is clearly pointed out in the recent review paper by Spak et al [12].

The authors have recently proposed a new formulation for the cable self-damping [13], starting from the characterization of the hysteretic bending behaviour of metallic strands presented in [14, 15]. The predictions of the proposed model were successfully compared in [13] both with those of the empirical power law in equations (1) and (2) as well as with available literature experimental data from vibrations tests performed on laboratory test spans.

Results show that the proposed formulation compares well with the experimental data, with similar accuracy of the empirical power laws adopted in the technical approach.

In this work, the approach proposed by the authors in [13] is extended. The analytical formulation proposed in [15] is adopted to carry out a parametric investigation of the hysteretic bending behavior of ACSR conductors, which are widely employed in overhead electrical lines and, as a major finding, a unified non-dimensional expression is found to express the dissipated energy per unit of length of the cable. This novel expression is then used to obtain a closed form analytical expression leading to an upper-bound estimate of the cable self damping. The new model for the cable self-damping is finally applied to study the aeolian vibration of a full-scale experimental test span for which experimental data are available in the literature [16]. The predictions of the proposed model are compared with those coming from the application of the empirical power law in equations (1) and (2) and with the available experimental data. The results highlight the paramount role played by the self damping model on the dynamic response of suspended cables subjected to vortex induced aeolian vibrations.

2. The hysteretic bending behavior of the cable cross section

Metallic strands are made of helical wires, twisted around a straight core (which is usually another wire) and grouped in concentric layers. ACSR conductors are characterized by a steel core wire, which can be also surrounded by one or more layers of steel wires, and several external layers of aluminium wires (see Fig. 1(a)). Each wire can be regarded as a curved thin rod, within the framework of the classic Clebsch-Kirchhoff-Love theory [17].

The main features of the hysteretic behaviour of a strand cross section subjected to a combination of planar bending and tensile load are first recalled in this section, referring e.g. to [12, 13-15, 18] for more details. Whenever the strand is bent, an axial force gradient is generated along the length of the wires, which gives the wires the trend to slip relatively one to each other. The effect of the axial force gradient is counteracted by the friction forces acting on the external surface of the wires. The friction forces depend on the geometric and material properties of the wires, on the friction coefficient of the internal contact surfaces and on the value of the internal contact pressures. The latter increase for increasing values of the axial load acting on the strand, as a consequence of the clenching effect due to the helicoidal shape of the wire centerlines. As long as the friction forces are large enough to prevent any relative displacement between the wires, the cross section of the strand can be considered as an ideal plane body. The bending stiffness, in this case, attains its maximum theoretical value ($EI_{\max}$), which is close to the one of a compact cross section with the same diameter of the cable and corresponds to the initial slope of the first loading branch of the moment-curvature diagram depicted in Fig. 1(b). The effect of the axial gradient increases for increasing values of the bending curvature and can overcome the resultant of the tangential forces acting on the external surface of the wire. For increasing values of curvature, hence, the wires of the strand start to slip relatively one to each other and the cross sectional bending tangent stiffness gradually decreases. Whenever the bending curvature is large enough to determine the slipping of all the wires, the tangent bending stiffness of the strand attains its minimum theoretical value ($EI_{\min}$), which is close to the one of a bundle of individually bent thin rods.

An analytical approach to model the non-holonomic bending of metallic strands has been proposed by the authors in [15]. Fig. 1(b) shows a typical moment-curvature diagram predicted by the authors' model by assuming that the strand curvature is cyclically variable in the range: $-\chi_{\max} \div \chi_{\max}$, with $\chi_{\max}$ large enough to reach the minimum bending stiffness condition previously discussed. The first loading branch of the diagram can be approximated through an ideal bilinear elastic-plastic curve. The initial and post-yielding stiffness of the approximate bilinear curve are assumed equal to the maximum and minimum theoretical values of the strand bending stiffness, respectively. Closed form expressions for the coordinates of the yielding point, which are denoted in this work as χ_0 and M_0 (see also Fig. 1(b)), can be easily obtained from [15].

The area of the hysteresis loops of, E_{ds}, has been evaluated through numerical integration for several ACSR cables, typically employed as conductors in overhead electrical lines, having widely different internal structure (*stranding*). Figure 1(c) depicts the results of this parametric analysis in terms of the ratio $E_{ds}/M_0\chi_0$ versus the ratio $\chi_{\max}/\chi_0$. As it can be appreciated from this figure, results from the numerical integration are practically independent from the stranding of the cable, and can be well interpolated by a simple quadratic function:

$$\frac{E_{ds}}{M_0\chi_0}=\frac{1}{2}\left(\frac{\chi_{\max}}{\chi_0}\right)^2 \tag{3}$$

3. Analytical estimate of the cable self damping

Once the hysteretic dissipation of the strand cross section is known in closed form through the Eq. (3), the cable self-damping can be easily estimated by applying the simplified approach proposed in [13]. The natural modes of the suspended cable are described according to the classic taut string model, i.e. by neglecting the effects of the sag and of the bending stiffness of the cross sections. Accordingly, the modal shapes can be described by means of sinusoidal functions of the coordinate x, defined along the chord of the cable (see Fig. 2 for notation). The maximum curvature to which a generic cross section is subjected during mono-modal vibration of the cable, then, can be expressed as:

$$\chi_{\max}(x)=\frac{4\pi^2}{\lambda^2}y_{\max}\left|\sin\left(\frac{2\pi x}{\lambda}\right)\right| \tag{4}$$

The energy per cycle and per unit length of the cable, E_d, is then evaluated, by exploiting Eqs. (3) and (4) and recalling that by its very definition $M_0 = EI_{\max}\,\chi_0$, as follows:

$$E_d=\frac{1}{\lambda}\int_0^{\lambda}E_{ds}(x)\,dx=\frac{4\pi^4 EI_{\max}}{\lambda^4}y_{\max}^2 \tag{5}$$

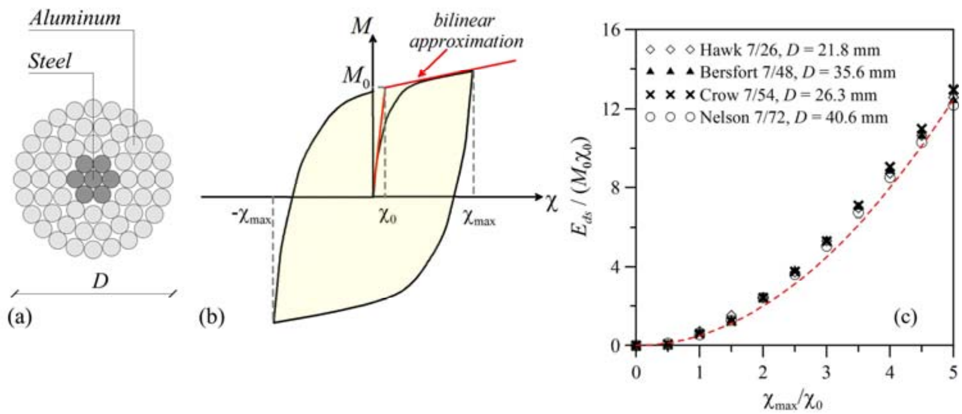

Fig. 1. (a) Typical cross section of ACSR strand. (b) Hysteretic bending response predicted by the proposed model (black solid line) and bilinear approximation of the first loading branch (red solid line). (c) Non-dimensional area of the cross sectional hysteresis loop, evaluated for different ACSR conductors through the proposed numerical model. Results are plotted vs. the maximum non-dimensional curvature χ_{max}/χ_0. The red dashed line is obtained through equation (3).

Finally, the power dissipated, P_d, per unit length of the cable can be obtained by multiplying E_d (Eq. (5)) by the vibration frequency f. By recalling the well known relations between the frequency and the wavelength for the natural modes of the taut string model, the following expression can be easily obtained:

$$P_d = 4\pi^4 m^2 EI_{\max} \frac{f^5 y_{\max}^2}{T^2} \tag{6}$$

It's worth noting that the proposed formulation allows to recover the same power law of the empirical equation (1) commonly used in the current technical approach. Moreover, the values of the exponents in Eq. (6) are well within the ranges of literature values reported in Section 1 of this paper. Differently from the empirical power law (1), however, the proposed formulation is dimensional homogeneous and leads to a proportionality coefficient which is related only to the mass and bending stiffness of the cable (compare Eq. (6) with the empirical Eq. (2) for the proportionality coefficient *k*).

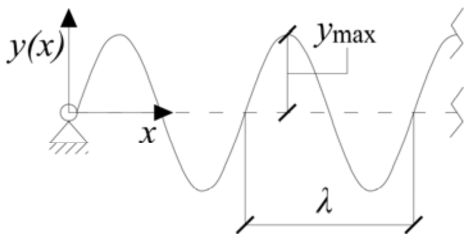

Fig. 2. Natural modes of the suspended cable. Definition of the single-peak amplitude $y_{\max}$ and of the wavelength λ.

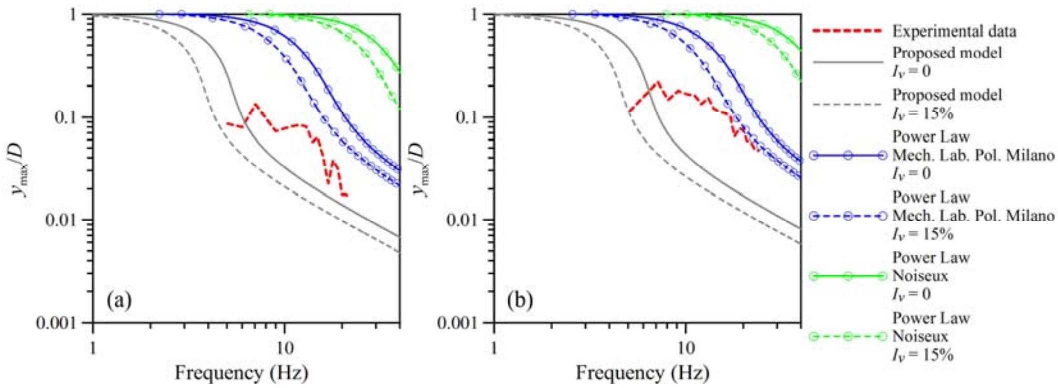

Fig. 3Maximum non-dimensional vibration amplitude computed through the Energy Balance Principle for a Bersfort 7/48 ACSR cable. Comparison among the predictions of the proposed model and those of the empirical power laws (Eqs. (1) and (2)) with the set of exponents listed in Table 1. Experimental results are from [16]. (a) axial load: 25% RTS. (b) axial load: 30% RTS.

4. Numerical application

The new formulation proposed in this work for the cable self damping is applied to evaluate the maximum amplitude of vibration of a full-scale experimental test span equipped with a Bersfort 7/48 ACSR and for which experimental data are available in the literature [16]. To this aim the Energy Balance Principle [1] is used together with the model fully detailed in [19] for the characterization of the power imparted by the wind to the cable. Computations are performed for two different levels of turbulence, which are compatible with the measured values reported in [16], i.e. zero turbulence ($I_v = 0$) and 15% turbulence ($I_v = 15\%$).

Results are reported in terms of the non-dimensional single-peak amplitude of vibration, which is shown in Fig 3 as a function of the vibration frequency for two different values of the cable axial force: the 25% (Fig. 3(a)) and 30% (Fig. 3(a)) of the conductor Rated Tensile Strength (RTS). The predictions of the proposed model are compared with those of the technical approach, based on the empirical equations (1) and (2). Two different sets of exponents (*l, m,* *n*) are considered, namely: the one measured by Noiseux [7] and the one measured at the Mechanical Laboratory of the Politecnico di Milano [1] (data are listed in Table 1 of this paper).

As Figure 3 shows, the predicted vibration amplitudes strongly depend on the adopted self-damping model, and, for the power law model, on the set of exponents. In this last case, since the law is of the power type, even small differences in the coefficients lead to large differences in the predicted vibration amplitudes. Depending on the vibration frequency, the proposed analytical model for the self-damping leads to vibration amplitudes as good (low frequencies), or as bad, as those coming from the best power-law empirical model. For higher frequencies, one empirical model appears in better agreement with experimental data. However, the proposed model is based only on the geometric and material properties of the cable, not requiring expensive and time consuming tests.

4. Conclusions

The Energy Balance Principle usually requires experimental testing to define the value of the internal damping of cables. A power law is usually adopted for damping. To reduce the need for expensive laboratory tests, the authors propose an extension of a previous analytical formulation that leads to a unified non-dimensional expression for the dissipated energy per unit of length of ACSR cables. This is a novel expression that allows to express in closed form the upper-bound of the cable self damping in the form of the power law commonly used in the current technical approach. The values of the exponents derived from application of the authors approach are well within the ranges of literature values, while the proposed formulation is dimensional homogeneous and leads to a meaningful proportionality coefficient.

The new damping model, applied to study the aeolian vibration of a full-scale experimental test span, highlights the paramount role played by the cable self damping, and compares favorably with the predictions stemming from the empirical power law and from available experimental data.

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