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A finite element approach to model galloping vibrations of iced suspended cables

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Abstract

The modeling of iced suspended cables under wind excitation is developed basing on aerodynamic elements superimposed on corotational beam finite elements. Eccentricity of the ice coating is accounted for and aerodynamic loads include the aerodynamic moment. The proposed formulation, applied to a suspended cables of the literature, highlights the importance of the eccentricity of the ice coating on the critical conditions for galloping and on the post-critical behavior.

Keywords: cable; galloping; corotational finite element; quasi-steady theory

Suspended cables are lightweight and lightly damped structures, which under the action of low or moderate winds (typically with average velocity in the range of 5-20 m/s) can experience galloping vibration whenever the circular symmetry of their cross sections is modified, e.g. by the presence of ice coatings.

Galloping of suspended cables is a special case of self-excited vibration, which can be triggered by the aeroelastic instability of the lower modes of the structure. It is typically characterized by large oscillations in the crosswind direction (up to the order of magnitude of the cable sag), although significant along-wind and torsional components can be sometimes identified.

The first recorded events of cable galloping were referred to iced conductors of overhead electrical power lines and can be traced back to the first decades of the twentieth century (see e.g. [1]). Galloping vibration of overhead

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electrical lines can lead to phase-to-phase flashover and cause large dynamic loads on the support structures. Indeed, severe damages and failures of both the conductors and their interconnected equipment (e.g. insulator pins, components of the support towers, damping devices) have been reported after galloping events [2, 3]. The relevant consequences of galloping on the design and maintenance of electrical lines, and their related costs, have motivated the interest of the mechanical engineering community on the assessment and mitigation of the galloping vibration of suspended cables. Since the capital work published by Den Hartog in 1932 [4], cable galloping has been widely studied by researchers with experimental, analytical and numerical techniques (see e.g. the recent review of literature in [5]). Despite such a long and rich history, however, cable galloping is still an open research topic, due to the complexity of the involved mechanical, aerodynamic and meteorological phenomena.

The present paper deals with the finite element modelling of iced suspended cables undergoing galloping vibrations, by assuming as a starting point a recently developed formulation by the authors [6, 7]. The proposed approach reposes on the corotational finite element technique to model the mechanical response of the cable and fully accounts for the cross sectional bending and torsional stiffness terms, so departing from the classic assumption of perfectly flexible elements (see e.g. [8]). The forces due to the action of the wind flow are evaluated within the framework of the quasi-steady aerodynamic theory [5] and by neglecting the effect of the aerodynamic pitching moment. These forces are applied on the structure via aerodynamic elements, explicitly conceived to be superimposed to the structural mesh for the evaluation of the generalized aerodynamic loads acting at the nodes of the finite element model during the motion of the cable.

The proposed formulation has been preliminary validated in [6] with reference to a benchmark small-sag cable in 1:2 internal resonance condition with a *U-shaped* ice coating uniformly distributed along its length. The results have highlighted the crucial role of the torsional rotations of the cross sections on the static equilibrium configuration under self-weight and average wind load as well as on the galloping response of the cable. Most noticeably, the proposed formulation predicts galloping vibrations only for a bounded range of wind velocities. These findings are in contrast with the results of general finite element discretizations neglecting the rotational degrees of freedom of the cable nodes.

In the present work the author's finite element formulation is extended to account for the eccentricity of the ice coating on the static and dynamic response of the suspended cable. Furthermore, the procedure for the evaluation of the aerodynamic loads is augmented by including the effects of the aerodynamic moment. The proposed formulation is applied to investigate the effect of the ice eccentricity and of the aerodynamic moment on both the static and dynamic response of the small-sag suspended cables already considered by the authors in [6].

1. Finite element modelling of the cable

1.1. The corotational beam element

The mechanical response of the cable is modelled by means of a corotational three-dimensional beam finite element developed by the authors [6-10], which is briefly outlined in this section. The proposed beam element is able to perform static and dynamic analysis with arbitrary large displacements and rotations. The total motion of the element is decomposed in two terms: a rigid body motion and an approximately pure deformational contribution. This is obtained, according to the classic corotational approach, by introducing a *local* or *co-rotated* reference system, which follows the element during its motion.

The finite element response is evaluated first in the local frame, where the assumption of small displacements and strains is assumed to hold true. This assumption makes the proposed formulation particularly well suited for cable elements, which typically can experience large displacements and rotations while retaining small strains. Furthermore, this kinematic assumption allows adopting linear stress and strain measures at the local element level without incurring in non-objective formulations. The latter point can greatly simplify the treatment of material non-linearities, which are of special interest in modelling metallic cables (see e.g. [11-14]).

The local response is modelled through a classic Euler-Bernoulli beam element, with cubic shape functions to interpolate the transverse displacements. The axial displacements and torsion, instead, are interpolated by means of linear shape functions. The low order geometrical non-linearity due to the so-called bowing effect is also accounted for, by following the approach proposed by Crisfield in [15]. The local nodal forces, $\mathbf{P}$, and tangent stiffness matrix,

$\mathbf{K}^{loc}$, can be evaluated through a standard application of the Virtual Work Principle. Within this context, the static effect of the eccentricity of the ice coating is modelled by introducing a distributed torsional moment, acting along the beam element. This distributed moment is evaluated as the product of the weight per unit length of the iced conductor times the distance between the centerline of the bare cable element and the centroid of the iced cable cross section (weight eccentricity, e).

The generalized nodal forces $\mathbf{Q}$ and tangent stiffness matrix $\mathbf{K}$ in the global reference system of the problem are then evaluated by means of the following corotational transformation rules: $\mathbf{Q} = \mathbf{T}^T \mathbf{P}$; $\mathbf{K} = \mathbf{T}^T \mathbf{K}^{loc} \mathbf{T} + (\partial \mathbf{T}^T/\partial \mathbf{q})\, \mathbf{P}$.

The above relations fully account for the geometric non-linearities related to the large displacements and rotations of the local reference system. The definitions of the transformation matrix $\mathbf{T}$ and of its derivative with respect to the nodal displacement vector, $\mathbf{q}$, are fully detailed in [6, 9-10].

1.2. The aerodynamic element

A three-node isoparametric aerodynamic element is superimposed in this work to the discretized structural model of the cable in order to evaluate the generalized nodal loads due to the action of a steady wind. The aerodynamic element adopted herein has been developed by augmenting the authors' formulation proposed in [6, 7], in order to include the effect of the aerodynamic pitching moment.

The wind forces acting on the cross sections of the cable in the deformed configuration are evaluated within the framework of the quasi-steady theory. Accordingly, (see e.g. [5]) the aerodynamic forces: (1) can be uniquely defined as a function of the instantaneous position and velocity of the cable cross section; and (2) can be defined on the basis of wind tunnel measurements of the aerodynamic coefficients of drag (C_D) lift (C_L) and moment (C_M) on a stationary structure subjected to the action of a steady flow. Starting from the cross sectional wind forces, then, the generalized forces acting on the nodes of the element can be evaluated through a standard application of the Virtual Work Principle.

2. Numerical application

The proposed finite element formulation is applied to investigate the static and dynamic response of an iced cable in 1:2 internal resonance conditions. This is a well documented numerical benchmark, already studied by different authors with both analytical and numerical techniques (see e.g. [6-8, 16-17]). The cable is suspended to level supports and uniformly coated by a *U-shaped* ice deposit (see Fig. 1(a)). The wind flow is assumed to be steady and normal to the plane of the cable centerline in the equilibrium configuration under the action of the self-weight only (see Fig. 1(b)). The ice deposit is assumed to be located on the leeward side, i.e. on the most favorable position to drive galloping vibrations, for this particular ice accretion shape [2].

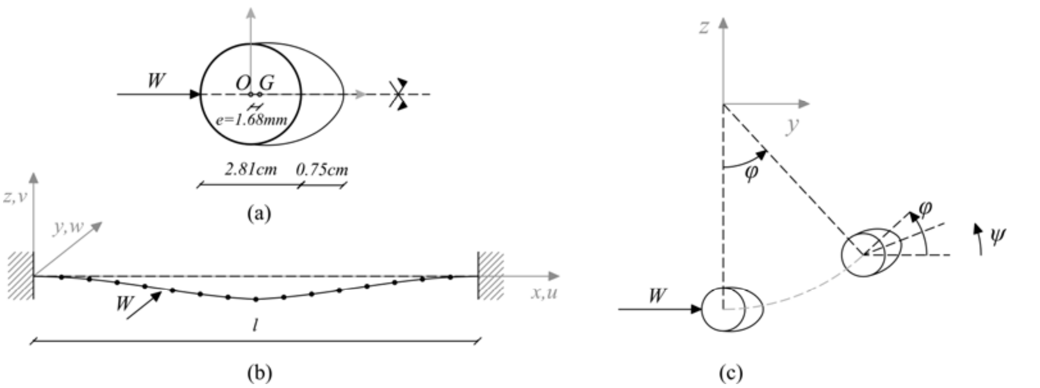

Fig. 1. (a) cross section of the iced cable in the reference configuration; (b) structural scheme and finite element discretization; (c) cross section of the iced suspended cable under the action of the average wind load: definition of the swing angle, φ, and of the aerodynamic twist, ψ.

The mechanical and aerodynamic properties of the cable cross sections are defined according to the data reported in [18]. A linear-elastic constitutive law is assumed for the cable cross sections. The axial stiffness (elastic modulus times effective area) of the cable is assumed to be equal to the measured value of 29700 kN. Due to the lacking of measured values, instead, the bending and torsional stiffness terms are estimated through the formulation proposed in [11], starting from the mechanical and geometric properties of an aluminum conductor steel reinforced (ACSR) Drake 7/26. Accordingly, the direct torsional stiffness is assumed to be equal to 0.180 kNm^2 while the bending stiffness is assumed equal to 0.74 kNm^2, which corresponds to one half of the maximum theoretical value obtained under the assumption of plane cross section. This correction takes approximately into account the possible occurrence of sliding between the wires of the conductor, which tends to reduce the bending stiffness of the element (see e.g. [11-13]). Axial-torsional coupling terms are neglected.

The finite element mesh of the cable is defined according to the criteria discussed in [6]. Seventeen equally spaced nodes, sixteen beam finite elements and eight superimposed aerodynamic elements are adopted. The rigid catenary equation is adopted to the define the reference (undeformed) configuration of the suspended cable and the rotations of the end sections of the cable are assumed fully restrained. The mass matrix for the discretized systems takes into account only terms related to nodal translations, although the authors have already extended the finite element formulation to include the effects of rotational inertia terms [10]. This choice has been made on purpose, in order to reproduce the assumptions of many literature analytical models (see [6] for further details). Static and dynamic parametric analyses are performed by varying the wind speed W. The effect of the ice eccentricity and of the aerodynamic moment is assessed by comparing the results of three-different numerical scenarios. The first assumes zero weight eccentricity (i.e. $e = 0$) and neglects the effect of the aerodynamic moment (i.e. $C_M = 0$). The second case assumes $e = 0$, while accounting for the effect of the aerodynamic moment (i.e. $C_M \neq 0$). Finally, the third case assumes e=1.68 mm and zero aerodynamic moment.

In order to present the static response of the cable response, the following definitions are introduced (see Fig. 1(c)): φ, is the swing angle, whose tangent is defined as the ratio between the out-of-plane (y) and in-plane (z) coordinates of a cable cross section. ψ is the aerodynamic twist, which is the rotation of a cable cross section with respect to the average wind direction, i.e. for the case herein considered the rotation of the cross section around the global axis x. It has been already shown in [6] that the swing angle is almost constant along the whole length of the suspended cable, since the structural response of the structure is mainly controlled by the membrane effect, except for two small boundary regions in the neighborhood of the rigid supports. Here the contribution of torsional and bending stiffness terms significantly affects the deformed shape of the cable (see also [19]). The aerodynamic twist angle, instead, varies along the cable length, being equal to zero at the supports and attaining its maximum value at the midspan.

Figure 2 depicts the static equilibrium path of the cable in terms of the swing angle (Figure 2(a)); in Figure 2(b) the aerodynamic twist angle at the midsdpan is shown as a function of the wind speed W (dead loads effects are also included). As it can be easily appreciated, the effects of the aerodynamic moment are practically negligible for the structure at study. The torsional moment due to the weight eccentricity e=1.68 mm has negligible effects in terms of the swing angle at the midspan (see Fig. 2(a)) and significant effects in terms of the aerodynamic twist angle (see Fig. 2(b)). In fact, the eccentricity of the ice coating induces a torsional rotation of the cross sections in the opposite direction with respect to the swing angle, leading to negative values of the aerodynamic moment for values of wind speed lower than about 12 m/s.

Figure 3 shows the distribution of the aerodynamic twist angle along the cable span for two different values of wind speed, namely: $W = 0$ (Fig. 3(a)) and $W = 15$ m/s (Figure 3(b)). The results obtained by considering e=1.68 mm are compared to those obtained by neglecting the effect of the weight eccentricity (i.e. $e = 0$). In both cases, the aerodynamic moment coefficient is assumed equal to zero. It can be clearly appreciated how, for both values of wind speed, the eccentricity of the ice coating has a non-negligible effect on the spatial distribution of the aerodynamic twist angles. The orientation of the cable cross sections in the static configuration, in turn, strongly affects the dynamic response of the structure, by determining the initial values of the angles of attack of the wind [6].

The galloping vibrations of the cable have been investigated through the numerical approach presented by the authors in [6, 7]. Stable galloping vibrations controlled by the first anti-symmetric in-plane mode have been detected for all the three different numerical scenarios previously described. Figure 4 shows the maximum galloping vibration amplitude at the quarter of the cable span. It can be easily noticed that the aerodynamic moment only slightly affects the galloping vibrations of the cable. The eccentricity of the ice coating, on the other hand, has a strong effect both on the critical conditions for the onset of galloping vibrations as well as on the post-critical behavior. More in detail, by comparing the solutions obtained for e=0 and e=1.68 mm it can be observed that: (1) the critical wind speed is increased from about 5 m/s to about 7 m/s; (2) the range of velocities related to stable galloping vibrations is increased of about 180%; (3) the value of the maximum galloping vibration amplitude is increased of about 130%.

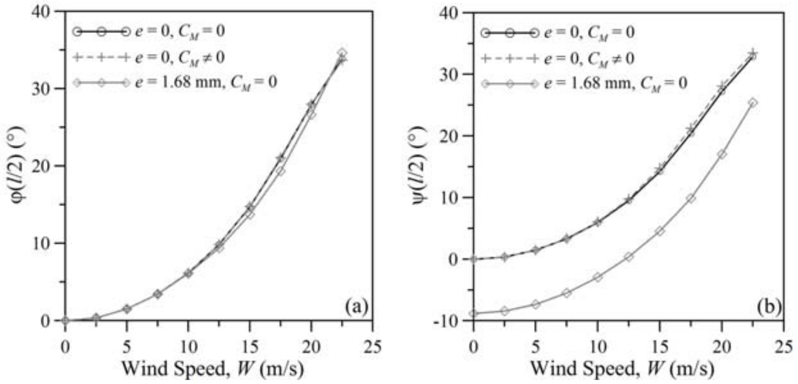

Fig. 2. Static response of the suspended cable under the action of the self-weight and of the average wind load. Comparison among the results of different assumptions regarding the self-weight eccentricity (e) and the aerodynamic moment coefficient (C_M). (a) swing angle at the midsdpan; (b) aerodynamic twist angle at the midspan.

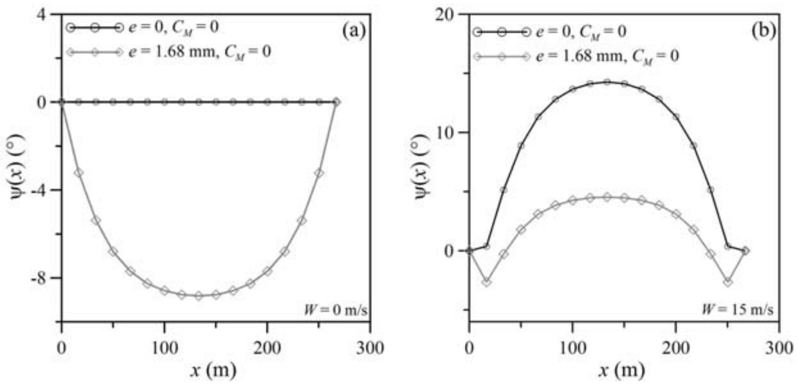

Fig. 3. Aerodynamic twist distribution under the action of the self-weight and of the average wind load. Comparison among the results of different assumptions on the self-weight eccentricity (e). The aerodynamic moment coefficient is assumed equal to zero (i.e.: $C_M = 0$) (a) wind speed: $W = 0$ m/s (self-weight only); (b) wind speed: $W = 15$ m/s.

4. Conclusions

The analysis of an iced small-sag suspended cable of the literature, modeled with the procedure proposed by the authors, has highlighted the effect of the ice eccentricity and of the aerodynamic moment on both the cable static and dynamic response. The aerodynamic moment only slightly affects the galloping vibrations whereas the eccentricity of the ice coating leads to an increase of the critical wind speed, of the wind velocity range of stable galloping and of the maximum amplitudes for the galloping motion.

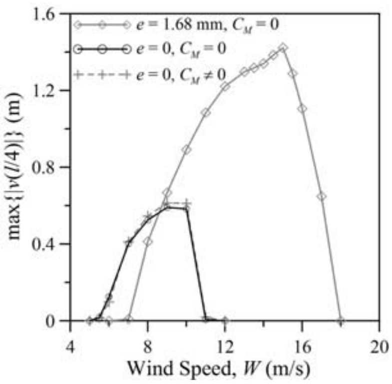

Fig. 4. Steady-state response. Maximum galloping vibration amplitude at the quarter of the span ($x = l/4$) vs. the wind speed W. . Comparison among the results of different assumptions regarding the self-weight eccentricity (e) and the aerodynamic moment coefficient (C_M).

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