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Catenary-induced geometric nonlinearity effects on cable linear vibrations

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ABSTRACT

This paper investigates the free undamped vibrations of cables of arbitrary sag and inclination according to the catenary theory. The proposed approach accounts for the catenary effect on the static profile around which the cable motion is defined. Considering first order geometric nonlinearities, exact expression of the curvature is obtained along with the ensuing correction of the well known Irvine parameter. Taking into account the new characterization, different regions of shallow and non-shallow profiles are identified for various inclinations. In view of such classification, the analysis carried out on cable linear modal properties shows the emergence of new dynamic features such as additional hybrid modes and internal resonances. Analytical and numerical results reduce to those obtained by classic formulations in the cases of both horizontal and inclined shallow/non-shallow cables.

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1. Introduction

It is well known since long time that the equilibrium profile assumed by a cable under its own weight is represented by a catenary [1]. Nonetheless, for engineering purposes, most studies on sagged cables have focused on the parabolic approach. Assuming a parabolic profile for the static equilibrium configuration and considering a quasi-static cable stretching, Irvine and Caughey explored the transverse dynamics of a horizontal shallow elastic cable [2] via a statically condensed model exploiting the great difference between transverse and longitudinal frequencies. The free linear oscillations of small sag cables were found to be governed by only one dimensionless ratio summarizing the mechanical and geometrical cable characteristics (the so called elasto-geometric parameter), denoted by λ. For special values of Irvine's parameter defined by $\lambda = 2k\pi; k \in \mathbb{N}^*$, the phenomenon of frequency crossover occurs causing the order exchange of symmetric and antisymmetric modes. On the other side, Triantafyllou extended the validity of the characterization based on the Irvine parameter to small sag inclined cables [3]. However, as long as the sagged cable gets more and more inclined, an asymmetry aspect is manifested by modal shapes. In addition, the elastogeometric ratio λ is corrected for increasing inclinations inducing smaller special values of λ defining the so called "avoidance" regions: in fact, taking into account the new expression of curvature obtained for inclined cables, frequency crossovers typical of horizontal sagged cables are modified into avoidance zones where couples of approaching frequency loci abruptly diverge from each other [4]. Later, a huge amount of research on cable finite amplitude vibrations around a parabolic

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static equilibrium profile has been accomplished, as overviewed in Refs. [5–7].

Nevertheless, in some recent papers, the catenary profile of static equilibrium has also been considered in the investigation of linear and nonlinear dynamics of non-shallow cables. Considering an approximate analytical expression of the cable curvature, the free linear oscillations of moderately loose horizontal cables have been addressed by Lacarbonara et al. [5] via an enhanced version of Irvine model [2], by also considering a more general non-condensed model accounting for longitudinal and transverse vibrations, later on used for investigations in nonlinear dynamics too [6]. Moreover, the in-plane vibrations of inclined taut cables have been the subject of refined condensed linear models proposed by Wu et al. [7] and Zhou et al. [8] based on a cubic approximation of the inextensible catenary solution [1]. The accuracy of both models has been shown via comparisons with results obtained numerically by Galerkin discretizations. For both horizontal non-shallow and inclined cables, the need to refer to at least two parameters - instead of the sole (original or modified) Irvine's parameter applicable for the parabolic configuration - to describe cable linear dynamics has been highlighted. It is also worth mentioning the consideration of catenary geometry in different contexts such as the numerical model developed by Sorokin and Rega [9] for the linear vibrations of arbitrarily sagged inclined cables in a quiescent viscous fluid, as well as the cubic approximation of the catenary solution used by Srinil et al. [10] in nonlinear dynamics. Still, it should be noted that the analytical and numerical models mentioned previously are mainly addressed to purely stretchable cables characterized by high pre-stressed configurations in which their compression resistance is neglected compression resistance. In order to overcome such limitation, recent efforts have been devoted to the development of analytical solutions based on the catenary approach and taking into account the flexural-torsional stiffness of elastic cables. As a matter of fact, the nonlinear static response of elastic cables has been determined by Arena et al. [11]. Furthermore, the effects of flexural rigidity on the dynamic properties of horizontal taut and loose cables have been investigated by Arena [12] and by Ni et al. [13], among others.

In the light of previous investigations, the present work provides an exact analytical solution of the free transverse vibrations based on the catenary geometry of suspended (horizontal/inclined) highly pre-tensioned cables. In order to properly explain the new approach, the paper is organised as follows. Section 2 is dedicated to the formulation of the differential equations governing the dynamic equilibrium and provides the analytical solution for the free linear oscillations. Since the proposed solution is presumed to be valid for shallow/non-shallow suspended cables, a classification of both weekly and deeply sagged cables according to the fundamental cable parameters is presented in Section 3. Taking into consideration the new nonlinear geometry of the static equilibrium, modal properties are addressed in Section 4. In particular, the accuracy of the developed catenary-based approach in providing natural frequencies is demonstrated via comparison with various analytical and numerical models, and the ensuing modification of the scenario of possibly activable internal resonances is pointed out. Finally, concluding remarks and some directions for further research are drawn.

2. Dynamic equations of arbitrarily sagged cables

2.1. Formulation of the problem

Keeping the elastic material assumption and considering only the axial rigidity, the cable's initial static configuration displayed in Fig. 1 is described by a catenary profile spanned by the curvilinear coordinate s and expressed in a fixed Cartesian coordinate system (x, y, z) as follows [1,14,15]:

$$\begin{cases} \dfrac{y(x,\tau)}{L} = -\dfrac{1}{\tau}\cosh\left(-\tau\dfrac{x}{L}+C_1(\tau)\right)+C_2(\tau) \\ x(s,\tau) = \dfrac{L}{\tau}\left[C_1-\sinh^{-1}\left(\sinh(C_1)-\dfrac{\tau}{L}s\right)\right] \end{cases} \tag{1}$$

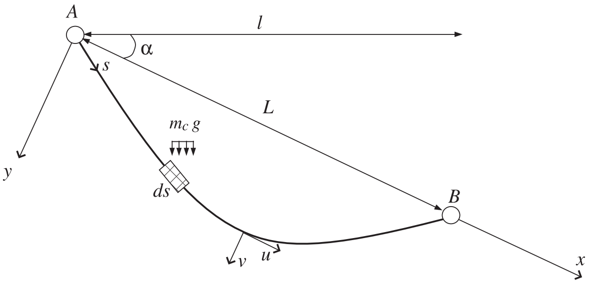

Fig. 1. Static equilibrium configuration of a suspended cable.

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