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Finite element modeling of temperature load effects on the vibration of local modes in multi-cable structures

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ABSTRACT

Understanding thermal effects on the vibration of local (cable-dominant) modes in multi-cable structures is a complicated task. The main difficulty lies in the modification by temperature change of cable tensions, which are then undetermined. This paper applies a finite element procedure to investigate the effects of thermal loads on the linear dynamics of prestressed self-weighted multi-cable structures. Provided that boundary conditions are carefully handled, the discretization of cables with nonlinear curved beam elements can properly represent the thermoelastic behavior of cables as well as their linearized dynamics. A three-step procedure that aims to replace applied pretension forces with displacement continuity conditions is used. Despite an increase in the computational cost related to beam rotational degrees of freedom, such an approach has several advantages. Nonlinear beam finite elements are usually available in commercial codes. The overall method follows a thermoelastic geometrically non-linear analysis and hereby includes the main sources of non-linearities in multi-cable structures. The effects of cable bending stiffness, which can be significant, are also naturally accounted for. The accuracy of the numerical approach is assessed thanks to an analytical model for the vibration of a single inclined cable under temperature change. Then, the effects of thermal loads are investigated for two cable bridges, highlighting how natural frequencies can be affected by temperature. Although counterintuitive, a reverse relative change of natural frequency may occur for certain local modes. This phenomenon can be explained by two distinct mechanisms, one related to the physics intrinsic to cables and the other related to the thermal deflection of the superstructure. Numerical results show that cables cannot be isolated from the rest of the structure and the importance of modeling the whole structure for a quantitative analysis of temperature effects on the dynamics of cable bridges.

1. Introduction

1.1. Context

Cables are widely used in modern civil structures. Typical applications are cable-stayed or suspended bridges, post-tensioned concrete, and suspended roofs. Such structures are subjected to various external forces. Among them, self-weight and environmental thermal loads are inevitable. These loads yield initial stress (prestress) and initial displacement (predisplacement),

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affecting both statics and dynamics.

The literature in modeling the dynamics of a single cable is large. Irvine's work [1] is one of the most important contributions, in which only one dimensionless parameter is needed to determine the natural frequencies of a single cable. Since then, many studies have aimed at taking into account more complicated mechanics, for instance by including bending stiffness [2–4] or nonlinear dynamic effects [5,6]. As far as the modeling of multi-cable structures is concerned, numerical methods are generally required. Several techniques have been proposed based on the finite element (FE) method. A first approach, known as the One Element Cable Stay (OECS) methodology, consists in replacing each cable by one truss element with equivalent Ernst modulus in order to approximate sag effect [7–9]. This procedure is yet limited to the dynamic analysis of the superstructure only. A second approach, called the Multiple Element Cable Stay (MECS) methodology, enables to improve the dynamic analysis by discretizing each cable with several truss elements [10–12]. More accurate approaches have also been proposed by developing specific cable elements based on curved isoparametric discretization [13,14] or based on analytical solutions [15–17]. A literature review is beyond the scope of this paper and these references are far from being exhaustive.

The investigation of thermal effects on the mechanics of cables has surprisingly not received a similar attention. Yet it represents an issue of theoretical and practical interest, particularly motivated by the need of thermoelastic models for vibration-based methods in structural health monitoring (SHM) or cable vibration control. It is well established that cable SHM methods are potentially attractive for tension estimation [18–20] and damage detection [21,22], but suffer a lack of robustness because of environmental temperature variation [23–26]: changes in modal parameters due to temperature can be larger than those due to structural damage or can mask them, yielding false-positive or false-negative alarms.

The literature focusing on the thermoelastic modeling of cables is quite recent. The static response under thermal load has been investigated for suspended cables in Ref. [27] and for stay cables in Refs. [28,29]. As for cable dynamics, an extension of Irvine's model has been proposed in order to account for thermal stress in horizontal cables, [30]. Similarly, the static and dynamic cable responses including thermal effects have been analyzed in Ref. [31]. The combined effects of temperature and bending stiffness have been considered in Ref. [32]. Making use of simplifying assumptions, the influence of temperature variations on the vibration of a stay cable has been investigated and compared to monitoring data in Ref. [33]. All these papers are yet restricted to the dynamics of a single cable. Concerning the effects of thermal loads on the dynamics of multi-cable structures, the literature is scarce up to the author's knowledge. Based on the OECS approximation, the simulation of temperature effects on the natural frequencies of a cable-stayed bridge has been reported in Ref. [34]. However, the OECS approach does not allow an accurate modeling of the dynamics of cable [13] and is not able to accurately account for thermal stress [28].

Indeed, the main difficulty with multi-cable structures is that environmental loads such as temperature change can substantially modify cable tensions, which are then undetermined. Furthermore, the thermal behavior of each cable cannot be analyzed separately: in practice, cables cannot be isolated from the whole structure because their end supports interact with the rest of the structure and do not remain fixed with temperature. Modeling the whole structure is hence required.

The goal of this paper is to apply a FE procedure that enables to accurately account for the effects of thermal loads on the dynamics of multi-cable structures. In the context of cable SHM, one is particularly interested in the temperature effects on the vibration localized in each cable of the whole structure (local modes). This excludes OECS-based approximations. To guarantee accurate modeling of cables, the technique adopted in this paper consists in replacing each cable by several curved beam elements. Such a technique could be viewed as a MECS-like approach, in which usually used truss elements are replaced with curved beam elements. This has two advantages. First, including the element curvature in the formulation significantly improve the convergence compared to the straight element assumption [13,35]. Second, the use of beam elements, although increasing the number of degrees of freedom (dofs), enables to naturally take into account the cable bending stiffness. Bending stiffness effects are known to be significant for the prediction of higher-order modes or large diameter cables [2–4,32]. Note that large diameter cables are typically encountered in suspension bridges for instance. Hence, the approach is not restricted to cable-stayed bridges. Another advantage of the approach is that commercial FE codes can be used provided that nonlinear curved beam elements are available.

The overall method is based on a thermoelastic geometrically non-linear analysis, which is essential to correctly determine the dead load deformed state in a first step, and the thermally loaded static response in a second step. This ensures, in a third step, the accuracy of the vibration analysis (considering small vibrations superimposed on large displacement equilibrium positions).

One difficulty in the modeling of cables with finite elements lies in the boundary conditions that are required at the extremities of each cable of the structure to properly include both the effects of thermal loads and dynamics. The tension in each cable is usually known by design rules, and therefore, can be initially prescribed as an applied force at the end (*i.e.* as a natural boundary condition). However, such a boundary condition cannot be applied in the determination of the thermoelastic static response or in the vibration analysis. This paper uses a three-step computational procedure to overcome this problem.

The paper is organized as follows. In Sec. 1.2, an analytical thermoelastic model is given for a single inclined cable. This model highlights the relevant dimensionless parameters that govern cable dynamics under temperature change and will provide reference solutions for assessing the accuracy of numerical results. In Sec. 2, the non-linear FE formulation is first outlined by incorporating self-weight, thermal loads, and inertia terms. The three-step procedure required for modeling cables with beam elements is then detailed. In Sec. 3, the accuracy of the numerical approach is assessed thanks to the analytical solution for a single cable. Finally, the method is applied to two cable bridges in Sec. 4.

This paper focuses on thermal additional loads typically due to climatic variations, but the proposed method can also apply to live and environmental loads, such as snow, ice or static wind loads.