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Nonlinear vibration behaviors of suspended cables under two-frequency excitation with temperature effects

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ABSTRACT

The aim of this paper is to investigate temperature effects on the nonlinear vibration behaviors of suspended cables under two-frequency excitation. For this purpose, two combination and simultaneous resonances are chosen and studied in detail. First of all, based on the assumptions of the temperature effects, the partial differential equations of the in-plane and out-of-plane motions with thermal effects under multi-frequency excitations are obtained. The Galerkin method is adopted to discretize the nonlinear dynamic equations, and the single-mode planar discretization is considered. Then, in the absence of the primary and internal resonances, the frequency response equations are obtained by using the multiple scales method. The stability analyses are conducted via investigating the nature of the singular points of equations. After that, temperature effects on nonlinear vibration characteristics of the first symmetric mode are studied. Parametric investigations of temperature effects on corresponding non-dimensional factors and coefficients of linear and nonlinear terms are performed. Numerical results are presented to show the temperature effects via the frequency-response curves and detuning-phase curves of four different sag-to-span ratios. It is found out that effects of temperature variations would lead to significant quantitative and/or qualitative changes of the nonlinear vibration properties, and these effects are closely related to the sag-to-span ratio and the degree of the temperature variation. Specifically, the softening/hardening-type spring behaviors, the response amplitude, the range of the resonance, the intersection and number of branches, the number and phase of the steady-state solutions are all affected by the temperature changes.

1. Introduction

The suspended cables is always lengthy and flexible, and the linear and nonlinear static, dynamic and stability analyses have received extensive attentions in the past few years [1–3]. As a typical kind of the nonlinear system which includes both quadratic and cubic nonlinear terms in equations of motion, its vibrations involve large displacements and are dominated by the geometric nonlinearities [2]. Under the excitation of the harmonic external and/or support motions, the local and global nonlinear dynamics have been illustrated by using the analytical, numerical, as well as experimental techniques [3], while some recent achievements are summarized in Ref. [4].

However, it is known that structures are always subjected to the varying environment in practice, especially the temperature changes. Previous investigations have shown that natural frequencies, mode shapes, damping ratios, elastic modulus and even

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the boundary conditions are all relevant to the temperature variations, more or less [5]. Although the qualitative and quantitative relationships between them need further research. It was found out that variations of natural frequencies caused by the damage effect are the same level as those induced by the temperature effects [6]. Therefore, due to the development of the health monitoring of cable structures, as well as the temperature sensitivity materials, researchers began to pay more attentions to temperature effects on vibration behaviors of the cables [7–15], not only on the beam [16–18] or the plate [19]. Many refined analytical and numerical techniques such as in Refs. [7–13], as well as the experimental techniques [14,15], have been proposed recently to study the vibration behaviors of horizontal/inclined cables with thermal effects. Recently, temperature effects on the nonlinear free and forced vibrations at primary resonances were investigated by Zhao et al. [13]. It was found out that some qualitative and quantitative changes of the vibration behaviors were induced by temperature variations.

For the cable structures, the environment temperature variation is just one of the most important factors, and another significant factor is the excitation resource. As a matter of fact, under the excitation of a single harmonic source is very limited. The external excitation is always multi-frequency, so it means that the system is always excited by two or more excitation sources, and the nonlinear vibration behaviors of the system become much more complicated. Hence, it is important and necessary to investigate the nonlinear oscillations of the system under multi-frequency excitations. In the field of the theoretical research, no matter the SDOF or MDOF systems, no matter the systems with the cubic, the quadratic and cubic, or the quadratic, cubic and quartic nonlinearities, their nonlinear vibration characteristics under two or multi-frequency excitations have been received widespread attention and investigated during the past few years [20–32].

Nevertheless, in all available works, the study of temperature effects on the nonlinear vibration characteristics of the suspended cable is very limited, not to mention the investigation of temperature effects on suspended cables subjected to the multi-frequency excitation. Therefore, to address the lack of research in this area, the objective of the present work is to investigate the temperature effects on the combination and simultaneous resonances. The rest of this paper is organized as follows: the governing equations of motion of the suspended cable with thermal effects are derived, and the in-plane equations are discretized by using the Galerkin method (Sect. 2). In the absence of the primary and internal resonances, the multiple scales method is used to solve two combination and simultaneous resonances cases. The frequency response equations are obtained and the stability analyses are given (Sect. 3). In Section 4, numerical results depicting the temperature effects on two resonance cases are presented through analyzing the frequency-response curves and detuning-phase curves. Finally, some conclusions are draw at the end of the paper (Sect. 5).

2. Mathematical formulation

Considering a Cartesian system of axes (x, y, z), the schematic representation of a horizontal cable under consideration is shown in Fig. 1, illustrating a homogeneous suspended cable that is hanged by its end at two fixed points O and B. Three different states are distinguished, namely the static, thermal stressed and dynamic configurations, respectively. The temperature variation is ΔT, L denotes the cable length, b and $b_{\Delta T}$ denote the sags under two static configurations, respectively. The displacements in the longitudinal, transverse and out-of-plane directions are represented by $u(x,t)(\bar{u}(x,t))$, $v(x,t)(\bar{v}(x,t))$ and $w(x,t)(\overline{w}(x,t))$, respectively.

2.1. Equations of motion without thermal effects

Firstly, the temperature variation is not considered, and the following assumptions are adopted: the static configuration is expressed by a parabola ($b/L < 1/10$), the gradient of the longitudinal in-plane motion is negligible with respect to unity, and any flexural, torsion and shear effects are negligible.

With the Lagrangian strain as strain measure, by using the Hamilton's principle and neglecting the inertia and viscous forces, in the absence of the external action in the longitudinal direction, the following two integro-partial differential equations of

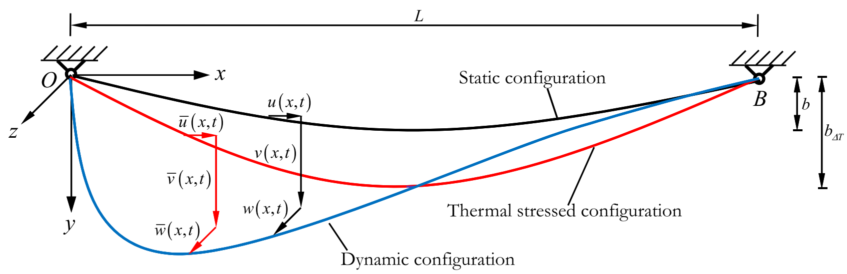

Fig. 1. Three different configurations of the suspended cable and its characteristics.