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Nonlinear dynamic analysis of parametrically excited space cable-beam structures due to thermal loads

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ABSTRACT

The objective of this study is to analytically investigate the nonlinear response and nonlinear power distribution of parametrically excited space cable-beam structures under the effects of simultaneous internal and external resonances. The general coupled thermo-elastic equations of cable-beam structures considering geometrically nonlinearity of cables are firstly developed using the finite element method. Linear modal analysis is then performed to decouple the nonlinear differential equations, and yields a complete set of system quadratic/cubic coefficients in modal coordinates. By the method of multiple scales, the first order asymptotic analysis under 1:2 internal resonance and primary resonance is accomplished. Based on acquired stable solutions, the analytical forms of nonlinear nodal and elemental power flows are further proposed. The nonlinear phenomena of a planar parametrically excited cable-beam structure, such as the bending of response curve, jump phenomena, instability regions, saddle-node bifurcation are verified and the corresponding power distribution is explored by means of numerical analysis.

1. Introduction

A variety of space structure forms were born to adapt to harsh space environments and accomplish special space missions. Among these structure forms, cable-beam structures are a large class of critical structures currently being developed and planned to achieve various missions of spacecraft. Representative structures include deployable mesh reflector antennas and large diameter space radio telescopes, which have been widely applied in the fields of satellite communications, earth observations, land remote sensing and deep space explorations. Examples include many renowned projects, such as ETS-VIII [1], THURAYA 1-3 [2], MBSAT [3], “NEXRAD in Space (NIS)” and GEO-mobile satellites.

Cable-beam structures are characterized by long spans and high load-carrying capacities, making full use of the compression and bending performances of beams and the tensile ability of high strength cables [4]. As the main component of space cable-beam structures, cable nets are light-weight and flexible tension structures. The price of their lightness is their low stiffness leading to large deformations. It is well known that cables change significantly their shape in order to equilibrate transverse loads, due to lack of shear and bending rigidity [5,6]. Hence, an important difference is noted between the initial geometry and the deformed one and the system's stiffness changes as the loads act on the structure, leading to a so-called geometric nonlinearity. The principle of superposition is not valid for such systems and separate nonlinear analysis must be performed for each loading combination [7]. Moreover, the cables must remain in tension under any load combinations, as cable slackening leads to large local deformations, sudden increase of the tension in adjacent cables. Cable nets with large curvatures lead to an increase of the system's stiffness for loads. High levels of initial pretension in cables can also mitigate the large deflections, rendering the system sufficiently stiff [8]. Due to these two properties, cable nets are considered as weakly nonlinear systems, as opposed to single cables, which are strongly nonlinear. Thought the nonlinearity of cable nets is weakly, it has a significant effect on dynamic responses of the overall cable-beam structure. Moreover, some new mechanisms will be generated due to the structural coupling of cables and beams, such as internal resonances between the modes of beams and cables, as well as the combinational resonances of systems.

The increasing interests of cable-beam structures in space applications have led to the growing demands for high surface accuracy and large size. These demands have great effects on performances of space explorations. For mesh reflector antennas, large diameter and high precision reflectors not only are capable of transmitting greater amount of data with higher resolution, but also can expand their working frequency bandwidth from S-band to Ku-band or Ka-band. However, the large-sized cable-beam

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structures easily vibrate induced by particular surroundings, such as plasma, particle, radiative outputs from the Sun, especially high and low temperature alternations [9]. The temperature excitations can induce the variations of structural stiffness and physical parameters of cable-beam structures followed by changes of their vibration amplitudes, as opposed to linear oscillations, which are invariable amplitudes. Moreover, the vibration amplitude with internal resonances may suffer from unstable region and bifurcation phenomena, such as, saddle-node and Hopf bifurcation. The saddle-node bifurcation, a static bifurcation, represents the abrupt change of the stability and number of periodic motion states. The saddle-node bifurcation point corresponds to the jump phenomena and phase delay. The Hopf bifurcation is a dynamic bifurcation corresponding to sudden change of the topology structure of phase trajectories. The consequence of the Hopf bifurcation is known as galloping or flutter. These devastating nonlinear phenomena are unallowed as they can drastically deteriorate surface accuracy of space cable-beam structures. Therefore, the analysis and suppression of nonlinear dynamic behaviors of space cable-beam structures are extremely pivotal and challengeable in further space applications.

Many studies have focused on the nonlinear responses of single beam or cable using single or multi-degrees of freedom (DOFs) [10–13]. From the perspective of the overall structure, Amer et al. investigated nonlinear behaviors of a string-beam coupled system subjected to parametric excitation including multiple solutions, and jump phenomenon in the resonant frequency response curves and chaotic motions [14]. Ding studied the periodic oscillations in a suspension bridge system using the variation reduction method [15], and found that the considered system had at least period-3 oscillations. Sun et al. presented a formulation for fully coupled oscillation analysis of long-span supported bridges [16], where a combination of the finite element approach and pseudo-excitation method was used. Domenico and Grimaldi investigated continuous and discrete models of cable-stayed bridges numerically and analytically considering the nonlinear behavior of the instability effect of the axial compression in the girder [17]. Yau and Yang [18] used an efficient numerical modeling to analysis the dynamic behavior of cable-stayed bridges subjected to railway loads, while considering the nonlinearities involved in the cable system. El Ouni et al. [19] numerically conducted the nonlinear dynamic analysis of a cable stayed bridge in construction phase under parametric excitations. A nonlinear inclined cable with small sag which takes into account the quadratic and cubic nonlinear couplings between in-plane and out-of-plane motion, is coupled with a finite element model of a cable stayed bridge. Cao and Zhang [20] explored the nonlinear and chaotic dynamics of a string-beam coupled system using a nonlinear system having two DOFs. In this paper, the method of multiple scales was applied to analyze the nonlinear responses, moreover the phase portrait, waveform, and Poincare map were used to study the periodic and chaotic motions of the system. Gattulli et al. conducted the one-to-two global–local nonlinear interactions between a beam and a cable in a cable-stayed bridge system [21]. In their analytical model, the global mode defines the motion of the beam with the cable being quasi-static; in the local mode, only the cable appears to be in motion. Wei et al. investigated the bifurcation and chaos of a cable-beam coupled system under simultaneous internal and external resonances considering the combined effects of the nonlinear terms due to the geometric and coupled behavior between the modes of the beam and the cable [22,23]. However, the available nonlinear dynamic model of cable-beam structures is not suitable for analyzing large-scale cable-beam system including multiple beams and cables. Moreover, to the authors' knowledge, the effects of thermal deformations on nonlinear dynamic behaviors of cable-beam structures are not investigated in the literatures. Since the temperature change is one of the major factors affecting the surface accuracy of space cable-beam structures, the time-varying thermal distortion must be considered.

The objective of this work is to investigate the nonlinear phenomena of parametrically excited space cable-beam structures due to thermal loads. The general thermo-elastic dynamic equations of space cable-beam structures are firstly established using the finite element method, which are characterized by quadratic and cubic nonlinearities. The alternating thermal loads are introduced in the form of stress excitations. The coupled linear elasticity terms of obtained dynamic equations exhibit the effects of cable pretensions, initial configuration and thermal stress. After boundary conditions are applied, the linear modal analysis is then performed to calculate natural frequencies and decouple nonlinear differential equations to obtain the quadratic/cubic coefficients of system. By modal decoupling, the motion equation for each DOF of parametrically excited cable-beam structures is a Mathieu equation in modal coordinates.

Considering simultaneous primary resonance and 1:2 internal resonance, the nonlinear dynamic model is solved by the method of multiple scales perturbation. The available perturbation techniques for nonlinear dynamic analysis include the Lindstedt–Poincare method, the method of multiple time scales, the averaging method [24] and the harmonic balance method [25]. The Lindstedt–Poincare method treats some systems inconveniently, such as damped systems. For the method of harmonic balance, one needs either to know a great deal about the solution a priori or to carry enough terms in the solution and check the order of the coefficients of all neglected harmonics. The averaging method in an ad hoc manner may lead to an incorrect answer. As a consequence, the method of multiple time scales is chosen for nonlinear dynamic analysis of parametrically excited space cable-beam structures because of its good generality. The nonlinear phenomena and power distribution of a planar cable-beam structure are explored by means of numerical analysis.

2. Thermal-induced dynamic model

The cable-beam structure for space explorations is mainly composed by a large-scale cable net and multiple supporting beams. The nonlinearities of the overall cable-beam structure are considered to be induced by geometric nonlinearities of the cable net due to its flexible and the characteristic of large displacement with small stress. The thermal loads yield time-varying stress affecting dynamical behaviors of cable-beam structures.

2.1. Cable element

Different from the cables for ground-based applications, cables for space applications are characterized by high tension, lightweight and zero gravity. The geometric nonlinearities of cable nets result from structural large displacements not the sag due to gravity. Therefore, space cable nets can be abstracted as three-dimensional truss structures, of which each member is modeled as bar and is only able to afford tension of elongation [26].

The undeformed and deformed configurations of the cable member are shown in Fig. 1 with nodes 1 and 2 as its two ends. The initial pretension of the kth cable is denoted as N_k. The coordinates of nodes 1 and 2 are denoted by $(x_{ini,j}, y_{ini,j}, z_{ini,j})_{j=1,2}$, and then nodal displacement vector after deformation can be described by

$$\{u_d\}_k = (x_{1,d}, y_{1,d}, z_{1,d}, x_{2,d}, y_{2,d}, z_{2,d})_k^T \quad (1)$$

By the Taylor-series expansion algorithm, the elastic strain of the kth cable, $ee_{t,k}$, is the function of elemental displacement vector, and can be given by