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Analysis of the bending behavior of a cable structure under microgravity

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ABSTRACT

A cable structure is composed of several wire strands wound together. Previously, the mechanical properties of cables mainly included withstanding axial tension and torsion. However, when applied in space deployable structures, the bending behavior of cables directly affects the dynamic response of deployment under the conditions of microgravity and zero tension. Existing cable bending models and their applicable conditions are assessed in this study. 1×7 cable structure models are established, and finite element analysis is conducted with ABAQUS. Equivalent bending modulus is obtained at different helix angles of the cable models. The effects of contact and friction among the strands are analyzed. The calculated and theoretical results from existing models are compared.

1. Introduction

A helically wound structure constitutes a wide class of important engineering components. This structure has various uses: from cables for stabilizing a deployable structure to large wire ropes serving as structural anchors for buildings and bridges [1–5]. When utilized in deployable structures, cables begin to contact and even knot with one another in the unfolding process [6]. This condition leads to the failure of the structure to unfold in the vacuum of space and in a microgravity environment. Thus, the behavior of cable structures needs to be studied extensively, especially bending behavior.

Complex analytical models have been established recently based on the assumption of beam theory that the wires are modeled using Love's curved beam equations [7]. Costello [8,9] described a cable structure as being formed by a number of string wires helically wound through the central core, and the outer wires are arranged in a cylinder-shaped manner. Thus, several central cores or outer wires with different helix angles and radii may be present in the cable structure and thus make the structure a very complex mechanical one. The wires or cores can be stretched, twisted, and bent; therefore, the contact condition affects the behavior of cable structure deformation. Many different hypotheses have been established to simulate cable structures. Considering the geometrics of cable structures, Chiang [10] utilized the finite element method to study the effect of six factors on the stiffness of cable structures. The six factors are the radius of the core line, the radius of the wire, the helix angle, boundary conditions, length of the model, and contact conditions between the core and wires. Chiang also observed the interaction among different cable structure parameters. The interaction between the helix angle and boundary conditions had a significant effect on the simulation results in the test. Papailiou [11] studied the effect of the coupling of tensile and bending loads and proposed a new model. The model considers the friction and slip that occur between layers during bending. A variable bending stiffness, in which the value of the model's bending stiffness varies with the change in bending curvature and axial tension applied on the wire cables, was thus obtained. The result was verified through an experiment.

Several researchers considered the bending of cables in another manner. The entire behavior of the assembly was inferred from its constituent wires or cable structure, thus giving rise to the discrete model. Another method was proposed by Cardou and Jolicoeur [12]; they considered all conductor layer wires as an equivalent orthotropic elastic continuum and thus established the semi-continuous or cylinder model.

Raoof and Hobbs [13] and Jolicoeur and Cardou [14] presented a semi-continuous model, wherein the helix wires of each layer are modeled as a complete cylinder with different mechanical properties to match the mechanical property of the entire layer of the cable structure. The same basic mechanics method was adopted; the similarity of all semi-continuous models is that each wire layer is modeled as a cylinder in a variety of methods. The effect of friction between wires and the stiffness of each wire are considered in these models. Recently Hong et al. [15] discuss the

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influence of the friction coefficient and interactions between wires with the wire curvature of the bent cable. Jolicoeur [16] published a comparative study of these uniform cylinder models and reported that Raoof–Hobbs' model is only applicable for calculation in axial tension or torsional loads and fails to obtain the exact value of bending stiffness. Therefore, whether the Jolicoeur–Cardou model can be utilized to predict the bending behavior of a cable structure is worthy of discussion. Raoof and Kraincanic compared and analyzed discrete and semi-continuous models and found that the former is more reliable for small-diameter structures because it has less cable chains; the latter is more applicable to large-diameter cable structures [17]. Triantafyllou used the beam bending model to study the coupling between axial and lateral vibration and obtained the value of the bending stiffness of the cable structure [18]. Chen Yuan Pei [19] also made use of finite element analysis to compare the bending behavior of different cable structures.

Previous studies mainly focused on strand wires because of their significant advantages, such as the ability to withstand large axial load and having a relatively small bending and torsion stiffness. Although bending characteristics are considered in several of these models, they are different from the model of flexible cable structures in microgravity conditions. For example, a large curvature may appear in the process of a flexible cable bending in a microgravity environment; hence, nonlinear behavior occurs. In addition, a structure becomes highly unstable because the effect of gravity and air damping in the environment is neglected. Therefore, validation and analysis of these models need to be conducted, particularly with regard to the bending behavior of a cable structure. A summary of the limitations of each model needs to be presented.

A 1×7 helix cable structure was selected in this study to assess the accuracy and validity of static pure bending behavior in several analysis models. The influence of assumptions in the different models is discussed by comparing the results of finite element (FE) modeling and the theory model. A conclusion is then obtained.

In Section 2, the relationships among the geometric parameters of a cable structure model are analyzed, and the geometry characteristics and corresponding parameters are investigated. Section 3 presents a description of three existing flexible models and an analysis of the assumptions and limitations of each model. A 3D FE model is presented in Section 4, and the FE results are compared with those of the existing theoretical model. Afterward, the results are analyzed and compared with those of the FE models. The model is then modified according to the analysis results.

2. description of the geometric model

A single 1×7 straight-strand cable made of six helical wires with a circular cross section wrapped around a straight core was considered (Fig. 1). The cord cable structure has a straight center core. The wire cable core is surrounded by outer circle wires. The angle of the laying wires along the axis of the outer layer is called the helix angle [3], denoted as α. The three laying types include left twist, right twist, and twist around each other according to the direction of the laying lines. We selected only the simple right twist 1×7 type cable structure for analysis. In the formula below, r is the radius of the helix, R_1 is the radius of the core wire, R_2 is the radius of the outer layer wires, and R_2' is the long axle size of the oval cross section of the outer wires. Good contact is achieved when no tangential clearance exists between the core and outer wires. The following relationship exists between them [20].

$$r = R_1+R_2, \quad R_2'=\frac{R_2}{\cos\alpha} \tag{1}$$

The section of each outer laying wire is oval. Pitch length, referred to as p, can be calculated with the following expression [21]. The relationship of pitch length, inner diameter, and laying angle is as follows:

$$\tan\alpha = \frac{np}{\pi d}. \tag{2}$$

The Helix angle and pitch length in the model are shown in Table 1.

The pure bending of a homogeneous beam is generally analyzed based on three assumptions: the deformed cross section of the beam remains a plane and is perpendicular to the axis of the beam, and no interaction occurs among the longitudinal elements. Many factors can cause a nonlinear problem. These factors include uneven cross section and internal damping among wires.

3. Descriptions of the analytical models

Free body equilibrium requires that the external applied bending moment is counterbalanced at each conductor cross section by the internal moments acting on each wire of this cross section. A cable structure follows with good approximation for the bending equation [11],

$$M=EI\boldsymbol{\kappa}, \tag{3}$$

where EI stands for the bending stiffness of the cable structure and $\boldsymbol{\kappa}$ stands for the curvature of the cable. The relationship with the radius of curvature ρ is

$$\boldsymbol{\kappa}=\frac{1}{\rho}. \tag{4}$$

The effect of friction on bending deformation is generally obvious, especially when the stress caused by the axial tension in the internal parts of the cable structure is considered. However, friction and slippage are ignored when the cable structure is purely bent. The friction caused by the interaction force resulting from pure bending is not discussed in this section (to be discussed later).

In the cable model of stress caused by axial tension, the result of the model analysis is sensitive to the friction coefficient. Thus, the choice of the friction coefficient between two adjacent wires is worthy of attention. For this reason, two cable models of different friction coefficients, $\mu_1 = 0.15$ and $\mu_2 = 0.5$, were adopted in this study.

The friction effects for the bending of the cable model vary based on the different causes. The deformation process generally involves three processes: stick, transition, and slip.

3.1. Costello's model

Costello [9] considered the macroscopic behavior of cable structures and published his theory in 1990. The assumption is that all wires are free and have no influence on one another. The stresses are then calculated. In his theory, the model study is sufficiently long, and the bending process is considered linear. However, the nonlinear factors caused by the interaction during the bending process are not considered. These factors are contact, friction, nonlinear distortion, and instability, as shown in Fig. 2. Thus, with the sum of all wire bending stiffness method, the smallest possible value of the bending stiffness of the cable model is obtained.

$$A^*=\frac{\pi E}{4}\left[\frac{2m\sin\alpha}{2+\upsilon\cos^2\alpha}R_2^4+R_1^4\right], \tag{5}$$