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Hybrid modeling for dynamic analysis of cable-pulley systems with time-varying length cable and its application

Jing Wang [a], Zhaohui Qi [a], Gang Wang [b,*]

[a] State Key Laboratory of Structural Analysis for Industrial Equipment, Dalian University of Technology, Dalian 116024, China
[b] School of Ocean Science and Technology, Dalian University of Technology, Panjin 124221, China

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ABSTRACT

The dynamic analysis of cable-pulley systems is investigated in this paper, where the time-varying length characteristic of the cable as well as the coupling motion between the cable and the pulleys are considered. The dynamic model for cable-pulley systems are presented based on the principle of virtual power. Firstly, the cubic spline interpolation is adopted for modeling the flexible cable elements and the virtual 1powers of tensile strain, inertia and gravity forces on the cable are formulated. Then, the coupled motions between the cable and the movable or fixed pulley are described by the input and output contact points, based on the no-slip assumption and the spatial description. The virtual powers of inertia, gravity and applied forces on the contact segment of the cable, the movable and fixed pulleys are formulated. In particular, the internal node degrees of freedom of spline cable elements are reduced, which results in that only the independent description parameters of the nodes connected to the pulleys are included in the final governing dynamic equations. At last, two cable-pulley lifting mechanisms are considered as demonstrative application examples where the vibration of the lifting process is investigated. The comparison with ADAMS models is given to prove the validity of the proposed method.

1. Introduction

Cable-pulley systems are widely used in construction machinery fields, such as the multi-rope friction hoisting system of deep coal mines [1,2], the luffing system of cranes [3] and the cable-driven parallel manipulator of Five-hundred-meter Aperture Spherical Telescope (FAST) [4]. In the cable-pulley system, a continuous cable passes through multiple pulleys to lift a load. Structural simplicity, quick lifting speed and low friction are the major advantages of this type of mechanism. Unfortunately, the improper coordination of the cable and the pulleys and the unreasonable lifting speed may cause the system vibration, which is unfavorable for the stability of lifting process. Consequently, it remains the need of further deep study on analyzing the complicated dynamic behavior of the cable-pulley system.

The main reason of vibration of the cable-pulley system is the extensible characteristic of the cable. Therefore, the primary task for dynamic analysis of the cable-pulley system is to model the cable by some kind of finite element. Various kinds of flexible cable elements have been proposed in the past decades. Gosling and Korban [5] developed a bendable finite

* Corresponding author.
E-mail address: wanggang@mail.dlut.edu.cn (G. Wang).

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element for flexible cable structures using fundamental strain-energy principles. Zhu and Meguid [6] proposed a new three-node locking-free nonlinear curved beam element for low tension cables in terms of Updated Lagrangian framework. Fritzkowski and Kamiński [7] modeled a rope as a series of discrete rigid rods with spiral springs in elastic joints. Abad et al. [8] proposed two new elements for three-dimensional finite element analysis of cable structures, namely, continuous and discrete catenary cable elements. All researches above focus on the static and dynamic finite element analysis for cable structures, whereas complicated hybrid motions between the cable and the pulleys exist in the lifting process of the cable-pulley system. Ju and Choo [3] presented a parametric super element model for cable passing through multiple pulleys, where the tensions at the two sides of a pulley were assumed to be proportional. Using the constraint equations, Hong and Cipra [9] presented a systematic way of representing complex cable-pulley mechanism configurations and a method to analyze its motion. Particularly, belt-pulley drive systems have been widely investigated by many researchers. Because the belt is usually short and tensioned, in some references, it is modeled with linear springs [10–13] or beam elements [14,15].

Although there are a series of researches on dynamic analysis of the cable-pulley system, it needs to be further investigated on some aspects. For instance, the most difficult problem are modeling the axially moving of the cable as well as the coupling motion between the cable and the pulleys. Wang et al. [16] investigated three dimensional underwater vibrations of a geometrically nonlinear cable with a weight at the lower end, where a set of nonlinear time varying differential equations were derived by Hamilton's principle and the variable domain finite element method. Tonoli et al. [17] analyzed dynamic behavior of a prototypical belt transmission layout with two fixed pulleys and an automatic tensioner. Babaz et al. [18] presented the dynamic model for the oscillations of a mass suspended to a cable with a variable length, where a nonlinearly elastic law was proposed in rate form and the model is applicable to problems without the restriction of small strains. Jimenez-Octavio et al. [19] presented a moving mesh algorithm, integrated into a general finite element method, which is applied to the catenary-pantograph dynamic interaction. Based on the absolute nodal coordinate formulation (ANCF) in the framework of the Arbitrary Lagrange-Euler (ALE) description, Hong and Ren [20,21] investigated dynamic modeling of a sliding joint on a one-dimensional medium and mass-flowing linear medium with large amplitude displacement and rotation. In their work, a moving node on the one-dimensional medium was proposed, which was realized by variable-length elements at either side of the joint. Du et al. [4,22,23] presented a dynamic model for cable-driven parallel manipulators with cables of slowly time-varying length. The cables were discretized by a variable domain finite element method, resulting in a set of ordinary differential equations.

Although the time-varying length characteristic of the cable has been considered in the above researches, there is few research about the coupling motion between the cable and the movable pulley. Moreover, the coupling motion between the cable and the pulleys have not been properly handled in the modeling phase or the solution phase. The existing modeling methods for the coupling motion of the cable and the pulleys are mainly divided into two categories, i.e., classical geometrical constraint approach and contact-interaction approach. In the classical geometrical constraint approach, the continuous contact is taken as the premise and the Coulomb's friction law is used to calculate the friction force. The contact-interaction approach handles the coupling interaction between the cable and the pulleys by using the contact force model, which has been included in ADAMS software. However, because there are many contact pairs between the cable elements and the pulleys, the integration step size for solving the contact-interaction model should be small enough to detect and simulate the dynamic contact behavior between the cable element nodes and the pulleys [4]. Therefore, the contact-interaction approach has a low computing efficiency. In this work, the coupling motion between the cable and the pulleys are turned into a kind of shape constraint by using the spatial description. On this basis, the dynamic analysis of the cable-pulley lifting system is investigated, where the time-varying length cable is discretized by flexible tensile cable elements with the cubic spline interpolation. Moreover, the time-varying length characteristic of the cable as well as the contacts between the cable and the pulleys are considered.

The organization of this paper is as follows: Section 2 gives the virtual power of the axial tensile strain of the cable, where the time-varying length characteristic of the cable is considered. Section 3 presents the discretization and the cubic spline interpolation for the flexible cable. The coupled motions between the cable and the pulleys are included in Section 4, where no relative sliding assumption is adopted. In Section 5, the condensation of degrees of freedom on the cable is presented. Two numerical examples are presented in Section 6 to validate the proposed method. At last, some remarking conclusions are summarized in Section 7.

2. Virtual power of the axial tensile strain of the cable

In the cable-pulley lifting system, the cable passes through different types of pulleys, including fixed and movable pulleys, as shown in Fig. 1. One end of the cable is attached to a fixed pulley and the other end is attached to a fixed point. The lifting weight is usually heavy and applied at a movable pulley. The entire system is driven by a fixed pulley, which results in that the flexible cable is moving between the fixed and movable pulleys. In the following sections, the flexible cable is discretized into several cable elements. Then, a new kind of modeling approach is presented, where the nodes of the cable elements are not fixed at material points, but spatial positions. Taking the spatial positions as the moving nodes, the moving mesh technique can describe both the position information of the material points at each moment and their flow information at different moments. Owing to the existence of the heavy load, the flexible cable is tensioned during the hoisting process. Furthermore, the flexible cable is so easy being bent and twisted that its bending and torsional stiffness are neglected in this work.