ARTICLE IN PRESS

JID: SAS [m5G;October 24, 2017;13:43]

International Journal of Solids and Structures 000 (2017) 1–19

Contents lists available at ScienceDirect

International Journal of Solids and Structures

journal homepage: www.elsevier.com/locate/ijsolstr

A sliding cable element of multibody dynamics with application to nonlinear dynamic deployment analysis of clustered tensegrity

Ziyun Kan, Haijun Peng*, Biaoshong Chen, Wanxie Zhong

Department of Engineering Mechanics, State Key Laboratory of Structural Analysis for Industrial Equipment, Faculty of Vehicle Engineering and Mechanics, Dalian University of Technology, Dalian 116024, PR China

ARTICLE INFO

Article history:
Received 2 May 2017
Revised 31 August 2017
Available online xxx

Keywords:
Sliding cable
Multibody dynamics
Clustered tensegrity
Dynamic deployment

ABSTRACT

This paper presents a sliding cable element for multibody system analysis. Unlike the existing literature on sliding cables developed using the finite element approach, the novelty of this approach is the use of the configuration of the attached rigid bodies as the generalized coordinates, rather than the traditional nodal displacements. The generalized force vector, and its related tangent stiffness and damping matrix, of the sliding cable and that of the classical cable element are analytically derived. It can also be found that the proposed sliding cable element can degenerate to the existing element formulated using the finite element approach. This allows us to use less generalized coordinates to address a system that contains few rigid or flexible body but with many pulleys. Then, this sliding cable element is employed to investigate the deployment of clustered tensegrity. Both quasi-static and dynamic analyses are carried out. Two representative examples show the effectiveness of the proposed element. The dynamic results also show that the motion characteristics of the system differ from the quasi-static solutions as the actuation speed increases. To achieve a fast actuation speed for deploying such systems, quasi-static analysis seems inadequate, and the dynamic effect must be taken into account. Under this background, the proposed element, coupled with the multibody dynamic methodology used in this work, does provide a powerful tool for analyzing the mechanical properties of such systems.

1. Introduction

In recent years, research into the theory and practice of active structures has been at the forefront of the fields of civil, mechanical and aerospace engineering (Korkmaz, 2011). Based on the active elements, structures can become dynamic objects capable of interacting with the environment. Among many active structural styles, the tensegrity concept may be the most promising for actively controlled structures (Sultan, 2009). Tensegrity structures are composed of struts and cables. The stability is provided by the self-stress state in tensioned and compressed elements (Juan and Mirats Tur, 2008). Tensegrity structures have a high strength-to-mass ratio, which leads to strong and lightweight structural designs (Skelton and Oliveira, 2009; Sultan, 2009; Bel Hadj Ali et al., 2010). Furthermore, tensegrity is flexible and easy to control using small amounts of energy (de Jager and Skelton, 2005). These features create situations where tensegrity structures are particularly attractive for active and deployable structures.

The clustered tensegrity (Bel Hadj Ali et al., 2011; Moored and Bart-Smith, 2009; Zhang et al., 2016, 2015) is a special type of tensegrity structure in which some classical cables are clustered into a continuous cable. To accommodate this structural style, some pulleys should be installed in the original linked nodes between the cables and struts, as shown in Fig. 1. The continuous cable can thus slide over one or more nodes through these frictionless pulleys. Compared with the classical tensegrity (without sliding cables), such a special style has the advantage of fewer actuators being necessary for control (Bel Hadj Ali et al., 2011; Moored and Bart-Smith, 2009). The disadvantage of using the clustered cables is that they damage the control authority and cannot effectively control all nodes. However, the actuation strategy using clustered cables can remarkably reduce the cost of a system, the power consumption, the fabrication complexity and the control complexity (Moored et al., 2011); thus, it is still particularly attractive.

During the past few decades, there have been an enormous number of studies on tensegrity, covering geometrical construction (Liu et al., 2016; Nagase et al., 2016), form finding (Gan et al., 2015; Lee and Lee, 2014; Tran and Lee, 2010; Veenendaal and Block, 2012; Zhang et al., 2014), and mechanical response analysis (from both the static (Faroughi and Lee, 2014; Li et al., 2016; Zhang et al., 2013b) and dynamic

* Corresponding author.
E-mail address: hjpeng@dlut.edu.cn (H. Peng).

https://doi.org/10.1016/j.ijsolstr.2017.10.012
0020-7683/

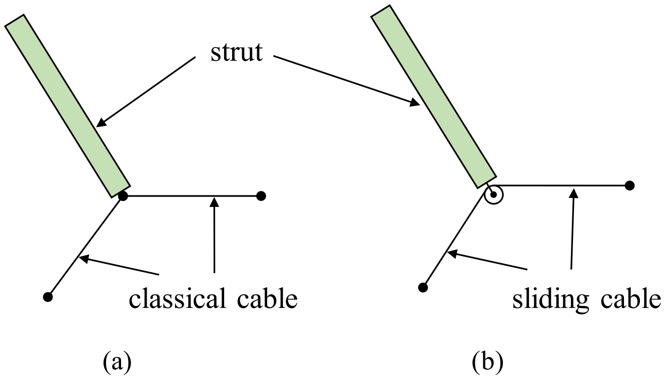

Fig. 1. (a) Classical connections; (b) clustered connections.

(Bel Hadj Ali and Smith, 2010; Cheong et al., 2014; Faroughi et al., 2015; Lazzari et al., 2003; Nagase and Skelton, 2014; Oliveto and Sivaselvan, 2011) aspect. The research methods of such topics include analytical research (Fraternali et al., 2015; Zhang and Ohsaki, 2012), numerical analysis (Estrada et al., 2006; Koohestani, 2013; Zhang et al., 2013a) and experimental study (Adam and Smith, 2008; Amendola et al., 2015; Dubé et al., 2008; Fraternali et al., 2015). However, almost all the previous studies focused on classical tensegrity, while clustered tensegrity has not often been be researched. The concept of clustered tensegrity is relatively new and was mainly proposed for control and deployment. The introduction of sliding cables makes such a structure more complicated than the classical type. The sliding effect of cables resulting from the use of pulleys must be seriously considered. These factors lead to a significant challenge for the structural analysis, and control of this special type of tensegrity. Sultan and Skelton (2003) first noted that the deficiency of having to control too many tendons can be overcome by connecting cables together and using only one motor to control them; however, their work focused only on the deployment of classical tensegrity. Moored and Bart-Smith (2009) first proposed the terminology ‘clustered tensegrity’ and systematically studied the prestress and stability performance based on the energy approach. Bel Hadj Ali et al. (2011) presented a modified dynamic relaxation method to investigate the static performance and quasi-static deployment of clustered tensegrity. By using continuous cables for control, Veuve et al. (2015,2016) experimentally studied the development characteristics of a tensegrity footbridge. Moored et al. (2011) investigated the mechanical properties of a class 2 planar tensegrity beam using different actuation strategies, including the single cable-routed clustered actuation. They also utilized this structure to design an artificial pectoral fin. Very recently, Zhang et al. (2016) proposed a finite element formulation for geometrically nonlinear and quasi-static deployment based on the co-rotational approach, and then they extended their work to the elasto-plastic analysis of clustered tensegrity (Zhang et al., 2015). These existing studies clearly show that the mechanical characteristics of clustered tensegrity are different from those of the classical type, although such works merely focused on the static or quasi-static mechanics/deployment research.

The core element needed to investigate the clustered tensegrity is the sliding cable. Sliding cables allow us to use clustered actuation to replace embedded actuation (Bel Hadj Ali et al., 2011; Moored and Bart-Smith, 2009). It is interesting to see that some sliding cable elements have already been proposed to analyze several engineering systems, such as the suspen-dome structure (Chen et al., 2010), airdrop system (Zhou et al., 2004) and tower crane (Ju and Choo, 2005). All these elements are based on the finite element formulation. For the tensegrity system, the struts are usually very rigid, and the cables are very soft and light such that the bending effect can be neglected (Skelton and Oliveira, 2009; Yang and Sultan, 2017). An ideal physical model of this system is modeling the struts as rigid bodies and the cables as massless springs (which only sustain tension). For the finite element approach, the struts and cables of the tensegrity system are usually modeled as bar elements (with different constitutive relationships). The rigid body condition of a strut may be approximately achieved using a very large axial stiffness. However, some researchers have noted that such an approach may encounter numerical problems, such as the ill-conditioned stiffness matrix, which results in difficulty with respect to convergence (Cheong et al., 2014). Moreover, if the strut is not conventionally thin and long, it is usually hard, if not impossible, to address the six degrees of rigid body motion of the strut for the bar element. Compared to the finite element approach, the multibody dynamic methodology can naturally overcome these unfavorable factors. The large overall rigid body motion of a strut is described by a local fixed frame, and all degrees can be easily handled. The rigid conditions are automatically satisfied for rigid body dynamics. The forces induced by cables are considered as external forces that are applied to the bodies. This methodology seems favored by the applications for tensegrity used in robotics and mechanical engineering; see, for instance (Graells Rovira and Mirats Tur, 2009; Paul et al., 2006, 2005). For the tensegrity used in such applications, the quasi-static hypothesis of active-control is customarily abandoned. Dynamic analysis is necessarily and can be easily performed based on the multibody approach (Graells Rovira and Mirats Tur, 2009; Paul et al., 2006, 2005).

The main objective of this paper is twofold. The first objective is to formulate a novel sliding cable element based on the multibody dynamic methodology. The generalized coordinates of the element are the configuration of the attached rigid bodies rather than the traditional nodal displacements of the finite element approach. This type of element can easily address the highly geometrical nonlinearity and the large rigid body motion of the system. Both the elastic and damping force are taken into account. To make it easy to understand, the formulation of the element is written in a simple engineering language. The second objective of this paper is to implement this element in the deployment analysis of the clustered tensegrity. To the best of our knowledge, most of the previous studies on clustered tensegrity merely focused on, as stated above, static analysis or quasi-static deployment analysis. Studies on the dynamic deployment analysis are rarely seen. However, quasi-static deployment is only an abstract concept in physics. The extent to which the deployment can be regarded as quasi-static is usually obscure. To satisfy the quasi-static conditions as much as possible, the deployment velocity and acceleration are required to be very small, which results in extremely long deployment times. In the present work, both quasi-static and dynamic analyses are carried out with the main aim to reveal the influence of dynamic effects on the deployment process and to find an acceptable actuation speed to achieve fast deployment action. The rest of this paper is organized as follows. Section 2 gives the formulation of the classical and sliding cable element. The related tangent stiffness and damping matrices, together with the extension of the cable element to the flexible multibody system, are presented in Section 3. The implement of the proposed element into analysis of the clustered tensegrity is given in Section 4. Numerical simulations of two representative examples are presented in Section 5, as well as observations and discussions related to the simulation results. Finally, some conclusions are summarized in Section 6.

Please cite this article as: Z. Kan et al., A sliding cable element of multibody dynamics with application to nonlinear dynamic deployment analysis of clustered tensegrity, International Journal of Solids and Structures (2017), https://doi.org/10.1016/j.ijsolstr.2017.10.012