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Thermal shock induced dynamics of a spacecraft with a flexible deploying boom

Zhenxing Shen [a,*], Huijian Li [a], Xiaoning Liu [b], Gengkai Hu [b]

[a] Key Laboratory of Mechanical Reliability for Heavy Equipment and Large Structures of Hebei Province, School of Civil Engineering & Mechanics, Yanshan University, Qinhuangdao 066004, China
[b] Key Laboratory of Dynamics and Control of Flight Vehicle, Ministry of Education, School of Aerospace Engineering, Beijing Institute of Technology, Beijing 100081, China

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ABSTRACT

The dynamics in the process of deployment of a flexible extendible boom as a deployable structure on the spacecraft is studied. For determining the thermally induced vibrations of the boom subjected to an incident solar heat flux, an axially moving thermal-dynamic beam element based on the absolute nodal coordinate formulation which is able to precisely describe the large displacement, rotation and deformation of flexible body is presented. For the elastic forces formulation of variable-length beam element, the enhanced continuum mechanics approach is adopted, which can eliminate the Poisson locking effect, and take into account the tension-bending-torsion coupling deformations. The main body of the spacecraft, modeled as a rigid body, is described using the natural coordinates method. In the derived nonlinear thermal-dynamic equations of rigid-flexible multibody system, the mass matrix is time-variant, and a pseudo damping matrix which is without actual energy dissipation, and a heat conduction matrix which is relative to the moving speed and the number of beam element are arisen. Numerical results give the dynamic and thermal responses of the nonrotating and spinning spacecraft, respectively, and show that thermal shock has a significant influence on the dynamics of spacecraft.

1. Introduction

The deployable booms have a wide range of applications in the space technologies, such as communication antennas, instrument carriers, and gravity gradient stabilizing [1–3]. In the course of boom deployed on orbit, the exposed part will have sudden heating changes due to the emitted thermal radiation and absorbed solar heat flux on the boom's outside surface, that is, the flexible boom is successively subjected to thermal shock during deployment. With the rapid changes of temperature gradients on the boom's cross-section, the time-dependent thermal bending moments that result in the deformations and vibrations of flexible structure are generated.

Many studies have focused on the thermally induced dynamic behaviors of deployable booms after deployment, that is, the length of boom is not changed over time. A notable example of deployable booms is STEM (Storable Tubular Extendible Member) [1], which is considered as a cantilevered beam structure and has been extensively researched by the analytical and numerical approaches. Thornton and Kim [4] derived an approximate solution for thermally induced bending vibrations of STEM as a closed thin-walled tube by means of the method of weighted residuals, and thermal flutter phenomenon was shown in the dynamic responses. Xue et al. [5] presented a numerical approach for investigating thermally induced bending-torsion coupling vibrations of STEM as an open thin-walled tube via the finite element method. By comparing the numerical results, it is found that the temperatures and deflections responses over time are similar between the closed and open cross-section beam models. Gulick and Thornton [6], and Ko and Kim [7] studied the thermally induced vibrations of an axially spinning closed thin-walled tube by the analytical method and the finite element method, respectively. Shen and Hu [8] also studied thermally induced attitude dynamics of a spinning spacecraft with an axial boom using the absolute nodal coordinate formulation and the natural coordinates method. Above researches, the coupled thermal-structural analysis model is extensively employed, which assumes that there is an interaction effect between the absorbed solar heat flux by the tube's outside surface and the structural motions including elastic deformation and rigid rotation.

Deployable boom during deployment can be addressed as an axially moving beam. It is obviously that its dynamic analysis is more difficult than that of beam structures with constant length. A finite element method for the axially moving beam was introduced by Stylianou and

* Corresponding author.
E-mail address: shenzx@ysu.edu.cn (Z. Shen).

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Tabarrok [9], in which the number of elements was fixed, and the size of elements is changed over time. Chang et al. [10] studied the vibration and stability based on the variable-domain element. Park et al. [11] presented a nonlinear analysis model, wherein considered the coupling effect between longitudinal and transverse vibrations of a beam with deployment and retraction. Al-Bedoor and Khulief [12], and Wang et al. [13] gave an approximate analytical solution for the free vibration of a cantilever beam with coupling of an axial translation motion and flexural deformation. Furthermore, the dynamic modeling of an axially moving beam in rotation was introduced by Yuh and Young [14], in which the approximated analytical solution was obtained by using the assumed modes method. Al-Bedoor and Khulief [15] also analyzed a beam with the rotational and translational motions, in which the softening effect due to the centripetal acceleration was included. However, the above proposed models cannot simultaneously describe the large rotation and deformation for the axially moving beam.

Thus, the absolute nodal coordinate formulation that is a non-incremental finite element method is adopted in this work. The global position and gradient vectors are selected as the nodal coordinates for modeling the rotation and deformation field of an infinitesimal volume within the element, which leads to a constant mass matrix, and eliminates the centrifugal and Coriolis inertia forces in the equations of motion [16–18]. The method has been widely used to study the dynamics of deployable space structures [19,20], and was also applied to thermally induced vibrations of flexible beam [21]. In addition, Kawaguti et al. [22] proposed a time-varying length tether element using the dimensionless variables in the frame of absolute nodal coordinate formulation. Tang et al. [23] developed also a variable-length tether element based on the absolute nodal coordinate formulation, in which the governing equations were derived by means of the hybrid Eulerian and Lagrangian framework, the arc-length coordinate of left node of tether element was a time-varying coordinate only, and the number of elements was increasing with the deployment of tether.

This paper focuses on developing an approach for determining the dynamic responses of a deployable beam structure during extension due to a sudden increase in external heating. A variable-length beam element with a constant number of elements is proposed based on the absolute nodal coordinate formulation. The coupled thermal-structural analysis model is adopted, which is to able to find the unstable dynamic response caused by thermal loading. The natural coordinates method is chosen to describe the rigid body, because of that the node coordinates are both in the global coordinate system for the absolute nodal coordinate formulation and the natural coordinates method [24]. Thermal and dynamic governing equations are solved by the weighted residual and generalized-α methods [25], respectively. Numerical results are conducted to illustrate the dynamic responses of a spacecraft with a deploying boom under non-thermal loading and solar heat flux.

2. Modeling of the spacecraft

Consider a spacecraft composed of a rigid hub and a flexible deployable boom is subjected to solar heat flux $\mathbf{S}_0$, as shown in Fig. 1. **XYZ** is the global coordinate system which is a fixed frame of reference, and **xyz** and $\overline{\mathbf{xyz}}$ are the local coordinate systems which are rigidly attached to the flexible boom and the rigid hub, respectively. The rigid-flexible structure can rotate about $\bar{z}$-axis with an spin rate Ω at the initial moment, and the boom simplified as a closed thin-walled tube is deployed along its axial direction with a moving speed $v(t)$ from the rigid hub, one end is fixed on the rigid hub, and the other is with a tip mass.

For the rigid hub described by the natural coordinates method, the position vector of one point is given by Ref. [26].

$$\bar{\mathbf{r}} = \overline{\mathbf{N}}(\bar{x},\bar{y},\bar{z})\bar{\mathbf{q}}(t) \tag{1}$$

where the matrix $\overline{\mathbf{N}}$ is independent of the system's motion and therefore remains constant with time, and $\bar{\mathbf{q}}$ is the vector of natural coordinates,

$$\bar{\mathbf{q}} = \begin{bmatrix} \bar{\mathbf{r}}_i^{\mathrm{T}} & \bar{\mathbf{r}}_j^{\mathrm{T}} & \mathbf{u}^{\mathrm{T}} & \mathbf{v}^{\mathrm{T}} \end{bmatrix}^{\mathrm{T}} \tag{2}$$

that is defined by two basic points i and j, and two unit vectors $\mathbf{u}$ and $\mathbf{v}$. As shown in Fig. 1, the vectors $\mathbf{u}$ and $\mathbf{v}$ are parallel to $\bar{x}$-axis and $\bar{y}$-axis in the local reference frame$\overline{\mathbf{xyz}}$, respectively.

For the flexible deployable boom modeled as an axially moving beam, the element position vector in the absolute nodal coordinate formulation of one point is proposed

$$\mathbf{r} = \mathbf{N}(x(t),y,z)\mathbf{q}(t) \tag{3}$$

where $\mathbf{q}$ is the element nodal coordinates, for the node k, the vector of the absolute coordinates includes the position and slope vectors is defined as [16].

$$\mathbf{q}_k = \begin{bmatrix} \mathbf{r}_k^{\mathrm{T}} & \frac{\partial \mathbf{r}_k^{\mathrm{T}}}{\partial x} & \frac{\partial \mathbf{r}_k^{\mathrm{T}}}{\partial y} & \frac{\partial \mathbf{r}_k^{\mathrm{T}}}{\partial z} \end{bmatrix}^{\mathrm{T}} \tag{4}$$

and $\mathbf{N}$ is the element shape functions written as

$$\mathbf{N} = [N_1\mathbf{I} \quad N_2\mathbf{I} \quad \cdots \quad N_8\mathbf{I}] \tag{5}$$

in which $\mathbf{I}$ is the 3 × 3 identity matrix, and the elements of matrix are

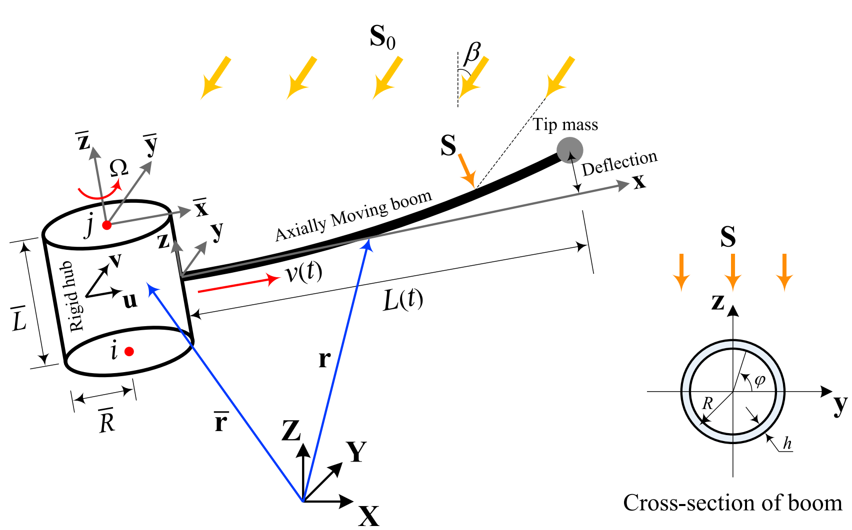

Fig. 1. Thermal-dynamic analysis model of the spacecraft with an axially moving boom.