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Deployment analysis considering the cable-net tension effect for deployable antennas

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ABSTRACT

This paper presents a cable-net tension analysis method during the deployment of deployable antennas. First, the dynamic model of a deployable antenna is established, and the influence of the cable-net tension on the deployment is discussed. Then, the mechanism analysis problem for the cable net during deployment is discretized to several instantaneous structural analysis problems. An elastic catenary element is used to model the tensioned/slack cable net, and an optimization method is adopted for the form-finding of the cable net. Therefore, the shape and the tension of each cable for each instantaneous condition can be calculated. Via synthesizing all of the discrete instantaneous analysis results, the time-dependent cable-net tension curve can be obtained and then applied to the dynamic model of a deployable antenna as external loads and can therefore achieve the dynamic property analysis for deployment. Numerical simulations and experiments demonstrate the validity and rationality of this method.

1. Introduction

Currently, the increasing demand for high-gain and high-resolution space-borne antennas motivates the enlargement of the antenna aperture. With constraints on the current delivery technology, the mass and volume of antennas are limited to an incomprehensive range. Therefore, the deployable property has become one of the typical characteristics of modern large-aperture antennas.

The AstroMesh deployable antenna is widely investigated and applied because of its facile folding, light mass, simple configuration and surface distortion [1], as shown in Fig. 1. It is mainly composed of a deployable truss, a wire mesh, and a cable net (including the front net, the back net and the vertical cables).

The deployment of an antenna from a stowed state to a deployed state is quite a complicated nonlinear dynamics process, and it is likely that a malfunction will occur during deployment [2]. Therefore, it is extremely necessary to accurately predict the dynamic behavior of the deployment through the precise analysis of nonlinear factors, such as the flexibility [3], the friction [4], the clearance [5] and the cable-net tension.

The cable-net structure is folded and curled in the truss structures during launch. Then, the tension gradually increases during deployment after the satellite enters orbit, and the predesigned parabolic surface finally forms. In view of its intrinsic characteristics (e.g., large displacement, small strain and geometric nonlinearity), the cable-net structure would generate a complicated nonlinear force on the deployable truss and lead to a non-negligible influence on the dynamic behavior of the deployment. Previous research has been mostly based on two assumptions [6]. First, the forces of the cable net start to affect the deployable truss at a particular moment, which is usually thought to be at 90% of the total deployment time. Second, the forces of the cable net are equivalent to spring forces, which increase from zero at that particular moment to the predesigned tension of the deployed state. In this treatment, the assumptions are derived from engineering experience and lack theoretical support. In the initial design stage, different choices of topology, cable length or cable tension generate different predesigned cable-net structures and result in different forces on the deployable truss. Therefore, the assumption method described above may only provide an approximate description and is not suitable in all situations.

During the deployment analysis, the form-finding of the cable-net structure is a critical problem. Namely, it is necessary to determine the equilibrium state of the slack cable net under the constraints of the structural boundary conditions and the original length of the cables. Previous form-finding studies have mostly focused on the fully tensioned cable net in the deployed state. Link elements are used to model the cable net, and then the nonlinear distance extrapolation method (DEM) [7], the dynamic relaxation

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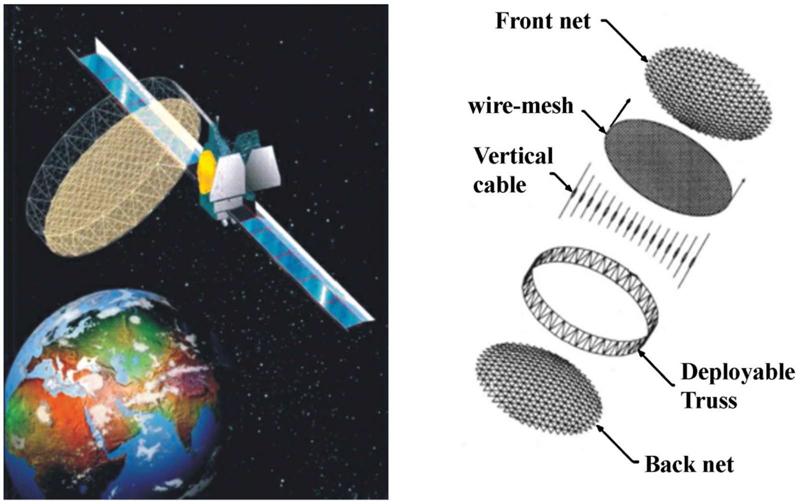

Fig. 1. AstroMesh deployable antenna.

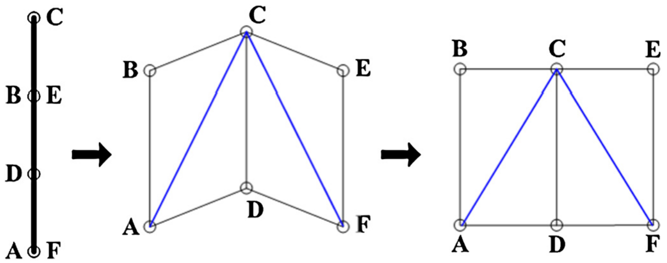

Fig. 2. Deployment of the deployable truss.

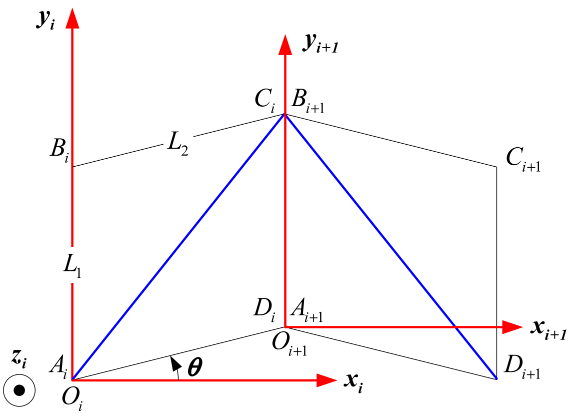

Fig. 3. Coordinate system of truss cell.

method (DRM) [8] or the force density method (FoDM) [9] can be used to solve the form-finding problem. However, if applying this idea to the slack cable-net structure, it should use the link (or beam) elements to model the slack cable approximately. This approximate model would result in a tremendous amount of computational time and, certainly, calculation error. Elastic catenary elements (ECEs) [10], which, in a mathematical sense, are exact for cables subjected to uniformly distributed loads along their lengths, provide a more suitable choice. Recently, a method [11, 12], which uses ECEs and is based on the FoDM, was developed that can address the form-finding problem for slack cables in the field of architecture. However, during deployment, the influence of the cable-net tension on the deployable truss is time-variant. FoDM can only address static structural analysis and cannot obtain the tangent stiffness matrix, which is the basis for future dynamic analysis.

In this paper, a cable-net tension analysis method based on the Finite Element Theory is presented. First, the basic flexible multibody dynamic model for the deployable antenna is established, and the influence of the cable-net tension on the deployment is discussed. Second, the principal equations of the ECEs are introduced. An optimization model is constructed for the form-finding problem, and the solving strategy is discussed. Then, with the tension distribution obtained as described above, the forces of the cable net on the deployable truss can be calculated and added to the dynamic model. Finally, based on a 2-m-aperture prototype model, numerical simulations and experiments are conducted. The results show the validity and rationality of this method.

2. Dynamic model of a deployable antenna

The deployable truss, which is assembled with several geometrically consistent parallelogram truss cells, is the fundamental support structure of a deployable antenna. Each truss cell consists of a three-dimensional hinge (point D), a five-dimensional hinge (point C), horizontal links (BC and AD), perpendicular links (lines AB and CD) and a diagonal sleeve (AC), as shown in Fig. 2. A servo motor provides the driving force by pulling the cables through the diagonal sleeve. Therefore, the deployable truss could deploy through the contraction of the diagonal sleeve.

As shown in Fig. 3, $Ox_iy_iz_i$ is the body coordinate system of the ith truss cell, where the axis y_i is coincident with the link A_iB_i and all four points A_i, B_i, C_i, and D_i of the truss cell are in the plane Ox_iy_i. Setting $Ox_1y_1z_1$ to coincide with the inertial coordinate system, θ is the deployment angle, which is the angle between A_iD_i and the axis x_i. Supposing that the deployable truss is composed of n truss cells, then the joint angle of x between the coordinate systems $Ox_iy_iz_i$ and $Ox_{i+1}y_{i+1}z_{i+1}$ is $\varphi = 360°/n$. The displacement, velocity, and acceleration for each point P_i on the truss cell can be calculated based on the following recursive kinematics equations:

$$s = \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

$$= \begin{bmatrix} \cos[(i-1)\varphi] & 0 & \sin[(i-1)\varphi] & \{\sum_{k=2}^{i}\cos[(k-2)\varphi]\}L_2\cos\theta \\ 0 & 1 & 0 & 0.5[1-(-1)^{i-1}]L_2\sin\theta \\ -\sin[(i-1)\varphi] & 0 & \cos[(i-1)\varphi] & -\{\sum_{k=2}^{i}\sin[(k-2)\varphi]\}L_2\cos\theta \end{bmatrix} \cdot P_i \tag{1}$$