Deployment dynamics of a large-scale ring truss mesh antennas

Pei Li, Cheng Liu, Qiang Tian, Haiyan Hu

School of Aerospace Engineering
Beijing Institute of Technology
5 South Zhongguancun Street, Haidian District, Beijing 100081, China

lipei0603@sina.com, liucheng_bit@aliyun.com,
tianqiang_hust@aliyun.com, haiyan_hu@bit.edu.cn

Abstract
The large-aperture ring truss antenna has been widely used in high precise and accurate communication satellites. The deployment dynamics of this kind of satellite antennas has attracted much attention [1]. However, most of previous studies merely focused on the dynamics of the antenna ring trusses, which can not accurately reflect the true dynamics features of the antenna system during the whole deployment process. In this work, an approach called Absolute-Coordinate-Based (ACB) method combining the Absolute Nodal Coordinate Formulation (ANCF) describing the flexible components and Natural Coordinate Formulation (NCF) describing the rigid components is used to predict the deployment dynamics of a large-diameter ring truss deployable antenna system. Based on the ACB method the equations of motions for a constrained rigid-flexible multibody system can be expressed as a set of differential algebraic equations with a constant mass matrix [2, 3] as following

$$\begin{cases} \mathbf{M}\ddot{\mathbf{q}} + \mathbf{F}(\mathbf{q}) + P_1\mathbf{\Phi}_{\mathbf{q}}^{\mathrm{T}}\boldsymbol{\lambda} + P_2\mathbf{\Phi}_{\mathbf{q}}^{\mathrm{T}}\mathbf{\Phi} - \mathbf{Q}(\mathbf{q},\dot{\mathbf{q}}) = \mathbf{0} \\ P_1\mathbf{\Phi}(\mathbf{q},t) = \mathbf{0} \end{cases} \tag{1}$$

where $\mathbf{M}$ is a constant mass matrix of the system, $\mathbf{q}$ is the generalized coordinates of the whole coupled rigid-flexible multibody system, $\mathbf{F}(\mathbf{q})$ is the elastic force vector of flexible bodies in the system which is a strong nonlinear function of nodal coordinates, $\mathbf{\Phi}(\mathbf{q},t)$ is the constraint vector of the system, $\mathbf{\Phi}_{\mathbf{q}}$ is the derivative matrix of constraint vector with respect to the generalized coordinates $\mathbf{q}$, $\boldsymbol{\lambda}$ is the Lagrange multiplier vector, $\mathbf{Q}(\mathbf{q},\dot{\mathbf{q}})$ is the generalized external force vector, P_1 and P_2 are the scaling coefficients for the constraint terms. Among the methods available to solve Equation 1, this work prefers to use the generalized-alpha method, which can eliminate contributions from nonphysical, high-frequency modes and preserve the responses of low frequencies well. In the generalized-alpha method, the following set of linear algebraic equations must be solved with a Newton iteration procedure

$$\begin{bmatrix} \mathbf{M} + \mathbf{K} + P_2\mathbf{\Phi}_{\mathbf{q}}^{\mathrm{T}}\mathbf{\Phi}_{\mathbf{q}} - \mathbf{Q}_{\mathbf{q}} & P_1\mathbf{\Phi}_{\mathbf{q}}^{\mathrm{T}} \\ P_1\mathbf{\Phi}_{\mathbf{q}} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \Delta\mathbf{q} \\ \Delta\boldsymbol{\lambda} \end{bmatrix} = -\begin{bmatrix} \mathbf{M}\ddot{\mathbf{q}} + \mathbf{F} + P_1\mathbf{\Phi}_{\mathbf{q}}^{\mathrm{T}}\boldsymbol{\lambda} + P_2\mathbf{\Phi}_{\mathbf{q}}^{\mathrm{T}}\mathbf{\Phi} - \mathbf{Q} \\ P_1\mathbf{\Phi} \end{bmatrix} \tag{2}$$

where

$$\mathbf{K}(\mathbf{q}) = \frac{\partial \mathbf{F}(\mathbf{q})}{\partial \mathbf{q}} \tag{3}$$

The problem size due to increased system scales and model accuracies gives rise to the computational burden. To improve the computational efficiency of ACB method, the static condensation method is used to eliminate the internal degrees of freedom for the each flexible component and reserve the boundary degrees of freedom. This method firstly deals with a flexible system partitioned into n non-overlapping subdomains. For subdomain k, Equation(2) can be concisely rewritten as

$$\left(\begin{bmatrix} \overline{\mathbf{K}}_k & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{bmatrix} + \begin{bmatrix} P_2\mathbf{\Lambda}_k^{\mathrm{T}}\mathbf{\Lambda}_k & P_1\mathbf{\Lambda}_k^{\mathrm{T}} \\ P_1\mathbf{\Lambda}_k & \mathbf{0} \end{bmatrix} \right) \begin{bmatrix} \Delta\mathbf{q}_k \\ \Delta\boldsymbol{\lambda}_k \end{bmatrix} = -\begin{bmatrix} \overline{\mathbf{F}}_k \\ P_1\mathbf{\Phi}_k \end{bmatrix} \tag{4}$$

where

$$\begin{cases} \overline{\mathbf{K}} = \mathbf{M} + \mathbf{K} - \mathbf{Q}_{\mathbf{q}}, \mathbf{\Lambda} = \mathbf{\Phi}_{\mathbf{q}} \\ \overline{\mathbf{F}} = \mathbf{M}\ddot{\mathbf{q}} + \mathbf{F} + P_1\mathbf{\Phi}_{\mathbf{q}}^{\mathrm{T}}\boldsymbol{\lambda} + P_2\mathbf{\Phi}_{\mathbf{q}}^{\mathrm{T}}\mathbf{\Phi} - \mathbf{Q} \end{cases} \tag{5}$$

The internal degrees of freedom and the boundary degrees of freedom are divided

$$\left(\begin{bmatrix} \overline{\mathbf{K}}_k^{ii} & \overline{\mathbf{K}}_k^{ib} & \mathbf{0} \\ \overline{\mathbf{K}}_k^{bi} & \overline{\mathbf{K}}_k^{bb} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} \end{bmatrix} + \begin{bmatrix} \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & P_2 \mathbf{\Lambda}_k^{b\mathrm{T}} \mathbf{\Lambda}_k^b & P_1 \mathbf{\Lambda}_k^{b\mathrm{T}} \\ \mathbf{0} & P_1 \mathbf{\Lambda}_k^b & \mathbf{0} \end{bmatrix}\right) \begin{bmatrix} \Delta \mathbf{q}_k^i \\ \Delta \mathbf{q}_k^b \\ \Delta \boldsymbol{\lambda}_k \end{bmatrix} = - \begin{bmatrix} \overline{\mathbf{F}}_k^i \\ \overline{\mathbf{F}}_k^b \\ P_1 \mathbf{\Phi}_k \end{bmatrix} \tag{6}$$

Therefore, the internal degrees of freedom can be determined by

$$\Delta \mathbf{q}_k^i = -\left(\overline{\mathbf{K}}_k^{ii}\right)^{-1} \left(\overline{\mathbf{K}}_k^{ib} \Delta \mathbf{q}_k^b + \overline{\mathbf{F}}_k^i\right) \tag{7}$$

Then, Equation(6) can be written in the following form

$$\left(\begin{bmatrix} \overline{\overline{\mathbf{K}}}_k & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{bmatrix} + \begin{bmatrix} P_2 \mathbf{\Lambda}_k^{b\mathrm{T}} \mathbf{\Lambda}_k^b & P_1 \mathbf{\Lambda}_k^{b\mathrm{T}} \\ P_1 \mathbf{\Lambda}_k^b & \mathbf{0} \end{bmatrix}\right) \begin{bmatrix} \Delta \mathbf{q}_k^b \\ \Delta \boldsymbol{\lambda}_k \end{bmatrix} = - \begin{bmatrix} \overline{\overline{\mathbf{F}}}_k \\ P_1 \mathbf{\Phi}_k \end{bmatrix} \tag{8}$$

where

$$\begin{cases} \overline{\overline{\mathbf{K}}}_k = \overline{\mathbf{K}}_k^{bb} - \overline{\mathbf{K}}_k^{bi} \left(\overline{\mathbf{K}}_k^{ii}\right)^{-1} \overline{\mathbf{K}}_k^{ib} \\ \overline{\overline{\mathbf{F}}}_k = \overline{\mathbf{F}}_k^b - \overline{\mathbf{K}}_k^{bi} \left(\overline{\mathbf{K}}_k^{ii}\right)^{-1} \overline{\mathbf{F}}_k^i \end{cases} \tag{9}$$

Finally, the deployment dynamics of a large-scale antenna system is studied based on the proposed computational strategy. The obtained results can be referred to for the prediction and control of the large-scale space deployable structures. Figure 1 gives the dynamic configurations of the ring truss system in specific simulation time. The efficiency of the parallel computations can be significantly improved via the static condensation approach.

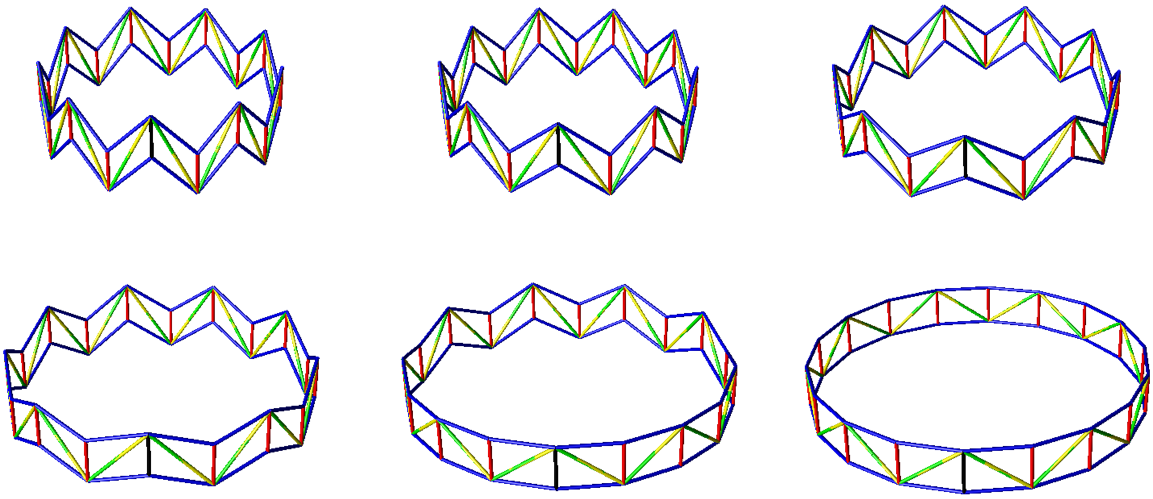

Figure 1: Dynamic configurations of the total deployment process.

References

[1] http://www.northropgrumman.com/BusinessVentures/AstroAerospace/Products/Pages/AstroMesh.aspx, Northrop Grumman Corporation.

[2] A.A. Shabana. Dynamics of Multibody Systems. Cambridge University Press, Cambridge, 2005.

[3] A.A. Shabana. Computational Dynamics, 3rd Edition. Wiley, New York, 2010.