Optimization of control strategy based on equivalent analysis during deployment of Hoop Truss Deployable Antenna (HTDA)

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Abstract: Satellite’s Hoop Truss Deployable Antenna (HTDA) dynamics and controlling, has attracted more and more attention. However, many previous studies were mainly confined to rigid body modelling, which couldn’t reflect the flexible characteristic of the HTDA. By using ANCF, the multi-flexible dynamics system model was established in this paper. After compare with varies strategies, controlling system based on cosine and second-order polynomial was designed in this paper. Complete simulation of the deployment of the HTDA was finished. Modelling method and control strategy are effective and optimized according to the result. The deployment can be controlled precisely by the controlling system and finished smoothly. By this simulation, the rationality of the route planning and validity of control strategy is verified.

1. Introduction

With the development of satellite communication technology, the application of large deployable antenna is urgently demanded. The large deployable antenna has to deploy only after the time the satellite on orbit, which will have deep impression on the satellite. Compare with the deployment of traditional antenna and solar battery, the large deployable antennas have long-period deployment, and low stiffness, these characters greatly impact the satellites. The features take an excursion to the attitude of the satellite and make adverse to the stable of the satellite. How to make a suitable control strategy to make the antenna deploying smoothly and reduce the influence on attitude of the entire satellite. The needs are very necessary and urgent.

For deployment dynamics of large developable antenna, the domestic and foreign scholars have carried out some research[1][2]. However most previous studies modeling the antenna by the method of multiple rigid body dynamics[3] independent of generalized coordinates[4] or center rigid body with flexible attachment[5], which couldn’t reflect the flexible characteristic of the antenna. This paper adopted modeling method of the absolute node coordinates formulation[6], which use the slope vector instead of corner coordinates of nodes from the traditional finite element method (fem). Differential equation of multi-body system deduced comes up with constant inertia matrix, no Coriolis force and no centrifugal force. It can accurately describe the flexible multi-body system by the inspection of relevant scholars[7]. Several schedules of path planning are analyzed for the controlling of deployment, including simple acceleration and deceleration path planning[8], path planning based on quantic polynomial [9], path planning based on Bezier curves[10] confined to the accuracy of dynamics modeling, the control strategy lacked effective modeling support. It could be very difficult even if an approximate dynamic equations.
By using ANCF, the multi-flexible dynamics system model was established in this paper. Controlling system was designed according to the application of antenna. An effective control strategy was obtained by using the method of parameter equivalence. Simulation of the deployment of the HTDA was finished. According to the result, modelling is effective. The deployment can be controlled precisely by the controlling system and finished smoothly. By this simulation, the rationality of the route planning and validity of control strategy is verified.

2. Dynamic Modeling of HTDA
The development of HTDA has been over thirty years with a variety of forms, among which the HTDA has a widely application, as shows in figure 1 and figure 2. The HTDA consists of a circular truss, flexible tension cable net, mesh metal reflector, tension springs and so on. The hoop truss is made up of a number of parallelogram truss units. The deployment uses the principle of that the parallel quadrilateral diagonal is scalable, which uses motor to contact a wine rope which in turn through all the parallelogram unit diagonal inclined rod to shrink diagonal.

Figure 1. structural sketch map of HTDA

Figure 2. sketch map of quadrangular cell of antenna

2.1 modelling of truss structure by ANCF
In order to describe the flexible character of HTDA, we uses the modelling method of beam element and reduce beam element by the absolute node coordinates formulation, which is first proposed by and Shabana and Yakoub as shows in figure 3. The length of the beam element is \( l_\text{e} \), with two nodal, and each nodal 12 generalized coordinates, so the beam element has 24 coordinates.

\[
q = [q_i, q_j]^T = [r_i, r_{i,x}, r_{i,y}, r_{i,z}, r_{j,x}, r_{j,y}, r_{j,z}]^T
\]

(1)

In it, \( r_{i,x} \) is the three dimensional partial derivative vector of node position vector to the x direction global coordinate system. \( r_{i,x} = \partial r_i / \partial x \). The vector to describe the deformation of the beam section along the x direction. The rest of the coordinates' meaning is similar. From any point on the unit, the absolute displacement with absolute node coordinates are expressed as \( r = [r_1, r_2]^T = S q \), which \( S \) is the shape function, the third order interpolation polynomial is used to describe the absolute displacement unit.
By ignore unit beam’s rotation around its own axis, shrink beam element is proposed by Gerstmayr and Shabana[11], which uses 12 generalized coordinates as slender beam unit to discrete the flexible member of loop antenna, so that we can improve the calculation efficiency, as shows in figure 4. For any point on the unit, the absolute displacement in coordinate system is expressed as:

\[
\begin{align*}
\mathbf{r} &= \begin{bmatrix} r_1 \\ r_2 \\ r_3 \end{bmatrix}, \\
\mathbf{X} &= \begin{bmatrix} X_1 \\ X_2 \\ X_3 \end{bmatrix}, \\
\mathbf{Y} &= \begin{bmatrix} Y_1 \\ Y_2 \\ Y_3 \end{bmatrix}, \\
\mathbf{Z} &= \begin{bmatrix} Z_1 \\ Z_2 \\ Z_3 \end{bmatrix},
\end{align*}
\]

\[
\mathbf{r} = \mathbf{X} + \mathbf{Y} + \mathbf{Z} = S \mathbf{q}
\]

And \(S\) is the shape function, \(\mathbf{r}\) means the point's position of unit beam in their own coordinate system. So each beam element has 12 generalized coordinates in total with each nodal has only 6.

\[
\mathbf{q} = [r_{i,\tau}, r_{i,\tau}, r_{j,\tau}, r_{j,\tau}]^T
\]

For \(r_{i,\tau}\) is the three dimensional partial derivative vector \(r_{i,\tau} = \partial r_i / \partial \tau\). The vector to describe deformation of the beam section along the \(\tau\) direction. The rest of the coordinates’ sense is similar. So in modeling of antenna, horizontal, vertical and diagonal rods obtain reduced beam element method.

### 2.2 Modeling of constraint in parallelogram unit

In the process of circular truss antenna, the modeling of joint constraints are as follows:

1. Up horizontal truss and down horizontal truss are head to tail, vertical truss and horizontal truss link. Nodes i and j locate in different component links, with constraint \(r_i = r_j\).

2. For four rotating hinge constraints in each truss surface, we directly use the generalized coordinates to calculate the direction of the rotating hinge axis. since the axial direction of the bar and the direction of the axis of rotation always keep vertical, we can establish rotating hinge constraint. Synchronous gear constraints ensure the open angle of the adjacent two sides, as shows in figure 5, \(r_s^C = T r_s^B, r_x^C, r_x^B\) mean two rail axial directions of AB and CD, \(T\) is rotation matrix.

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**Figure 3. sketch map of three-dimensional beam**

**Figure 4. sketch map of three-dimensional curtail beam**

**Figure 5. diagram of synchronization gear**

**Figure 6. diagram of glide acclivitous beam**
(3) Diagonal movement constraint is shown in figure 6, thin rod can slide freely in bulky rod, at the same time thin rod and the bulky one are always in the surface of the quadrilateral element during deployment, \( r^E_s = -r^H_s, r^F_s = -r^G_s, (r^A_s - r^C_s)/l = r^H_s \).

2.4 Load of Deployment

2.4.1 Driving Force

We should firstly consider the rope twine around the bearing parts, the friction with the structure of bearing parts leads to attenuation of pull \( t \), the attenuation of the driving force can be expressed by formulation \( T_{n+1} = T_n (R - f \cos(\theta/2))/(R + f \cos(\theta/2)) \) between the adjacent truss unit. In which, \( R \) is radius of pulley, \( f \) is coefficient of friction, \( \theta \) is angle between two rods.

2.4.2 Driving Force from Torsion Spring

In order to enable the structure can deploy rapidly at the beginning, we install torsional spring in synchronous hinge torsional spring. Torsional spring provide extra drive power only within the scope of its torsional. During the whole process we set torsional spring force \( \tau \) changes linearly in certain ranges.

2.4.3 Static Friction Torque

Early in the process of truss, the truss is driven by the torsional spring, measured according to experiment, in this period of time, truss unit can be expanded to 50%, at that time each torsional spring still provides the driving force of 3 Nm. We can summarize that each truss antenna unit in the process of expansion has always been constant friction torque of 6 Nm.

2.4.4 Friction Damping in Diagonal Expansion

In the expansion process of diagonal, due to the sliding of thin rod inside the bulky rod, friction generates, has certain effect to the antenna’s development. We can attribute the friction to viscous friction, which is proportional to the relative speed between the bars, \( F_\mu = -\mu \times V_s \), in it, \( V_s \) is relative speed of the two endpoints of the conterminous diagonal rod, \( \mu \) is damping coefficient, \( F_\mu \) impacts at the two endpoints of the conterminous diagonal rod.

3. Control Strategy

3.1 Feedback Control Mode of Limiting Deploy Speed

Due to the complex nonlinear character of HTDA, directly using of dynamic equation to control the deployment is very complex, so we need to find other ways to control the process. The commonly used control method is controlling of range of angular velocity, namely by a feedback system to ensure expansion of truss does not exceed a certain limit, especially come th e end of the stage. By controlling the input driving force, it makes the angular velocity at a certain range. This process is shown in figure 7.

Obviously, effect of the process by this kind of control mode is not ideal. During deployment, the driving force changes drastically. The mode doesn't suit for actual application., and the angular velocity has a larger range of shock, does not favor the process smoothly.
3.2 Path planning method based on cosine and second-order polynomial

Path planning method based on cosine and second-order polynomial can be expressed as

$$\phi = b_1 \cos \left(2 \pi t / T \right) + b_2 \left(t/T \right)^2 + b_3 t / T + b_0 \quad (4)$$

Its angular speed, acceleration and derivative of acceleration can be expressed as follows:

$$\dot{\phi} = - \frac{2 \pi}{T} b_1 \sin \left(2 \pi t / T \right) + \frac{2 \pi}{T} b_2 \left(2 \pi t / T \right) + b_3 / T, \quad \ddot{\phi} = - \frac{4 \pi^2}{T^2} b_1 \cos \left(2 \pi t / T \right) + \frac{2 \pi}{T}, \quad \dddot{\phi} = \frac{8 \pi^3}{T^3} b_1 \sin \left(2 \pi t / T \right) \quad (5)$$

In it, $b_1$, $b_2$, $b_3$, $b_0$ are desired parameters, $T$ is planning cycle, $t$ is time. We can configure $b_1$, $b_2$, $b_3$, $b_0$ to make deploy angle to 90°with angular speed, acceleration to 0 when time comes to $T$ as shown in figure 8. The shake of system can be avoided near the end of the deployment.

3.3 Control system based on equivalent analysis

Since the control method of limiting deploy speed isn’t ideal, we need to come up with a new thinking of the dynamic control of the complex model object. First of all, the whole control process can be summed up in the following process: the modeling object, under different driving force of the $F$ function, deploy state will happen different corresponding changes. For a system’s dynamic model, under the role of driving force, dynamic equation exists as follow

$$M \ddot{\phi} + C \dot{\phi} + K \phi = F \quad (6)$$

For complex dynamic model of antenna, we can also think of a existence of an approximate type equation. Under different driving force of the $F$ function, corresponding changes in Angle, but the coefficient matrix $M$, $C$ and $K$ of the formula are unable to express out directly. However, in order to make the deploy angle in accordance with the planning of a path of change, we need to provide a driving force of the $F$ can be calculated by a formula

$$F = M \ddot{\phi} + C \dot{\phi} + K \phi \quad (6)$$

In it, $\ddot{\phi}$ is ideal Angle based on path planning. At the same time, in order to make every moment in the process of situation according to planned, we need effectively adjust a most suitable driving force $F$.

$$F = R + M \ddot{\phi} + C \dot{\phi} + K \phi + M(\ddot{\phi} - \dot{\phi}) + C(\dot{\phi} - \phi) + K(\phi - \phi) \quad (7)$$

In it, $\phi$ is actual deploy angle, $\bar{\phi}$ is deploy angle planned, $R$ is modified parameter. By this method we can calculate a proper driving force according to the state expressed by $\phi$, $\dot{\phi}$, $\ddot{\phi}$. The last and most hard work is to find the parameter $R,M,C,K$. In order to find the three coefficient $M,C,K$ and modified parameter $R$ in equation (7), the paper adopts the method of multiple equivalent analysis. Equivalent analysis method\(^{(15)}\) is often used in looking for the relationship between two or more
variables. A certain relationship exists between these variables, what we can't or can't exactly give up with a clear function equation to express, and hopes to use much observation data to fit a mathematical model, in which linear model is a relatively simple method.

![Diagram](image)

Figure 9. controlling process of system

Figure 10. change of parameter during deployment

So the question comes to that how to find the effective observation data again. At this time we can use the simulation data of section 3.1. Although its control effect is not ideal, but can actually reflect the characteristics of the model. The driving force and Angle change information data is real, effective and credible. Considering the control effect is not ideal, it is necessary to carry out all the data in the simulation process of screening. We should make a selection of control driver, angular velocity and angular acceleration which are in the scope of the corresponding ideal.

The deploy simulation is finished as figure 10 by the control system designed above. What we find in the simulation is that he antenna deploy as to the route planned, by which validate the effective of the designed control system.

4. Conclude
By using ANCF, the multi-flexible dynamics system model was established in this paper. Controlling system was designed, based on a second-order polynomial with cosine path planning and data analysis method of equivalent analysis, for the application of antenna. Simulation of the deployment of the HTDA was finished. The simulation results show that, this control strategy is simple in form, effective control formula is achieved by using the equivalent analysis method, make deployment smoothly according to the process planning, control strategy is practical and effective.

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