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Research Article

Deployment Impact Experiment and Dynamic Analysis of Modular Truss Antenna

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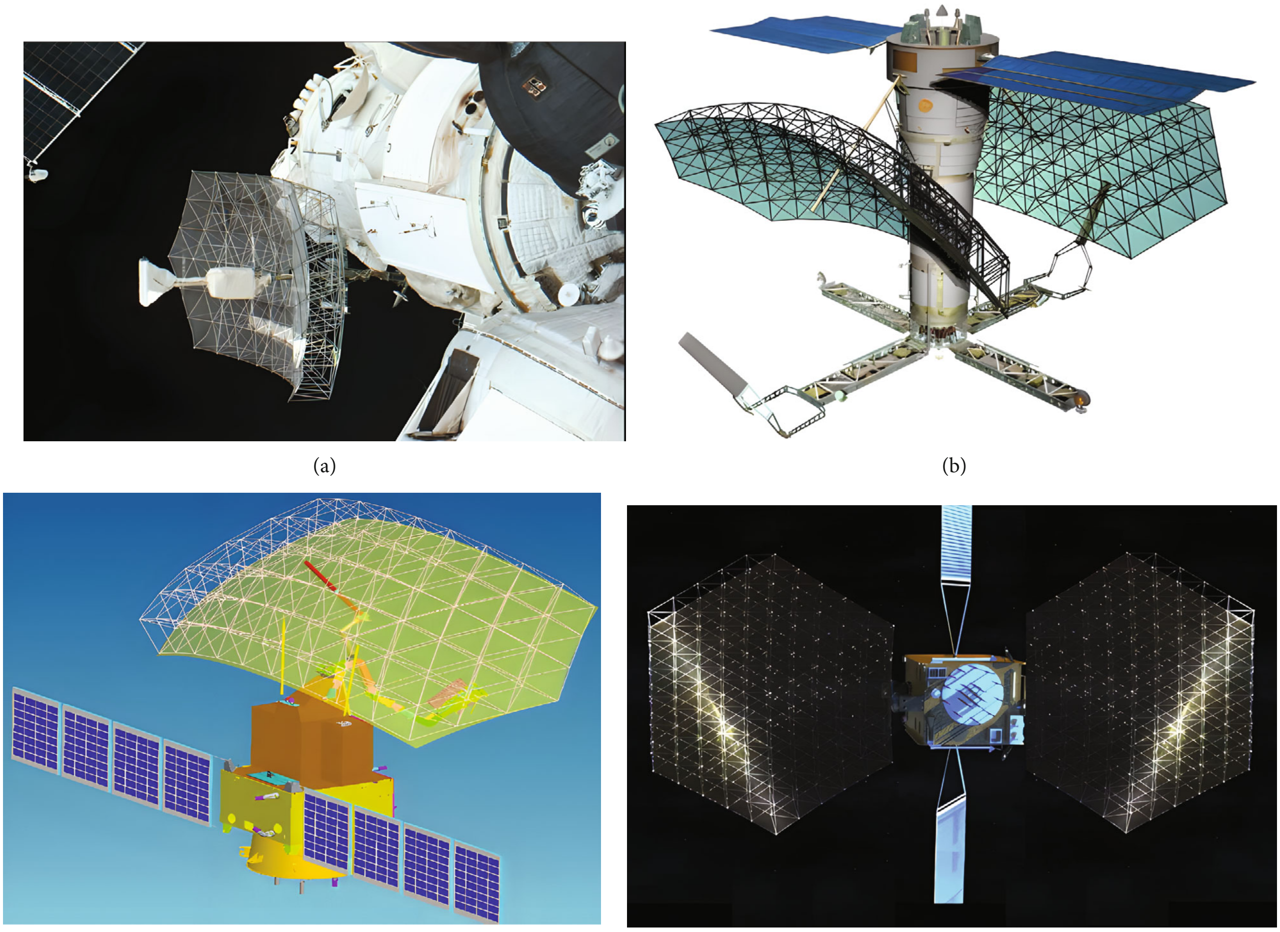
The deployment of a modular truss antenna reflector is relied on the driven energy of the springs between the components of the structure. The deployment process is characterized by fast speed and large impact. In order to study the impact characteristics of antenna deployment on the boundary, the deployment dynamic analysis of a modular truss antenna reflector is carried out. The deployment impact experiment is performed to obtain the impact forces of the reflector on the boundary. The dynamic model of the modular truss reflector is modified according to the experiment results. The dynamic analysis of a satellite with an arm and a modular truss reflector is conducted by using the modified reflector model. The dynamic behavior of the satellite in orbit during the modular truss antenna reflector deployment is predicted.

1. Introduction

In recent years, in order to meet the increasing demands of satellite communication, navigation, and earth observation, more and more large deployable antenna reflectors have been developed and applied in satellite engineering. When the satellite is in the launch stage, this kind of antenna is placed in the rocket fairing in a folded state. After the satellite being launched into space, it is gradually expanded to the working state through the deployment function of the antenna itself. Large deployable antennas usually include solid surface deployable antenna, cable-net deployable antenna, and inflatable deployable antenna [1]. Among them, the cable-net deployable antenna composed of a support structure, and a metal mesh is the most widely used one. Common cable-net deployable antennas include umbrella-type antenna [2], modular truss antenna [3], wrap-rib antenna [4], and hoop modular truss antenna [5–7]. Among them, the modular truss deployable antenna is widely used in various satellites due to its high storage ratio, large structural stiffness, and good stability.

The modular truss deployable antenna reflector structure was first proposed by National Aeronautics and Space Administration (NASA) in 1968 [8]. By changing the size and number of modules, it can adapt to the needs of different calibers. The basic unit that makes up the modular truss deployable antenna includes tetrahedron, quadrangular pyramid, hexagonal column, and hexagonal platform. So far, the modular truss deployable antenna with tetrahedron as the basic unit is the most widely used. For example, the 5.2 m diameter PETA truss antenna is developed by General Dynamics Corporation (GDC) [9]. The 7 m diameter truss deployable antenna reflector developed by Johnson Space Center (JSC) was successfully applied to the "Kondor" spacecraft [10]. And Jet Propulsion Laboratory (JPL) in the United States has studied a modular truss deployable antenna based on shape memory composite deployment hinge for large aperture and high surface accuracy antenna [11]. Among foreign researches, Russia has the most extensive research and application of modular truss deployable antennas. The tetrahedral modular truss deployable antenna developed by Russian Space Agency has been successfully applied to spacecraft such as "Nature," "Soyuz" spacecraft, and "Mir" space station since 1985. The application of truss



(a) (b) (c) (d)

Figure 1: Applications of modular truss antenna. (a) "Mir" space station. (b) Pion satellite. (c) Environmental disaster reduction satellite. (d) BeiDou navigation satellite.

antenna in various countries is shown in Figure 1. The SAR antenna of the "Mir" space station adopts a $6\,m \times 2.8\,m$ modular truss antenna, as shown in Figure 1(a). The Pion satellite launched by Russia in June 2021 uses a modular truss antenna with a diameter of $12\,m \times 4\,m$, as shown in Figure 1(b). At the same time, domestic research on modular truss deployable antenna has also been carried out; meanwhile, offset feed and normal feed modular truss antennas have been developed one after another, which have been applied to BeiDou navigation, environmental disaster reduction, satellite communication, and other fields. The antenna diameter ranges from 6 m to 9 m, and the working frequency band covers the UHF ~ S frequency band, as shown in Figures 1(c) and 1(d).

Usually in the design process of the tetrahedral modular truss antenna, the designer is concerned about the structural rigidity and structural strength, and the shape distortion error of the reflecting surface is concerned by designers [12–15]. There are relatively few related literatures on deployment dynamics of truss antenna. Wang et al. [16, 17] created a dynamics model of tetrahedral element by using commercial software ADAMS and carried out simulation and experimental research on its deployment process. At the same time, they analyzed the deployment process of a tetrahedral modular truss antenna reflector under zero gravity and no boundary conditions and studied the force of the rod during the deployment process of the reflector. Guan and Liu [18] tested the deployment process of a kind of tetrahedral modular truss antenna and proposed a control method to reduce the impact load but did not conduct the on-orbit impact analysis. Huang et al. [19] analyzed the impact force of a kind of offset-fed modular truss antenna but did not study the satellite motion law during the deployment of the reflector. However, the above research did not consider the influence of reflector deployment on the boundary.

Considering that tetrahedral truss antenna has the characteristics of fast deployment and large impact, the deployment of the antenna reflector will inevitably have a significant impact on the satellite attitude. Therefore, in this paper, the dynamic characteristics of a class of normal feed tetrahedral modular truss deployable antennas are studied, and the dynamic simulation and experimental verification of the impact characteristics of the reflector expansion on the boundary are carried out, respectively. The reflector dynamics model was modified by the experimental data, and the on-orbit dynamics behavior of the reflector-deployment arm-satellite combination during the reflector deployment was predicted by dynamic simulation.

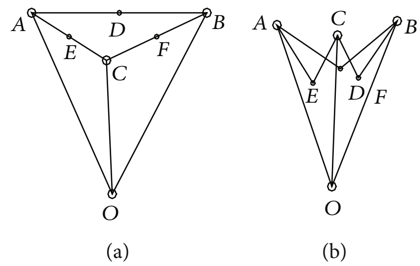


Figure 2: The principle of tetrahedral element expansion. (a) Folded state. (b) Expanded state.

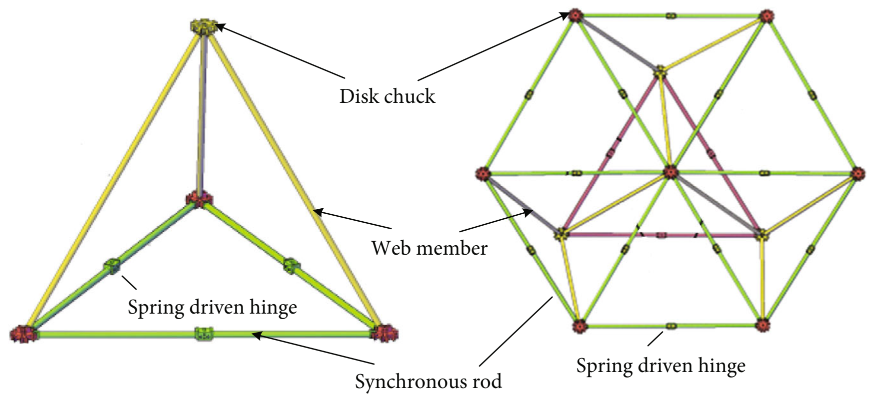


Figure 3: Tetrahedral element and its geometric extension structure.

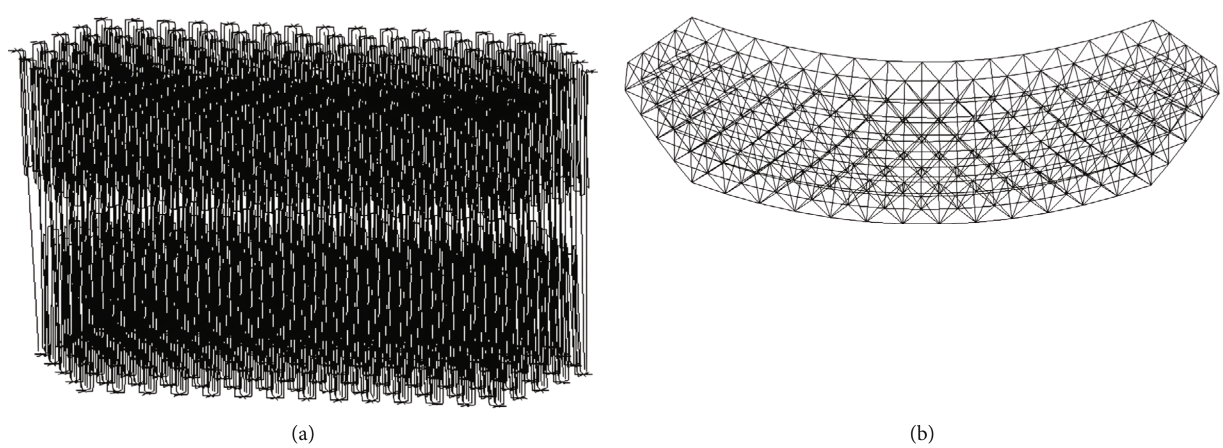


Figure 4: A tetrahedral truss antenna reflector. (a) Folded state. (b) Expanded state.

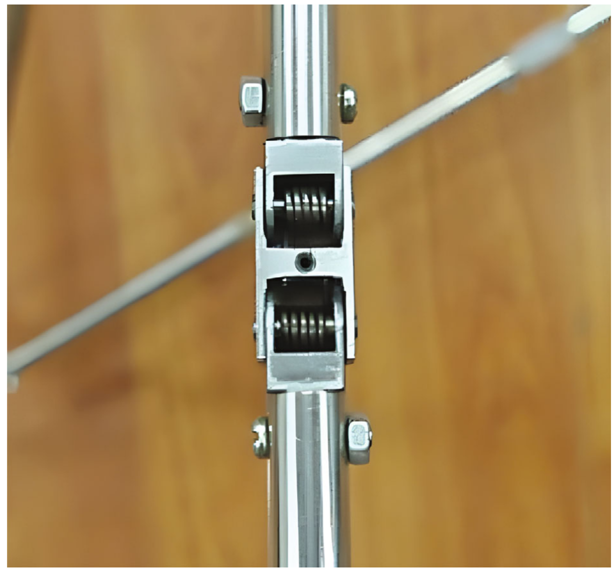
2. Tetrahedral Modular Truss Antenna Reflector

The tetrahedral modular truss antenna is assembled by a series of tetrahedral elements, as shown in Figure 2. Each tetrahedral element contains six rods and four nodes. The three rods AB, AC, and BC on the bottom edge constitute the upper and lower chords of antenna truss, and the three edges OA, OB, and OC are the web members connecting the upper and lower chords. The nodes in the middle of the three chords are designed with folding/deploying function, so that the chord has deployable characteristics.

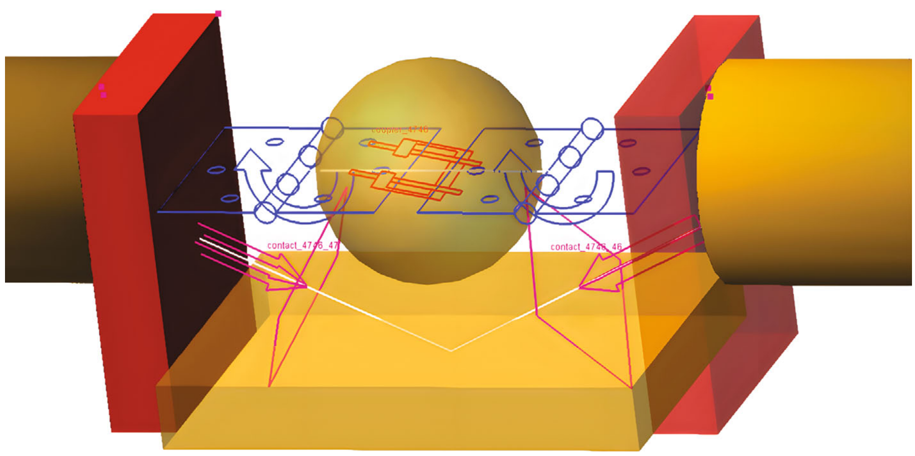
Figure 3 shows the composition structure of the tetrahedral truss element. The tetrahedral element can be conveniently expanded to form a larger scale truss structure.

According to the above theory, the required reflector truss structures of different diameters can be obtained by means of topology expansion using this principle. Figure 4 shows a normal feed tetrahedral modular truss antenna reflector.

As shown Figure 4, the drive nodes in the middle of the reflector's chords store energy during the folding process. When the reflector is unlocked, the drive node releases energy, which drives both the upper and lower chords to



(a)



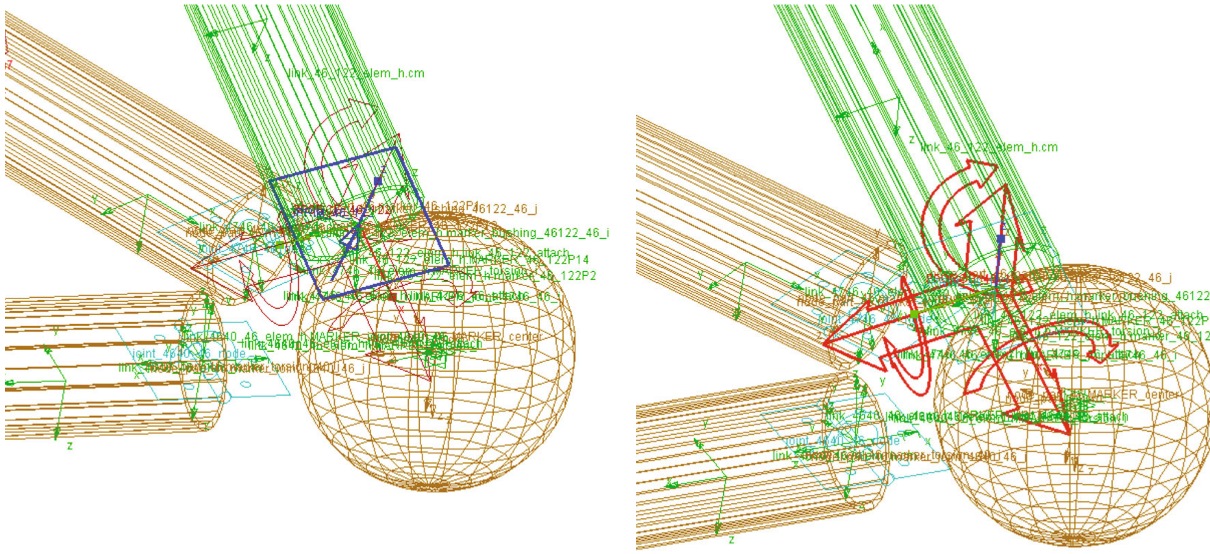
(b)

Figure 5: Synchronous hinge products and models. (a) Synchronous hinge products. (b) Synchronous hinge models.

Figure 6: Connection between disk and web.

expand outwards, and the web members rotates outwards around the designated rotation pair. Finally, the antenna reflector is expanded to form a certain surface under the action of the elastic strain energy from the torsion spring. This kind of instantaneous expanding antenna drove by torsion spring will inevitably produce strong impact collision during the deployment process. In order to accurately predict the impact of reflector deployment on other satellite components, the dynamic analysis of antenna reflector deployment is needed.

The dynamic model is established by using the commercial software ADAMS. The components of the reflector are considered as rigid bodies. The Revolute Joint is used to model the connection between the synchronous rod and the synchronous hinge. Synchronous hinge products and models are shown in Figure 5. In order to simulate the synchronous motions of the adjacent folding rods, the Coupler Joint is added for two adjacent Revolute Joints between the folding rods and the hinge housing, so that the rotations between the two folding rods and hinge can be synchronous.



(a) (b)

Figure 7: Modeling of connection between disk and web. (a) Inline Primitive Joint. (b) BISTOP force function.

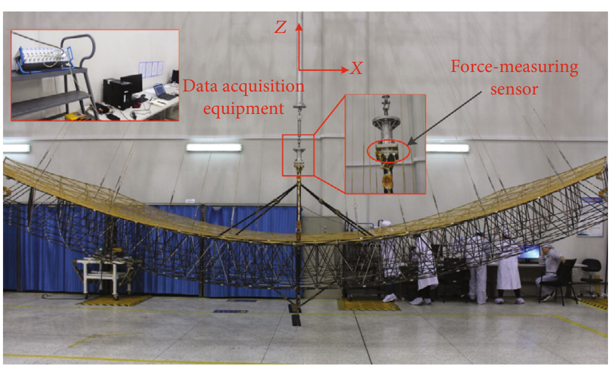


Figure 8: The impact test of reflector deployment.

Figure 9: Kistler 9119AA2 force sensor.

The contact between the folding rod and the hinge is also created, and then the deployment state can be maintained when the reflector is unfolded completely.

In order to avoid the overconstraints of the dynamic model of the reflector, the busing force is used as the flexible connection to model the connection between the disk and the synchronous rod. The stiffness coefficient of the bushing force in the rotational direction between the disk and the folding rod is set to zero, and the stiffness coefficients the other directions are set as large numbers.

As shown in Figure 6, there is a clearance between the disk and the web. In order to model the clearance accurately, the combination of the Inline Primitive Joint and the BISTOP force function in the ADAMS are used to model the connection of the disk and the web, as shown in Figure 7.

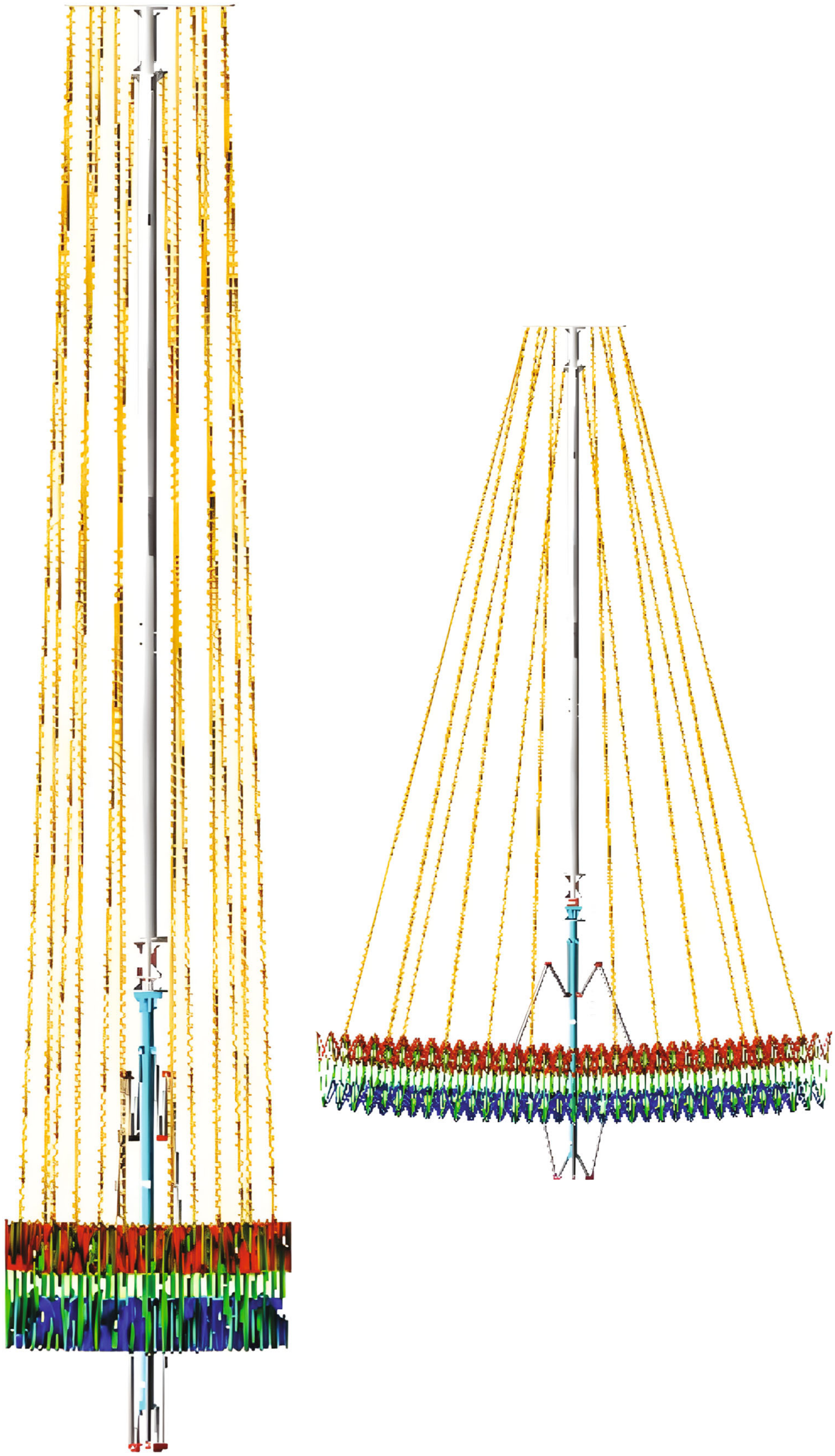
3. Ground Deployment Simulation and Experiment

In this paper, the deployment process of a normal feed tetrahedral modular truss antenna reflector under gravity unloading environment is studied as shown in Figure 8. The ground deployable experiment device of antenna reflector is designed, and the unloading plate is fixed on the unloading truss. In order to eliminate the influence of gravity, the unloading system including the cables, and the spring balances is used to connect the reflector unloading point and unloading plate lifting point, respectively. The unloading system can not only realize the gravity unloading of the reflector but also resist the external vibrations in the experiment.

Using the Kistler 9119AA2 compact multicomponent dynamometer as shown in Figure 9 as the force sensor, the compact six components can be measured. The Dewesoft data acquisition system is used for the data acquisition. The force sensor is installed at the connection between the reflector component and the external component to measure the impact force of the reflector deployment on the boundary. The force sensor experiment status is shown in Figure 8.

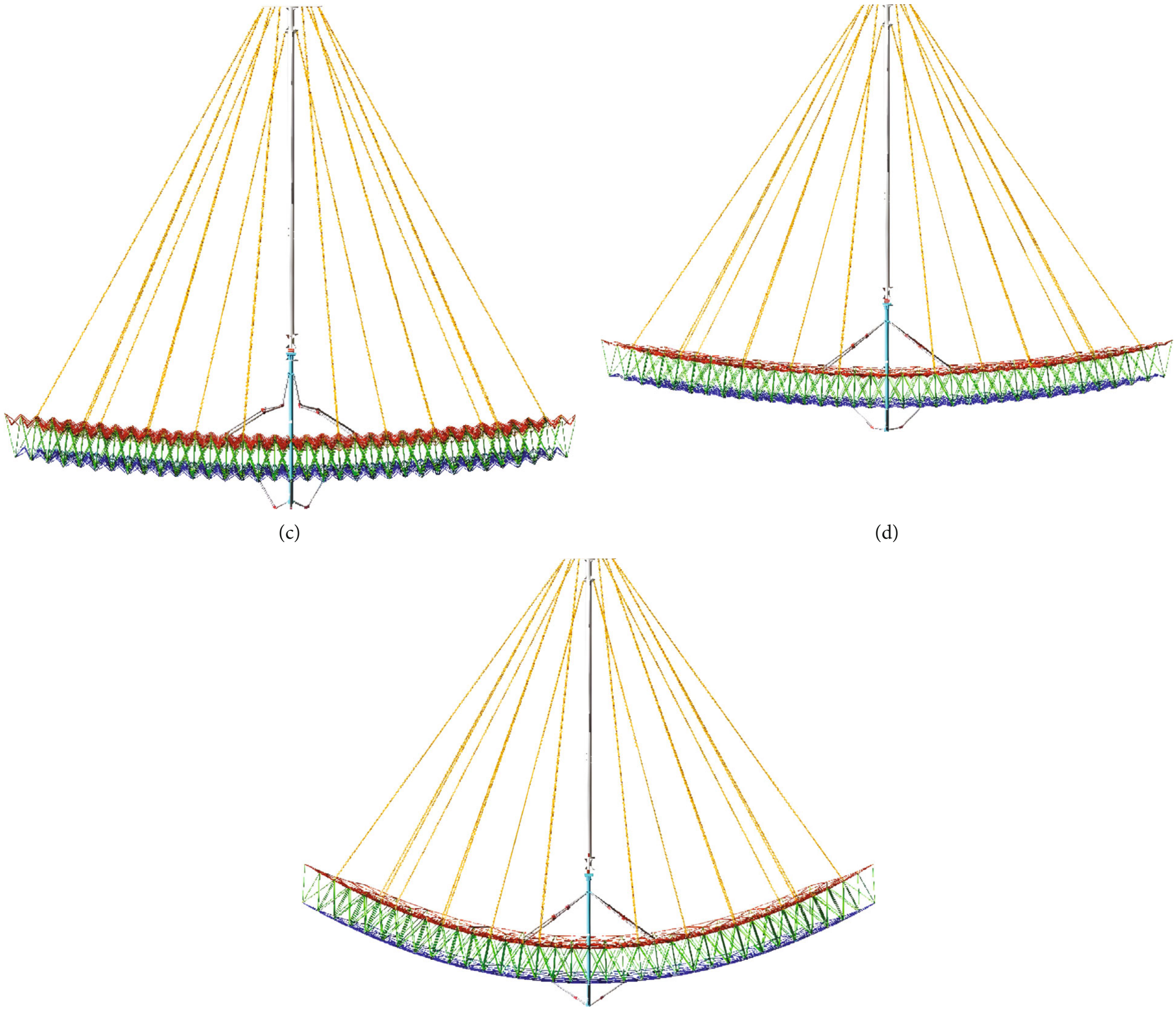
The method described in the previous section is used to establish the reflector dynamics model and carry out the dynamics simulation of the reflector deployment process. The reflector deployment process obtained from the dynamics simulation calculation is shown in Figure 10.

Considering that the reflector is symmetrical about XZ plane and YZ plane, the impact of its deployable process on the outside is mainly reflected in the Z direction. The



(a) (b)

Figure 10: Continued.



(c) (d)

(e)

Figure 10: The simulation of reflector deployment process. (a) Deployed process 1. (b) Deployed process 2. (c) Deployed process 3. (d) Deployed process 4. (e) Deployed process 5.

parameters of the dynamic model are modified according to the impact force Fz measured by the force sensor.

The modified parameters of the dynamic model include the clearance of web and disk, damping coefficient, static friction coefficient, and dynamic friction coefficient. Taking the difference between the impact force measured by experiment and the impact force of dynamic simulation as the objective function J, the following optimization model is established:

$$\begin{aligned} &\text{find} \quad \Delta x = [x_1 x_2 x_3 x_4], \\ &\min \quad J = F_m - F_s(x_1, x_2, x_3, x_4), \\ &s.t. \quad x_{\text{imin}} < x_{\text{i}} < x_{\text{imax}}, i = 1, 2, 3, 4, \end{aligned} \tag{1}$$

in which x_1 is the clearance between web and disk, x_2 is the damping coefficient, x_3 is the static friction coefficient, x_4 is the dynamic friction coefficient, F_s is the impact force obtained by dynamic simulation, and F_m is the impact force measured by experiment. First, input a set of parameters to be corrected for dynamic simulation and make the difference between the impact force measured by the experiment and the impact force obtained by the dynamic simulation to obtain the function value of the objective function J. Then, the value of the objective function is minimized by adjusting the parameter $x_i (i = 1, 2, 3, 4)$ to be corrected, and the model parameters should be controlled within a reasonable range when modifying the model parameters. The group of correction parameters that minimizes the objective function value is the corrected model parameters.

The modified model parameters are as follows: the clearance between web and disk is 1 mm, the damping coefficient of the flexible connection between the disk and the bar is 5.0, the dynamic friction coefficient is 0.2, and the static friction coefficient is 0.4. After model modification, the impact force comparison between the simulation results and the ground test results is shown in Table 1.

Table 1: The comparison between the simulation and test results.

No.	Parameters		Test results	Simulation results
1		$Fx\|N$	55.2	2.43
2	Peak impact force during deployment (amplitude)	$Fy\|N$	79.1	53
3		$Fz\|N$	491.2	513.8

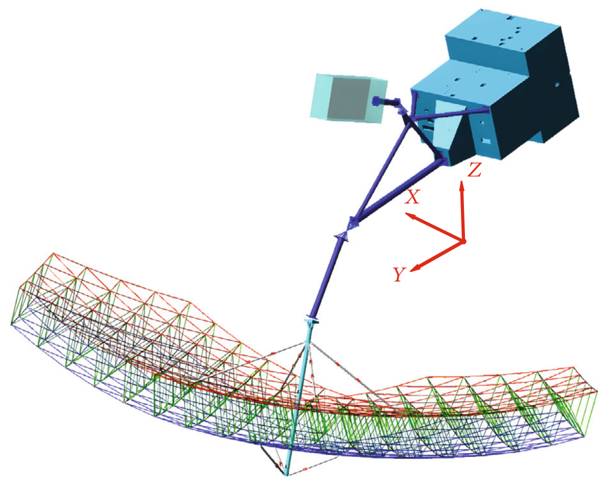


Figure 11: The schematic diagram of normal feed truss antenna satellite.

Both simulation and test results show that the impact force in the Z direction is significantly greater than that in the other two directions, which is consistent with expectations. Moreover, the maximum impact force calculated by the simulation is basically equal to the maximum impact force Fz measured by the ground test, and the error is about $(513.8 - 491.2)/491.2 = 4.6\%$. The reflector is symmetrical with respect to the Plane YOZ, so that the simulation result Fx is close to 0. And the reflector is quasisymmetrical with respect to the plane XOZ, so that the Fy is larger than Fx, but much smaller than Fz. But to the assembly errors of the unloading system in the experiment, the test results of Fx and Fy are larger than the simulation results. Since the size of the reflector in the X direction is significantly larger than the size in the Y direction, Fx is more significantly affected by the assembly errors.

4. Impact Dynamics Analysis on Orbit

In order to analyze the impact characteristics of reflector deployable on orbit, a rigid-flexible coupling dynamic model is established for a small satellite of CAST2000 platform as shown in Figure 11, which includes reflector, deployment arm, and satellite platform. The solar wing and satellite are merged into a satellite platform. The weight of the satellite platform is 750 kg, and the moments of inertia around the center of mass X, Y, and Z axes are $2.2 \times 10^3 Nm^2$, $1.4 \times 10^3 Nm^2$, and $2.5 \times 10^3 Nm^2$, respectively. The weight of antenna reflector, feed, and deployment arm is 75 kg, 65 kg, and 43 kg, respectively.

The reflector is modeled by the modified dynamic model. The feed and the satellite are considered as rigid bodies, and the arms connecting the satellite, the feed, and the reflector are considered as flexible bodies by using the modal synthesis method, which is treated by importing the modal neutral files generated by the finite element analysis software in the ADAMS model in this paper.

For the above dynamics model, the deployment dynamics simulation of the reflector under gravity-free condition is studied. And the displacement curve of the satellite centroid is shown in Figure 12(a).

It can be seen from Figure 12(a) that with the deployment of the antenna reflector, the centroid position of the satellite moves in a small range. Because the reflector deployment is basically symmetric with respect to the YZ plane, there is almost no position change of the satellite centroid along the X direction. So, the deployment has little influence on the displacement change of the centroid in the X direction. The curves of velocity and acceleration are shown in Figure 12(b) and (c).

Figures 12(d)–12(f) , respectively, show the curve of satellite attitude angle, attitude angular velocity, and attitude angular acceleration changing with time. It can be seen from Figure 12(d) that the on-orbit deployment of antenna reflector has a great influence on rolling angle and a small influence on attitude angles in the other two directions. In the early stage of reflector deployment, the rolling angle increases to 1.1°. With the rapid deployment of antenna reflector, the rolling angle decreases rapidly. The change of rolling angle reaches a stable stage during a period of oscillation.

The attitude angular velocity of the satellite shows that the deployment of antenna reflector has the greatest influence on the rolling angle. The attitude angular velocity

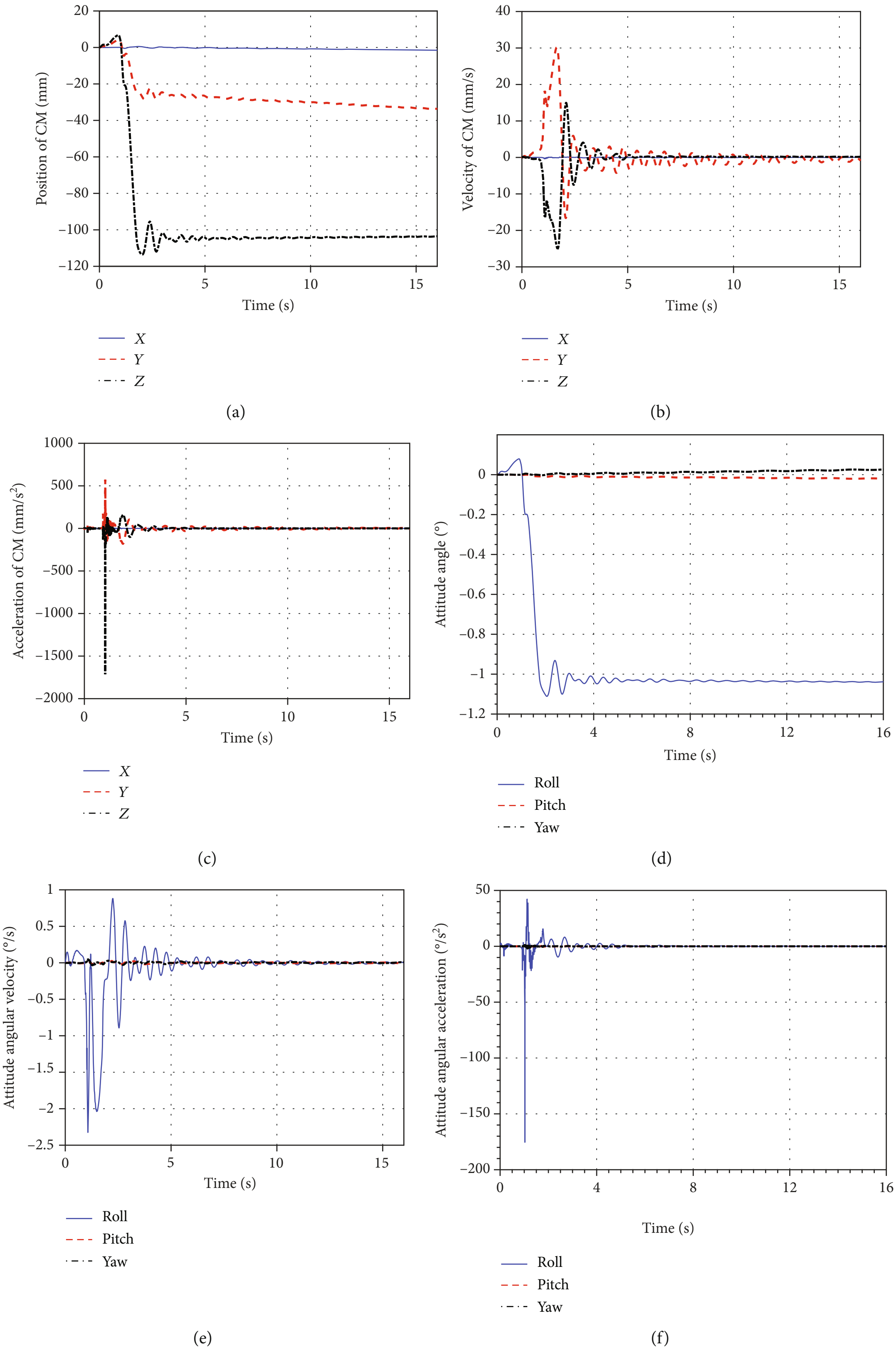


Figure 12: Simulation results of the system on orbit. (a) The displacement curve of the satellite centroid. (b) The velocity curve of the satellite centroid. (c) The acceleration curve of the satellite centroid. (d) The attitude angle of the satellite. (e) The attitude angular velocity of the satellite. (f) The attitude angular acceleration of the satellite.

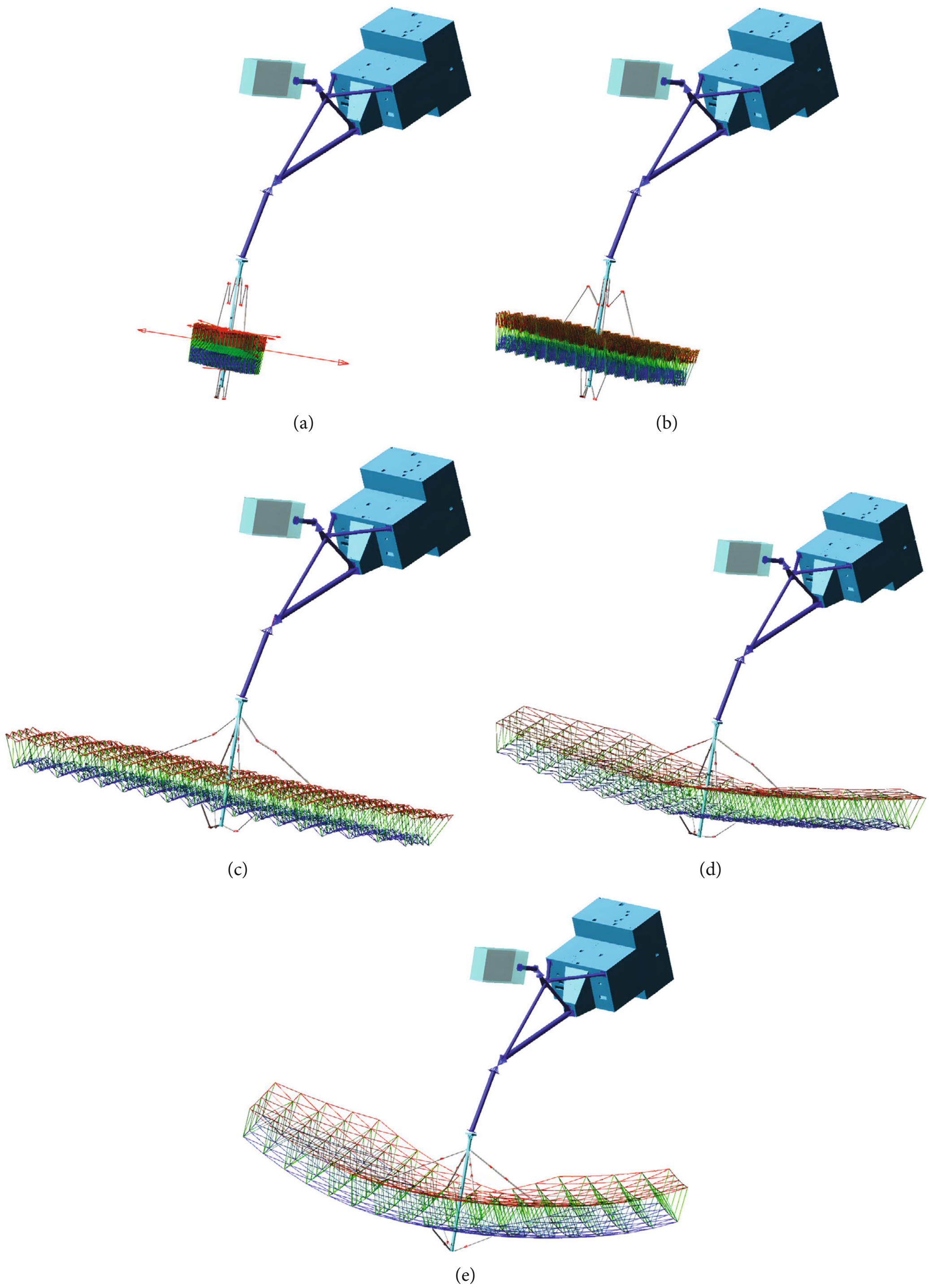


Figure 13: The deployment process of normal feed truss antenna satellite. (a) Deployed process 1. (b) Deployed process 2. (c) Deployed process 3. (d) Deployed process 4. (e) Deployed process 5.

shows a trend of oscillation attenuation and gradually decayed to close to zero over time. When the satellite is completely stable, the satellite-antenna reflector will keep uniform rotation without the external disturbance. The deployment process of normal feed truss antenna satellite obtained from the dynamics simulation calculation is shown in Figure 13.

5. Conclusion

In this paper, a multibody dynamic model of a tetrahedral framed deployable antenna reflector is established. In order to optimize the accuracy of the dynamic model, dynamic simulation and experimental research were carried out for the ground deployment test of the frame antenna reflector, and the impact force on the boundary of the reflector deployment under ground conditions was obtained. The reflector dynamics simulation model is modified by minimizing the objective function. With the revised reflector dynamics simulation model, we can predict the impact of the antenna deployment on the satellite platform in the on-orbit state. In order to predict the impact of the antenna deployment on the satellite platform, the dynamic analysis of the spacecraft on-orbit deployment including the satellite platform, deployment arm, feed, and reflector was carried out. In the change law of angular velocity and angular acceleration, the results show the following:

(1) By comparing the impact force of the experiment and the simulation experiment, the correction parameters of the dynamic simulation are determined

(2) Since the reflector expansion is basically symmetrical with respect to the YZ plane, the expansion has little effect on the displacement change of the centroid in the X direction

(3) The deployment of the antenna reflector has the greatest influence on the roll angle. As time goes by, the attitude angular velocity exhibits a trend of oscillation attenuation and gradually attenuates to close to zero

Based on the research results of this paper, it can provide a reference for the attitude adjustment of the frame antenna reflector in the deployment process. Make the satellite attitude adjustment process smoother and more stable. The model can be further modified and optimized according to the expansion of the on-orbit antenna.

Data Availability

Data is available on request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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