Original Article

COSMIC MANEUVERS: INNOVATING SATELLITE FLEXIBILITY WITH ADVANCED ATTITUDE AND VIBRATION TECHNIQUES

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Abstract: Early space exploration was characterized by relatively small lunar equipment, which necessitated straightforward mechanical models and limited changes in elastic models. Satellites designed during this period, whether actively controlled or passively stabilized, were often treated as rigid bodies in motion. However, the landscape of space missions has evolved over time, leading to the widespread use of larger spacecraft. The diverse array of missions demands higher standards for spacecraft state, action precision, stability, and endurance [1]. Consequently, addressing the issue of coupling between the flexible satellite's attitude control system and the flexible structure has become pivotal. Unlike rigid body dynamics, which are commonly employed in planet manipulation, flexible components are more complex, and their motion is not simplistically treated as rigid body movement. Violent oscillations of these flexible components can pose a threat to the integrity of the control system. In light of the increasing use of flexible spacecraft for Earth observation and the growing importance of precise pointing in flexible launch vehicle operations, it has become imperative to conduct an in-depth study of flexible launch vehicle attitude control modes.

Keywords: Space Exploration, Flexible Satellite, Attitude Control, Flexible Structure, Launch Vehicle Operations

1. Introduction

In early space exploration, due to the small size of the lunar equitope, the mechanical model is simple, and the elastic model does not change significantly. Therefore, the satellites designed during this period, whether active fixed or passively stable, are considered to be rigid bodies of controlled stars. However, with more and more aircraft models, the use of large spacecraft has become the norm. Moreover, due to the diversity of aviation missions, higher standards are given for the state, action accuracy, stability and duration of the satellite[1]. In view of this, how to solve the coupling problem between the flexible satellite attitude control system and the flexible structure is crucial. Because flexible accessories are usually not simply regarded as rigid body motion, and the planets are manipulated according to the principle of rigid body dynamics, the control system may be damaged when the swing of the attachment is relatively violent. Therefore, there are increasing observation of the earth and more and more common use of flexible spacecraft nowadays, in order to further improve the pointing accuracy of flexible launch vehicles and improve the measurement and control performance, it is necessary to deeply study the attitude control mode of flexible launch vehicles.

2. Difficulties in flexible satellite attitude control

Unlike the semi-rigid body that regarded satellites as rigid body motion in early space exploration, the research fields of large-scale flexible satellites include system dynamics, mathematical models, distributed calculation parameter system approximation, optimization, control design, numerical calculation, etc. And these branches are intertwined and interdependent[2]. At the same time, the implementation of large-scale flexible satellite measurement and control methods has also been affected by the on-board controller. In addition, the attitude control technology of flexible satellites belongs to a multi-system and multi-output strongly coupled nonlinear factor control system, which is affected by many factors such as changes in orbital conditions and structural parameters. And the attitude control technology is relatively complex, and there are mainly difficulties in the following aspects of control.

2.1. It is difficult to establish an all-star model accurately.

Modern large spacecraft can be used as a distributed network structure parameter control system (DPS), and its model needs to apply the theory of multi-flexibility. Although the system has infinite dimensions in theory, it is only approximated in finite dimensions in reality. Moreover, there are many higher-precision flexible satellite all-star mathematical models, generally more than 50 times, so that the controller cannot carry out experiments[3].

For flexible appendages in simple structures, such as columns, beams, etc., their structures can also be regarded as distribution function systems. At this time, their shape structure can also be characterized by partial differential equations. However, due to the increasingly complex structure of flexible aircraft, the analysis results of the characterization of partial differential equations of complex components can no longer be obtained. By characterizing the flexible appendages by the centralized parameter method, flexible appendages with continuous layout are regarded as rigid body systems that bind ideal springs and damping, so that the overall structure of flexible spacecraft can be transformed into the structure of pairs of multi-rigid bodies[4]. However, this method only describes variables when they swing slightly on a rare basis. The more commonly used method is the finite element model, which solves variable nodes that are not suitable for weather. The elastic displacement and rotation of nodes are considered displacement vectors, and the displacement vector of air resistance is gained by interpolating the displacement vector of finite nodes. The system order obtained by discretization using this model is usually very high. However, no matter which method is used, the results obtained after discrete modeling are finite-order equations, that is, only infinite-dimensional unmodeled dynamics will occur. If a bias downgrade is set in a further model using the controller, a truncation mode will be generated, which can be used to calculate overflows and observe the interruption of overflow.

2.2. Flexible attachment vibration

Due to its large span, small stiffness and weak damping, the flexible accessory system forms a huge low-frequency oscillation mode during oscillation. Therefore, when setting the attitude controller, we generally adopt the idea of frequency isolation, so that the bandwidth of the controller is much smaller than the base frequency of the flexible satellite, so as to reduce the damage situation system to the satellite when the flexible attachment oscillates. However, due to the dense existence of low-frequency oscillation modes, it is easier to interact with state control, which leads to the good activation of this low-frequency mode in the movement process of high-speed orientation, orbital movement and rendezvous interaction. In this way, in the process of attitude control of the star, it will inevitably generate a large number of flexible attachment vibrations, but at the same time, it will cause the vibration to attenuate more slowly due to the weaker damping of the flexible attachment. On the contrary, the vibration of the flexible attachment will directly reduce the accuracy and stability of the planet's attitude control. The resonance of sexual attachment and attitude control processes may also lead to unbalanced motion with planets. In addition, in the process of high inclination of the earth, the vibration of the flexible attachment has become the key to directly affecting its high speed. Generally speaking, flexible attachment vibration will increase the planet's change distance and direction accuracy, and the energy loss of the whole planet will also be increased if the active vibration control strategy is adopted.

3. Basic mechanical principles of flexible satellite dynamics

For the analysis of flexible satellites with solar windsurfing, the basic physics principles used mainly include vector hydrodynamic methods and hydrodynamic methods. Generally, there are two schemes:

(1) Newton-Euler rule: It refers to using Newton's laws of motion, D'Alembert's principle and other physical principles to derive the equations of an object, then remove its multiple interactions, and finally obtain the analysis of the dynamic equations of the whole system. Each equation covers a wide range of simple variables, so it can be directly explained by simple design steps, but because there are many steps, it is only suitable for solving simple physical problems, not for more complex problems[5].

(2) Lagrange method: This method mainly uses the total dynamic and average elastic motion of the measurement system to establish the Lagrange differential equation, and then the Lagrange dynamic differential equation can be obtained. Compared with the Newton-Euler rule, it is relatively simple to list the total dynamic and total potential energy equations of the system, so it is quite convenient to use the Lagrange method to solve the dynamic problems of highly flexible satellites. At the same time, because the interaction between celestial bodies can also be spontaneously eliminated, the problem has greatly improved.

4. Full physical simulation system for flexible satellites

We are designing and developing the satellite uniaxial air flotation platform full physical simulation device with a highly flexible design. It can generally be divided into three parts.

4.1. Body of the system

The uniaxial air flotation platform is used as the main support equipment to simulate the rigid body of the satellite center. The air bearing is almost wear-free to simulate the thermodynamic conditions of the satellite not worn in the universe.

All kinds of necessary equipment required by the satellite in normal operation, including the airframe, sensitive equipment, power supply, data acquisition system, measurement and control computer, and high-pressure air-conditioning cylinders, are installed on the uniaxis atmospheric floating platform, while the connection of the whole test device to the outside world is connected with a bundle of soft cables about 0.02 cm long in the direction of the OZ axis along National Taiwan College of Physical Education to simulate the independent operation of rockets in the universe.

The flexible plate (one or two pieces, each 1800mm x 10mm x 3mm) is placed on the uniaxial air flotation platform to align the swing direction with the load direction, so as to simulate the flexible solar sail in a weightless environment. Compared with the zero Z-axis, the maximum inertia of the flexible structure is about 30%-50% of the total inertia J. Through experimental calculations, J = 14.0kgm2, while the first modal frequency is $\omega 1$ = 0.7Hz, the second-order modal frequency is $\omega 2$=4.5Hz, and the damping coefficient of the flexible plate is ξ = 0.004.

4.2. Actuator

The actuator of the all-physical simulation control system of the flexible satellite adopts the form of a "flywheel-jet" structure, which is in line with the current actuator model of most satellites in China. Its flywheel can transmit forward and reverse continuously changing flight power, and its maximum transmission power is T; while the ejector can provide discontinuous control power with stable positive and reverse amplitudes, as well as the function of unloading the engine. The constant power unit provided by the ejector is Tp, and there are: Tf<Tp

Flywheels, high-pressure cylinders (cooling) and air injection devices are placed on the uniaxis air flotation platform to control the aerodynamics of the flexible plate base. This method is not only simple and easy to understand, but also based on the current level of technical development of actuators. Post-test test: Tp = 0.14Nm, Tf = 0.07Nm.

4.3. Sensor

The simulation system mainly uses three sensitive devices: frequency gyroscope, synchronizing sensor and linear accelerometer; one frequency rotating gyroscope, installed on a single-axis air flotation table, is used to detect the rotational angular speed of the central rigid body of the satellite; and a synchronizing sensor, installed on the base of the bench, is used to detect the rotation Angle 0 of the central rigid body of the satellite; and the linear accelerometer is installed on the flexible plate to sensitively detect the vibration line acceleration change of the flexible plate at the point, so that the vibration line displacement and linear speed of the flexible plate at each point can be obtained after calculation. Because sensitive devices, like linear accelerometer, are small in size and light in weight, equipping them on satellite flexible accessories not only has little interference to the structural characteristics of the original system, but also become a concentrated mass directly built in the model for implementation on the engineering structures. In addition, the types of linear acceleration meters must be determined according to the actual needs of the whole system.

To sum up, all parts of the design of this highly flexible satellite single-axis air flotation platform all-physical simulation control system meet two prerequisites: one is that it can be implemented in engineering, and second, it is consistent with the actual equipment on China's current satellite. Hence, the development of control methods and experiments based on this system has produced great engineering application value.

5. Design of a shape memory alloy compression release device

At present, most spacecraft compression release devices are pyrotechnic devices, and the damage caused by the impact load released by the pyrotechnic devices to electronically sensitive devices and deployable precision components has attracted more and more attention from the aerospace community. In order to reduce impact, a number of non-pyrotechnic compression release devices have been developed at home and abroad. Among them, a variety of the compression release devices of shape memory alloys (SMA) have successfully implemented in-orbit applications. SMA acts as a direct drive compression release device (such as compression bolts which use a large recovery force generated by SMA columns or ring phase transition to break the limit pins or prefabricated notches), its structure is simple but the cross-sectional area is large, so the time required for energized heating or conduction heating is long, and the power consumption is large. The triggered SMA compression release device that uses the SMA wire as the trigger mechanism and the energy storage spring as the release mechanism can use a trigger force of about 10N to trigger the release force of hundreds of Newtons.

In this case, the need to provide resilience to SMA is lower than that of the direct-driven compression release device. The release time of the device is short and the power consumption is low, but the multi-stage release structure is too complicated, the transmission path is long, and the requirements for the matching accuracy of the components are high.

5.1. Proposal design

The large-load-bearing low-impact group roller SMA compression release device (hereinafter referred to as the SMA compression release device later) that the paper puts forward is based on small clearance (≤0.05m) and reliable separation. The main size of the part below the top cover 17 is Φ46mm×80mm, and the above part can be customized according to the compression object.

Under the compression state of the satellite launch segment, the hoop ring holds the disc nut tightly to make it a complete thread pair. The bolts are screwed into the disc nut through the anti-shear cone and tightened by the external torque to compact object A and object B; When the transverse overload is too large and exceeds the friction between object A and object B, the anti-shear cone sleeve can actively bear the transverse load, so that object A and object B only have a slight dislocation (≤0.05mm); The top of the impact spring tightens the hoop ring to avoid the unexpected release of the SMA compression release device due to its movement under the vibration load in the emission stage. After the satellite reaches the designated orbit and gives the release instructions, the power supply electrifies the SMA wire to shrink, pull the hoop ring down, and the hoop ring rolls the roller down. After the split nut loses the radial constraints, it is separated radially under the action of the separation spring and the separation top block 6, and the bolts eject under the action of external forces, so as to realize the release of object A and object B.

After release, the SMA wire is manually elongated until the impulse-resistant spring pushes the hoop ring upwards, driving the roller to roll out of the arc groove of the split nut. The split nut moves inward under the action of the top cover and the separation of the top block to form a complete thread pair. At this point, the machine has completed the reset, and the next separation operation can be carried out after loading.

5.2. Design method

Based on the Liang constitutive model and compression spring design theory, this paper proposes a method to solve the release resistance and SMA recovery force of SMA compression release device. Compared with the SMA wire performance parameter as the input method, the pre-tightening force P is used as the input to explain the release resistance F and SMA recovery force Fr, and the required SMA performance parameters are directly obtained to reduce the number of iterations, so as to be closer to the actual application of the project. Through the composition and design method of the device, it can be seen that the anti-shear cone micro gap realization method, the release resistance solution method, and SMA recovery force prediction are the key to realizing the function of this device. This paper designs and analyzes the parameters of the above three.

6. Testing verification

Through the scheme principle, it can be seen that the hoop displacement characterizes the recovery displacement hr of SMA wire. Therefore, after the assembly of the SMA compression release device, the device is electrified, and the observation hole on the shell is used to measure the relationship between the displacement of the hoop ring with time to evaluate the actual driving performance and design consistency of the SMA wire. In the case of pre-tightening force of 12000N, -15°C vacuum environment and power supply current 2A, the relationship between hoop measurement displacement with time is compared with the analysis curve. By comparison, it can be seen that the release time of the SMA compression release device is 7.6s, and the displacement of the hoop ring is 2.1mm at the time of release. The movement law of the hoop is consistent with the trend of the SMA drive performance prediction curve. Compared with the actual results, the error of the release time and the recovery displacement is less than 5%.

7. Conclusion

To sum up, today's space missions are difficult and the demand for accurate control is increasing, however, satellites are often flexible nowadays and therefore accurate control cannot be used as physical strict behavioral control. In this paper, the attitude maneuver of flexible satellites is discussed, and a shape memory alloy compression release device is designed accordingly. After testing verification, the error between the release time and the design value of the recovery displacement and the test value is less than 5%. This error shows that the design method is correct and the device can be suitable for the compression and release of deployable precision components, which has engineering application potential.

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