Design and Structural Analysis of DSO On-Orbit Detection Scheme (Postprint)

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Abstract

To demonstrate whether the main telescope truss structure of the deep space solar observatory can withstand the harsh launch environment during rocket launch and continue to operate normally, and whether the telescope requires an on-orbit adjustment system to precisely maintain the relative position between the primary mirror and collimating mirror after experiencing the harsh launch environment, a feasible on-orbit detection scheme is proposed. Static stress analysis, dynamic load analysis, modal analysis, and frequency response analysis are performed on the main telescope truss structure to evaluate its safety. It is found that the truss structure requires a vibration damping mechanism to reduce the response caused by jitter, thereby preliminarily demonstrating the necessity and feasibility of on-orbit adjustment and verifying the rationality of the structural design and process flow. For the sinusoidal vibration test and on-orbit detection test of the main telescope truss, specific test procedures and implementation plans are provided, offering technical support for subsequent experimental work.

Full Text

Design and Structural Analysis of the On-Orbit Detection Scheme for DSO

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Abstract

To demonstrate whether the truss system of the main optical telescope for the Deep Space Solar Observatory (DSO) can withstand the severe launch environment and continue normal operation, and to determine whether an on-orbit adjustment system is necessary to maintain precise relative positioning between the primary mirror and collimator after experiencing such conditions, this paper proposes a feasible on-orbit detection scheme. Static stress analysis, dynamic load analysis, modal analysis, and frequency response analysis were performed on the primary telescope' s truss structure to evaluate its safety. The analyses revealed that the truss system requires vibration attenuation structures to reduce responses caused by POGO (longitudinal coupling vibration), thereby preliminarily demonstrating the necessity and feasibility of on-orbit adjustment and validating the rationality of the structural design and manufacturing process. Specific procedures and implementation plans are provided for the sine vibration test and on-orbit detection test of the primary telescope truss, offering technical support for subsequent experimental work.

Keywords: Mechanics analysis; On-orbit detection; Static stress; Dynamic load; Frequency response analysis

1. Introduction

Deep space solar exploration represents a critical objective in China's deep space exploration program and constitutes an inevitable direction for future aerospace development. Chinese scientists have independently proposed the Deep Space Solar Observatory (DSO), which carries a primary optical telescope, an extreme ultraviolet imager, a high-energy radiation spectrometer, a solar and interplanetary radio spectrometer, and a Lyman-alpha telescope for coordinated solar observations. This mission will transform China' s current limited capabilities in deep space solar monitoring, significantly enhance research in solar physics and space science, improve solar storm monitoring and early warning capabilities, and play a vital role in achieving China' s overall deep space exploration goals.

As an extremely precise instrument, the large space telescope must endure severe mechanical launch environments while operating reliably in harsh space thermal conditions. Before launch, it is essential to confirm whether an on-orbit adjustment system is required for DSO, considering optical system tolerances, structural design and manufacturing feasibility, and previous work experience.

2. Structural Design of the Truss System

The DSO primary telescope truss structure consists of multiple ring beams, with counterweight structures simulating other optical instrument payloads mounted on the topmost ring beam. The overall truss dimensions are approximately 1.5 m × 1.5 m × 4.1 m, with a total mass of about 1,200 kg. To reduce weight, the ring beams feature edge lightening holes. The primary mirror cell is located on the bottom ring beam, while the collimator mount is positioned on the top ring beam. The satellite will be launched aboard a CZ-3B (G2) carrier rocket.

To minimize the degrees of freedom for on-orbit detection and adjustment, a basic structure has been designed between the primary mirror and collimator within the DSO primary optical telescope truss to create a translatable configuration. The ability to maintain relative positioning between the primary mirror and collimator after launch, along with their translatability, serves as the primary basis for determining whether DSO requires an on-orbit adjustment system.

3. Structural Safety Requirements

Considering safety during rocket launch, the truss structure must satisfy the following requirements:

1. **Sufficient stiffness and strength:** The safety factor must exceed 1.25 to withstand maximum static forces and dynamic loads throughout the entire launch process, preventing unacceptable permanent deformation.
2. **Fundamental frequency requirements:** The primary truss and payload must meet the launch vehicle's base frequency requirements, with the first-order lateral natural frequency greater than 10 Hz and the first-order longitudinal natural frequency greater than 30 Hz.
3. **Vibration mitigation:** To address longitudinal coupling vibration (POGO) during launch, response spectrum analysis must be performed to identify resonant frequency ranges and implement necessary vibration attenuation measures.
4. **Reliability verification:** The truss structure must undergo sine vibration testing per launch vehicle requirements to verify it can withstand mechanical stresses and operate normally, while also identifying material and manufacturing defects to ensure satellite reliability.

4. On-Orbit Detection Scheme

The on-orbit detection system consists of an upper mirror system and a lower mirror system, with corresponding components shown in Figure 1 and the DSO primary telescope truss structure illustrated in Figure 2.

Upper Mirror System: Comprises a large plane mirror and a reticle with crosshairs.

Lower Mirror System: Consists of a small plane mirror, a small spherical mirror, and a 45° reflective plane mirror fixed to the collimator mount.

4.1 Principle and Method **Relative Tilt Measurement:** The autocollimator is focused at infinity, and the reflected image of the crosshairs through the large plane mirror and upper small plane mirror is observed. The two small plane mirrors are pre-adjusted to appropriate orientations and fixed. By recording the displacement readings of the reflected image in X and Y directions, the relative tilt between the primary mirror and collimator can be determined. If the angular deviation between primary mirror and collimator in the Y-direction is α, the tilt can be calculated using the mathematical formula: $\alpha = \arctan(b/h)$, as shown in Figure 3(a). Similarly for X-direction deviation.

Eccentricity Measurement: The autocollimator is focused on the crosshairs reticle mounted on the collimator mount, adjusted to position the crosshairs precisely at the center of curvature of the small spherical mirror on the primary mirror. The displacement readings (x, y) between the reticle crosshairs and their reflected image in X and Y directions are recorded to determine eccentricity. If the eccentricity in the Y-direction is d, it can be calculated as shown in Figure 3(b). The same principle applies for X-direction eccentricity.

By recording the relative tilt and eccentricity before and after sine vibration testing, the positional accuracy retention between primary mirror and collimator can be evaluated.

5. Structural Analysis

5.1 Static Stress Analysis Based on data and requirements from the Long March launch vehicle user manual, finite element analysis was performed. The maximum deformation and safety factor at the collimator mount were recorded. The overall minimum safety factor of the structure far exceeds 1.5, meeting user manual requirements. The Y-direction represents the primary deformation direction, and the translatability between collimator and primary mirror satisfies design requirements.

Table 1 shows the static stress analysis results of the truss system under various loading conditions, with all cases demonstrating safety factors greater than 1.5.

5.2 Dynamic Load Analysis During powered flight, the launch vehicle' s dynamic environment can cause structural damage to the satellite and its components, potentially leading to equipment failure and mission loss. The influence of this mechanical environment on satellite reliability cannot be ignored.

Using longitudinal acceleration data from the user manual (Transonic, Phase & Stage-1 Engines, Stage Separation, Stage-1 Engines Shutdown), dynamic load analysis was performed. With a modal damping value of 0.025, the maximum stress and overall displacement under full-step loading are shown in Figure 5. The maximum stress does not exceed 47 MPa, with a safety factor far exceeding 4.2, and maximum displacement of 0.092 mm, satisfying user manual requirements.

5.3 Modal Analysis and Response Spectrum Analysis According to user manual requirements, the first five vibration modes were analyzed. Table 2 presents the truss system' s first five natural frequencies:

The first mode at 16.505 Hz is lateral swing; the second mode at 16.565 Hz is also lateral swing, perpendicular to the first mode; the third mode at 38.153 Hz is lateral twist; the fourth mode at 54.046 Hz is longitudinal swing; and the fifth mode at 55.126 Hz is longitudinal swing, perpendicular to the fourth mode. These results meet the structural safety requirements specified in the user manual.

5.4 Frequency Response Analysis During launch, coupling between the liquid rocket structure and propulsion system generates unstable low-frequency longitudinal vibration (POGO) that persists throughout flight, threatening launch vehicle safety and reliability. Response spectrum analysis calculates the dynamic response at each frequency under oscillatory loads.

Based on the satellite qualification test conditions in the user manual, frequency response analysis was conducted in three directions. The reference point results are shown in Figure 6.

Key findings: - When rocket vibration frequency is 16–20 Hz, the maximum acceleration response exceeds 22 g, indicating destructive vibration. - In the Y-direction at 73–81 Hz, maximum acceleration response exceeds 65 g, causing significant structural damage. - In the Z-direction at 16–20 Hz and 73–81 Hz, maximum acceleration response exceeds 17 g, with some points exceeding 65 g.

The truss experiences destructive vibrations in three directions within these frequency ranges, necessitating vibration damping measures in the structural design to reduce responses and prevent structural failure.

6. Sine Vibration Test

To simulate launch conditions, sine vibration testing is required per GB/T 2423.10-2008 (Environmental testing for electric and electronic products). Sensors are arranged on the truss structure to monitor vibration and obtain amplitude-frequency characteristics. Table 3 specifies the sine vibration test requirements.

7. Conclusions and Future Work

The analysis results indicate that static stress and dynamic load analyses meet safety requirements, but frequency response analysis reveals insufficient safety performance. Vibration attenuation measures are required to reduce structural responses. The primary deformation direction satisfies design requirements, and the translatability between primary mirror and collimator meets specifications.

Current work demonstrates the on-orbit detection scheme's design is incomplete, as frequency response analysis reveals excessive vibration intensity in critical frequency bands that could cause structural damage. Due to time and resource constraints, verification of relative position retention between primary mirror and collimator remains pending. Future work will focus on sine vibration testing and analyzing the truss response after implementing vibration attenuation measures to draw further conclusions.

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