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Research Article

Dynamic Characteristics of Satellite Solar Arrays under the Deployment Shock in Orbit

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Understanding the dynamic characteristics of solar arrays is important for satellite structural design and attitude control design. Considerable theoretical researches have been carried out towards this problem, but they have not been supported by actual orbit data from outer space yet. In this paper, the on-orbit vibration characteristic data of solar arrays under the deployment shock are measured by using vibration measurement apparatuses based on structural strain. With these valuable experimental data, more eigenfrequencies of the solar arrays in the microgravity environment are obtained, and the prediction that the vibration of solar arrays will have larger amplitude and longer decay time under vacuum conditions is verified. Moreover, by comparing the eigenfrequency of main vibration under the space condition with that under the ground condition, the accurate value of the system damping ratio is gained, which has an important guideline significant for the structural design of solar arrays.

1. Introduction

In order to meet the increasing power requirement, modern large satellite platform usually carries large solar array structures. Due to the capacity restriction of launch vehicles, the satellite solar arrays are generally designed to be deployable, which means that they are stowed in a folded configuration at the sides of the satellite body during the process of launching and then spread in a target deployed configuration by certain driving mechanisms (such as preloaded torsional springs and flexible driving cable loops with motor gear units) when the satellite is separated from the launch vehicle and enters into the predetermined orbit [1–4]. Therefore, the successful deployment of solar arrays is always considered as a critical event in the procedure of each space launching mission.

However, the deployment and locking process of satellite solar arrays, which is always completed in a very short time (usually less than 5 seconds), will lead to a large transient impulsive forces and moments exerting on the satellite system. Consequently, these disturbing loads will result in a large vibration behavior of solar arrays due to their structural flexibility, and this may affect the flight orbit and attitude of satellite [5–10]. Hence, it is very necessary to analyze and forecast the structural vibration behavior of solar arrays under the deployment shock.

So far, a great amount of research has been directed towards the area of deployment dynamics and simulation for satellite solar arrays by employing various methods. For example, Joni et al. [11] presented an analytical, computational, and experimental study of the deployment dynamics of an elastically deployable solar array; Oskar and Simon [12] simulated the deployment of a satellite solar array three-dimensionally by using the multibody program Simpack; Birhanu et al. [13] conducted the modeling, simulation, and assessment of deployment and locking operations of satellite flexible solar panels by using ANSYS and ADAMS software. Wu et al. [14, 15] proposed an efficient reliability analysis method for a multibody solar array structure. Unfortunately, the on-orbit structural vibration response of solar arrays aroused by deployment shock has little been seen in the published literature yet, and there are also no actual orbit data about the deployment vibration.

This paper reports an on-orbit deployment-induced vibration measurement conducted on the solar arrays of the Chinese Gaofen-2 (GF-2 for short) satellite. Through a series of unique and exquisite design technologies, a vibration measurement apparatus based on structural strain that can meet the requirements of space application is developed. By utilizing the designed apparatus, valuable on-orbit vibration data caused by solar array deployment shock are acquired quantitatively for the first time. Moreover, by comparing the on-orbit results with those obtained in the ground deployment testing, some beneficial conclusions are gained. The research presented in this paper will be of great significance for acquiring the actual dynamic characteristics of satellite solar arrays and guiding the structural design of satellite solar arrays.

The paper is organized as follows. Section 2 gives a brief description of the designed vibration measurement apparatus, including the operating principle, system composition, installation position, and mounting method. In Section 3, the vibration measurement results of the ground deployment testing and the on-orbit flying experiment are presented, respectively. Detailed comparisons of the on-orbit measured result and the ground results from both the standpoint of time domain and frequency domain are made, and some valuable conclusions are drawn. Finally, summary of the whole work with a few remarks are made in Section 4.

2. Vibration Measurement Apparatus Design

Figure 1 shows a schematic diagram of an on-orbit data acquisition system presented in this work. As can be seen from Figure 1, the GF-2 satellite [16] has a pair of large solar array structures. Each solar array consists of two solar panels, a yoke, and some joint hinges used for connecting the panels or the panel and the yoke. The solar panel employs the traditional rigid substrate design, which uses a honeycomb sandwich structure substrate onto one side of which (named as the front side) solar cells used for producing electricity are mounted. When the GF-2 satellite entered into its orbit, the solar array will be deployed to the unfolded configuration shown in Figure 1. The deployment process of solar arrays will lead to the generation of severe structural vibration.

For the purpose of exactly measuring the vibration of flexible solar arrays in the extreme space environment, the vibration sensors employed in the measurement apparatus must satisfy the following requirements of space application:

- Have a compact structural size
- With a light additional mass
- Can survive in the thermal environment of high- and low-temperature alteration
- Have the capacity of signal sampling frequency at least larger than two times of the solar array fundamental frequency
- Almost have no obvious impact on the measured solar array structure

Considering the above space limitations or special requirements comprehensively, we designed a vibration measurement apparatus based on the conventional strain gauges, which will be addressed as below.

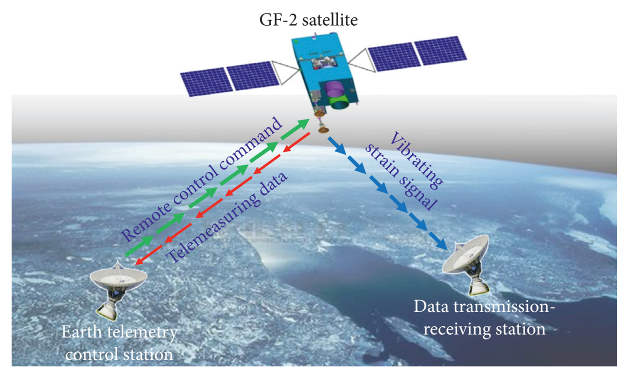


Figure 1: Diagram of the on-orbit vibration data acquisition system.

2.1. Measuring Principle. A strain gauge (also named as strain gauge) is a device used to measure strain on an object. With the advantages of lightweight, inexpensive, and robust, strain gauges are very attractive for measurement needs. For this reason, strain gauges are used as the sensing device for acquiring the vibrating signals in our work.

The basic operating principle of the vibration measurement apparatus by using strain gauges is when the external stress is applied on the object and it takes deformation, the strain gauge will be stretched or compressed within the limits of its elasticity following the deformation of the object, which consequently increases or decreases its electrical resistance end-to-end. From the measured electrical resistance of the strain gauge, the amount of applied stress may be inferred.

Based on the above measuring principle, we developed a vibration sensor to sense the strain signals due to vibration, which is named as the strain-gauge cluster. The designed strain-gauge cluster, as shown in Figure 2, is composed of a carbon fiber substrate, four strain gauges (denoted as R_1, R_2, R_3, and R_4), connecting terminals and some conducting wires. The four strain gauges with almost identical electrical resistance values have constituted a Wheatstone full-bridge circuit.

In the bridge, strain gauges R_2 and R_4, placed in the length direction of the solar array, are active to measure the strain and named as working gauges, while strain gauges R_1 and R_3, which are placed in the width direction of the solar array (transverse to the applied strain), are little affected by the strain and used for compensating temperature; therefore, we name them as dummy gauges. The final designed vibration measurement apparatus, with a structural dimension (length × width × height) of 40 mm × 40 mm × 2.5 mm, a weight less than 4.5 g, and a resistant temperature range from −196°C to 250°C, can well satisfy the requirements of space application.

2.2. System Composition. By using the developed strain-gauge cluster as the vibrating signal sensor, we have

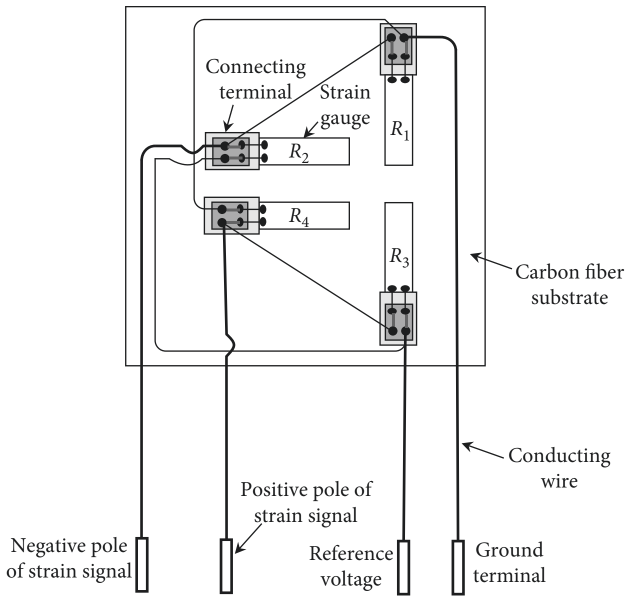


Figure 2: Schematic of the designed strain-gauge cluster.

established a vibration measuring system to measure the deployment-induced vibration of the GF-2 satellite solar array. The system composition of the entire vibration measuring system is illustrated in Figure 3.

It can be seen from Figure 3 that the strain signals from the strain-gauge cluster are first sent to the CPU via the processing of the signal conditioning and collecting circuit. Then, the CPU communicates the processed strain signals with the data transmission module through the communication interface circuit. Finally, the data transmission module sends the acquired vibration strain signals to the ground receiving station via the data transmission channel. In addition, the data transmission module can receive the remote commands from the ground to achieve the control of the vibration measuring system.

The signal conditioning and collecting circuit, the CPU, and the communication interface circuit constitute the data processing module, which is powered by a self-prepared set of batteries. The functions of the components of the data processing module are described as follows:

(1) Since the outputs of the strain-gauge cluster are weak analog signals with the amplitude from $-108\,\mu$V to $+108\,\mu$V and frequency less than 1 Hz, the main functions of the signal conditioning and collecting circuit are to make amplification, filtering, and conversion using analog-to-digital converter for the strain signals.

(2) The first function of the CPU is to read the strain signals after the analog-to-digital converter according to the sampling frequency, which is set to be larger than 0.8 Hz because the fundamental frequency of the GF-2 solar array is very low, with a value of about 0.4 Hz. The second function of the CPU is to make a second filtering to the strain signals by the way of software achievement. In the research, the second filtering employs a 2-order recursive Butterworth filter. The filtering algorithm is as below:

$$\begin{cases} a_1 \cdot y(n) + a_2 \cdot y(n-1) + a_3 \cdot y(n-2) \\ \quad = b_1 \cdot x(n) + b_2 \cdot x(n-1) + b_3 \cdot x(n-2), \\ y(1) = x(1), \\ y(2) = x(2), \end{cases} \tag{1}$$

where x and y denote the sampling data before filtering and the measured signals after filtering, respectively, $n = 3, 4, 5, \ldots$, and the recursive coefficients a_1, a_2, a_3 and b_1, b_2, b_3 are

$$\begin{cases} a_1 = 1.0000, \\ a_2 = -1.3750, \\ a_3 = 0.5000, \\ b_1 = 0.0625, \\ b_2 = 0.0625, \\ b_3 = 0.0625. \end{cases} \tag{2}$$

The signal filtering algorithm used here with a high-computational efficiency increases the filtering quality of the vibration strain signals with low frequency and avoids the substantial attenuation of signals after filtering effectively.

(3) The communication interface circuit can send the vibration strain signals of solar arrays to the data transmission module for output.

2.3. Installation Position. In order to acquire the best measuring signals, one has to determine the optimal locations of sensors. According to the theory of advanced structural dynamics [17], when the vibration behavior of solar arrays is occurred, the root of the solar array will arise up a large strain, while the free end will generate a maximum displacement. Hence, we choose two positions located on the edge of the root of the solar array to mount the measurement apparatuses in our experiment.

Figure 4 shows the specific positions on the solar array for mounting the developed vibration measurement apparatuses. Because the face side of the solar array is used for fitting up the solar cells, the strain measurement apparatuses are mounted on the back side of the solar array. In addition, the data processing module is installed at the end of the yoke used for connecting the satellite body and the solar panel, while the data transmission module is installed on the interior of the satellite body.

2.4. Mounting Manner. As known to all, the usual way for applying the gain gauges to sense the strain signals of a structural object is to paste the gain gauges on the surface of the object directly. However, due to the special structural characteristic of the solar array surface, we cannot paste the gain gauges on the solar array surface directly. The GF-2 satellite solar arrays use the conventional aluminum

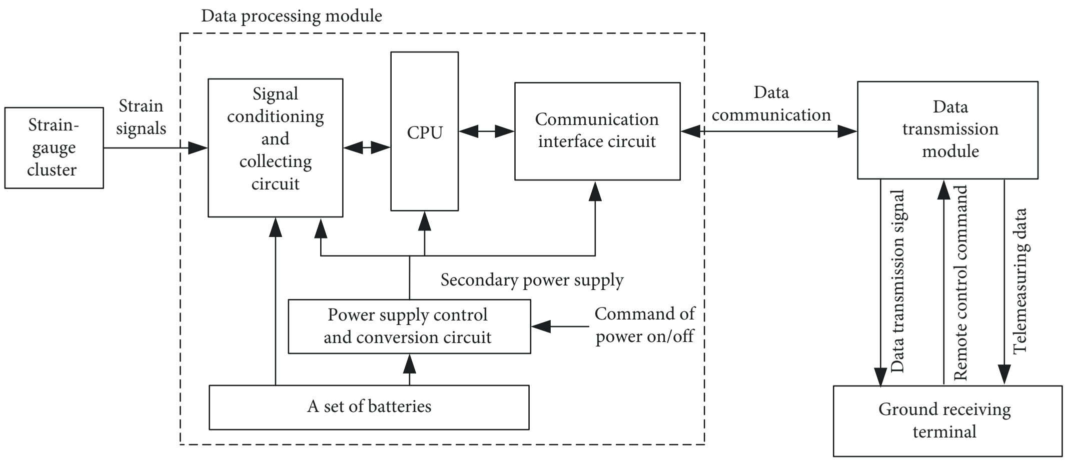


Figure 3: System composition of the vibration measuring system.

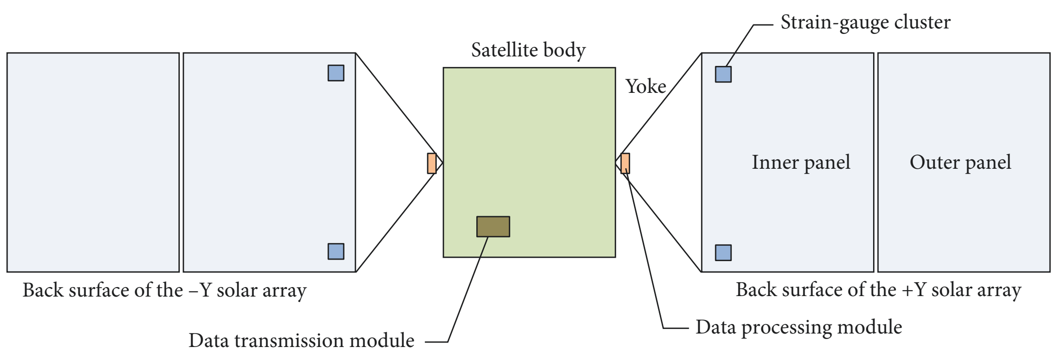


Figure 4: Mounting positions of the strain measurement apparatuses.

honeycomb base-plate structure. To assure the performance of heat elimination, the surface of the base-plate employs a discontinuous carbon-fiber fabric structure. It is a sparse mesh grid structure with many regular mesh holes on the surface. Considering this special structural characteristic of the solar array surface, the strain gauge cannot sense the strain in the place of mesh holes and thus should be not directly bonded on the surface of solar arrays. Hence, we employ a continuous carbon-fiber piece, called carbon-fiber substrate, as a transition in the design. In the specific technology of manufacturing, the four strain gauges are first pasted on the carbon-fiber substrate, and then the whole measurement apparatus is pasted on the solar array surface via this carbon-fiber substrate.

Via a complex technological process of surface cleaning, grinding with sand papers, location marking for carbon fiber substrate, bonding with adhesive, and checking up for soundness, the experimental on-site picture of the apparatus stuck to the solar array surface is shown in Figure 5. In this figure, the white jelly body covering on the surface of the strain gauges is the GD-414 silica gel, which is used for separating the damages existed in the working environments and protecting the strain gauges.

In our work, four strain gauges with the model of KFG-1-120-D17 (manufactured by Japanese Kyowa Electronic Instruments Co. Ltd.) are used in the measurement

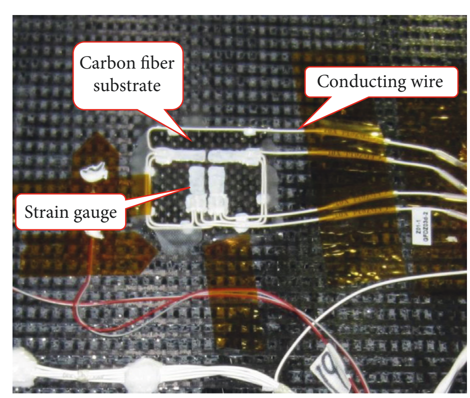


Figure 5: On-site picture of the designed measurement apparatus stuck to the solar array surface.

apparatus. The resistance values of these four strain gauges are strictly controlled to be completely identical, which are equal to 350 Ω. The strain sensitivity and resolution of the designed measuring equipment is about 0.1 $\mu\varepsilon$.

3. Experimental Results and Analysis

With the developed vibration measurement apparatus, we conduct both the ground deployment testing and on-orbit flying testing for the GF-2 satellite solar array, and strainform vibration signals of the solar array caused by the deployment and locking shock are successfully measured in the two tests.

The main sensor device used in the experiments is the designed strain-gauge cluster, and the experimental setup is illustrated in Figure 3. Firstly, the vibration strain signals are detected by the strain-gauge clusters installed on the root of the solar array. Then, these signals are processed by the signal conditioning and collecting circuit and sent to the CPU. Next, the strain signal data stored in the CPU communicate with the data transmission module through the communication interface circuit. Finally, the data transmission module sends the acquired vibration strain signals to the ground computer.

3.1. Ground Deployment Testing. To assure that the solar arrays will be deployed successfully, a ground simulation testing experiment of solar array deployment was conducted. The ground deployment testing scene is shown in Figure 6. The test object is the +Y solar array of the GF-2 satellite. By the triggering of discharge-induced explosion devices mounted in the joint hinges, the two panels of the solar array started to slowly unfold like an accordion, until the wing fully extended across the floor. The deployment test will demonstrate the ability of the solar array to unfold once in the orbit.

Due to the need to overcome the effects of Earth's gravity, we suspended the +Y solar array vertically in the test. Therefore, this ground test can only measure the horizontal bending and torsional vibrations of the solar array.

With the developed vibration measurement apparatus, the strain signals due to vibration caused by the deployment are obtained. The result curves are shown in Figure 7. In this figure, Sensor 1 and Sensor 2 are the two strain-gauge clusters bonded on the back surface of the +Y solar array.

From Figure 7, it can be seen that a structural vibration with a maximum strain amplitude of $54.93\,\mu\varepsilon$ has been occurred on the solar array in this ground deployment simulation test.

3.2. On-Orbit Flying Testing. When the GF-2 satellite launched into orbit, the solar arrays deployed successfully according to definitive programs. During the process of deploying and locking, the vibrating strain signals of the solar array induced by this complicated deployment motion had been measured. As shown in Figure 1, we started up the vibration measurement apparatuses by sending relevant remote-control commands at the earth telemetry control station. The measured strain data were then transmitted by the radio digital transmission channel to the earth receiving station. The final results obtained in the on-orbit flying testing are shown in Figure 8.

From Figure 8, it can be easily observed that a structural vibration with maximum strain amplitude of $65.27\,\mu\varepsilon$ has been occurred on the solar array in the on-orbit flying testing.

3.3. Result Analysis and Comparison. In order to make clear the difference between the vibration in the outer space and that in the ground, we compare the on-orbit measuring results with those obtained in the ground test.

3.3.1. Time-Domain Results. The strain contrast curves in the time domain are shown in Figure 9.

From Figure 9, it can be seen that the basic regularity of vibration on orbit coincides with that on the ground. However, the vibration amplitude and decay time consumed are different in the two cases. The detailed comparisons of these parameters are listed in Table 1.

Taking the vibration measuring Sensor 1 as an illustrative example, it can be seen from Table 1 that the vibration amplitudes in the ground and in outer space are $52.79\,\mu\varepsilon$ and $65.27\,\mu\varepsilon$, respectively, while the decay time (the time consumed for the vibration attenuated to a level less than $5\,\mu\varepsilon$) for these two cases are 2.709 s and 4.552 s, respectively.

Only considering the first-order bending vibration, the solar array structure can be equivalent to a simple cantilever beam. The bending deflection is a unique variable in its vibration equation. According to the damped free vibration equation of a single degree of freedom system [17],

$$x = Ae^{-\xi\omega_{\mathrm{n}}t}\sin\left(\omega_{\mathrm{n}}\sqrt{1-\xi^2}\cdot t+\varphi\right), \tag{3}$$

where ω_{n} is the natural frequency of the system, φ is the initial phase angle, ξ is the damping ratio, A is a constant, x denotes the vibration displacement, and t denotes the time.

It can be seen from Equation (3) that vibration amplitude $Ae^{-\xi\omega_{\mathrm{n}}t}$ is related to damping ratio ξ. The damping ratio ξ can express as

$$\xi = \xi_{\mathrm{a}} + \xi_{\mathrm{f}}, \tag{4}$$

where ξ_{a} denotes the air damping and ξ_{f} denotes the structural friction damping of the solar array.

Because the outer space is almost a vacuum environment, which lacks air damping (in other words, air damping ξ_{a} is close to zero), the damping ratio in outer space is smaller than that in the ground. Therefore, the vibration amplitude in outer space will be greater than the ground, and meanwhile, the vibration will be more difficult to decay. This phenomenon well coincides with our prediction for the solar array vibration caused by deployment shock in outer space.

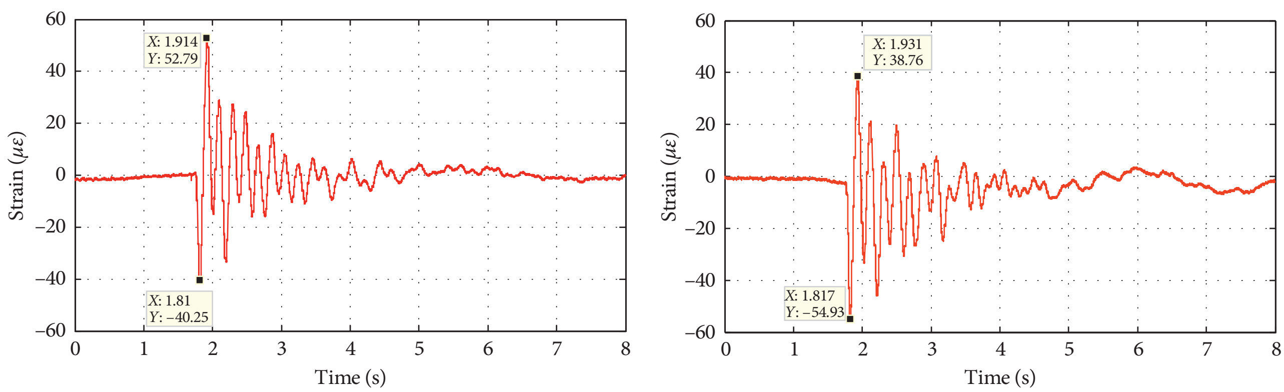
3.3.2. Frequency-Domain Results. Further, we make the fast Fourier transform (FFT) for the time-domain strain singles to acquire the frequency-domain characteristics. The frequency-domain contrast curves of the on-orbit and ground measuring results are shown in Figure 10.

From Figure 10, it can be observed that more comprehensive eigenfrequencies of solar arrays are gained in outer space, and the vibration eigenfrequency in the outer space is higher than that in the ground. This is because the outer space is in a microgravity environment and the solar array will be at a free and unconstrained state in outer space.

Additionally, we can compute the air damping ratio in the ground by using the frequency spectrum diagram shown in Figure 10. Taking the main vibration as an

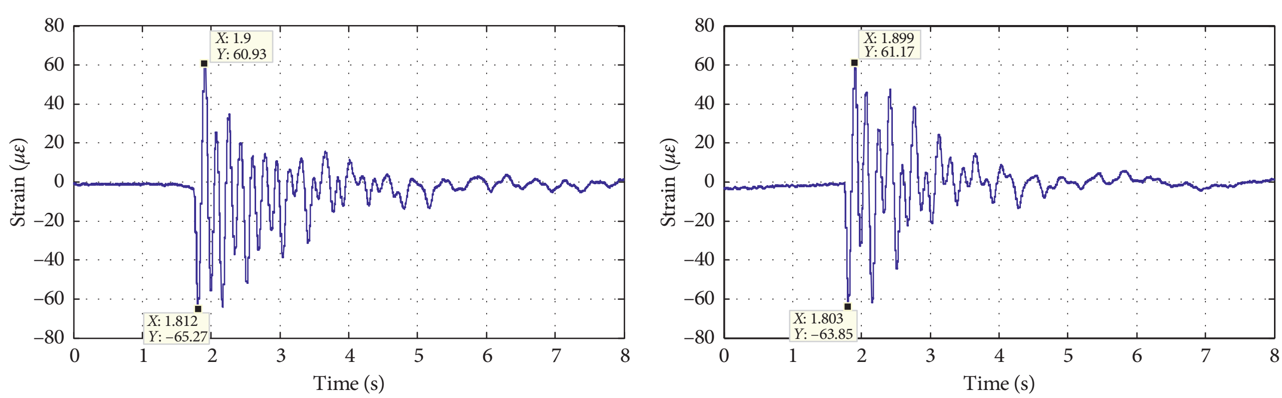
(a) (b)

Figure 6: Ground deployment testing experiment of the GF-2 satellite solar array. (a) Before deployment. (b) Fully deployed.



(a) (b)

Figure 7: Stain measurement results of the ground deployment testing. (a) Sensor 1. (b) Sensor 2.



(a) (b)

Figure 8: Stain measurement results of the on-orbit flying testing. (a) Sensor 1. (b) Sensor 2.

example, its frequency in orbit is $\omega_A = 5.625$ Hz (point A of a maximum amplitude in Figure 10), while the frequency in the ground is $\omega_B = 5.125$ Hz (point B in Figure 10). According to the formula for describing the relationship between the actual vibration frequency and the natural frequency, that is, [17],

$$\omega_B = \omega_A \sqrt{1 - \xi^2}. \tag{5}$$

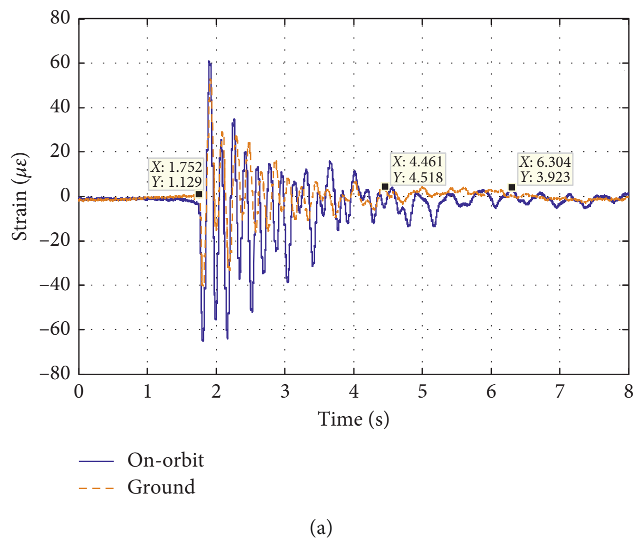


Figure 9: Comparisons of the vibrating strain signals in the time domain. (a) Sensor 1. (b) Sensor 2.

Table 1: Comparisons of the measured results obtained in ground and in outer space.

Apparatus	Maximum amplitude ($\mu\varepsilon$)		Decay time (s)	
	Ground	On-orbit	Ground	On-orbit
Sensor 1	52.79	65.27	2.709	4.552
Sensor 2	54.93	63.85	2.321	4.454

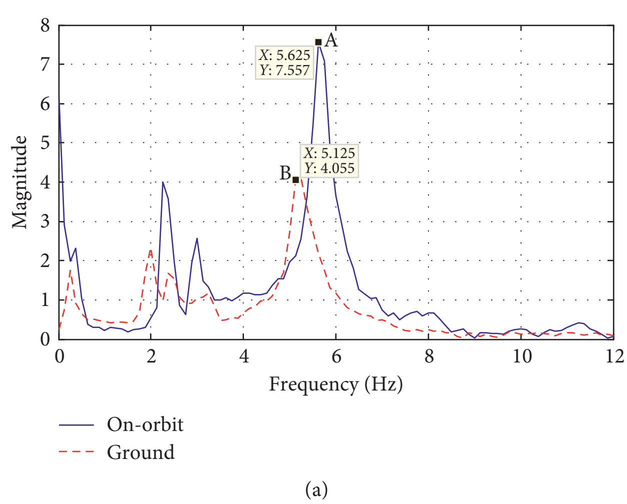


Figure 10: Comparisons of the vibrating strain signals in the frequency domain. (a) Sensor 1. (b) Sensor 2.

The mode damping ratio of this main vibration of the solar array due to air damping can be computed as

$$\xi = \sqrt{1-\left(\frac{\omega_B}{\omega_A}\right)^2} = 0.4122. \quad (6)$$

From this, we can conclude that the exact value of the system damping can be obtained by using the measured value of eigenfrequency under vacuum and the value under the ground condition with damping, which thus can provide an accurate damping ratio coefficient for the structure design of solar arrays.

4. Conclusions

Flexible vibrations of satellite solar arrays are undesirable from the view of structural safety and platform stability. However, the deployment and locking process of solar array structures in the launch will inevitably result in large vibration on the solar array. With the designed vibration measurement apparatus based on strain gauges, this paper conducted an on-orbit vibration measurement research on the solar array of the Chinese GF-2 satellite during this deployment process. The main contribution of this paper can be summarized as below:

(1) An efficient vibration strain measurement apparatus that suits the space application is developed

(2) Valuable on-orbit vibration data of the GF-2 satellite solar arrays caused by deployment shock are acquired for the first time

(3) Some beneficial conclusions are obtained and verified: (a) the deployment-induced vibration in the outer space will be of larger amplitude and harder to attenuate than that in the ground, which well coincides with our prediction of the deployment-induced vibration response of solar arrays in the case of the vacuum condition and almost no air damping; (b) more comprehensive mode eigenfrequencies of solar arrays can be acquired at an unconstrained state in outer space, which are not available under the ground gravity field conditions; (c) the air damping ratio in the ground can be further obtained, which would provide an important reference for predicting the on-orbit natural frequencies of other large flexible space structures in the future.

The research presented in this paper will be beneficial for us to clearly master the actual dynamic characteristics of solar arrays, which consequently can provide a useful guide for checking the safety and reliability of the solar array structural design in the ground manufacturing phase.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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