Research on Spacecraft Strain Measurement System and Impact Sensing Technology Based on Fiber Grating Sensors and All Fiber Optic Sensing

Yuxiang Luo*, Qingzhi Zhang, Jiande Zhang, Daqiang Feng, Panfeng Wu, Yongwei Zhang, Hongbin Lv, Ning Yang, Dingding Wang, Hao Zhan, Lin Cheng
Shandong Institute of Space Electronic Technology, Yantai, Shandong, 264010, China
*Corresponding author’s e-mail: luoyuxiang10@tsinghua.org.cn

Abstract. In the process of flight for in-orbit spacecraft, debris and particles in space will collide with the spacecraft at a high speed. These collision will produce strain, pit or perforation on the surface of the spacecraft cabin, forming damage accumulation. Therefore, it is necessary to monitor the strain and impact position of the spacecraft cabin in real time, which will provide a basis for ensuring the reliability and safety of the spacecraft. In this paper, the achievement of strain and vibration information during the process of impact is designed in two ways: touched style and untouched style. The design of touched style needs to meet the requirements of large capacity/ultra-high speed monitoring. The design of untouched style needs to meet the acquisition of high frequency vibration signal in the impact process.

1. Introduction
Distribution of space debris exceeds the normal operation range of the spacecraft in space objects, it includes micrometeoroid and human space activities waste, the harm of space debris orbiting spacecraft has become a threat of a potential killer[1]. At present, the satellites haven’t taken protective measures for space debris impact. Once them are shot, system components are destroyed, or the loss of function of the satellite will occur[2-4]. In order to reduce the risk of collision between space debris and spacecraft, and ensure the safety of spacecraft and astronauts, the in-orbit perception and monitoring of the impacting has become an urgent research topic[5,6].

At present, piezoelectric and optical fiber methods are usually used to monitor the strain and vibration of spacecraft cabin.

(1) Piezoelectricity. Due to the relatively high frequency of collision stress wave, piezoelectric sensors with a frequency measurement range from 0.1Hz to several hundred kHz are often used for monitoring, which can generally meet the measurement requirements. However, for spacecraft, piezoelectric sensors have been gradually replaced by new sensors because of their large volume, weight, large power consumption and poor anti-electromagnetic interference ability.

(2) Optical fiber. Fiber Grating sensors have many advantages, such as small size, light weight and high sensitivity, which have attracted great attention and application in China's space system. However, the current application state is that the number of single optical fiber sensors is low, and the demodulation rate is difficult to break through.

In this paper, a large capacity/high speed strain detection system based on optical fiber sensing and a high speed vibration detection system based on all-optical fiber are both proposed, which can realize the accurate acquisition of strain and vibration information with high frequency in the impact process.
2. Materials and Methods

For the non-contact mode, Sandia National Lab got the velocity by means of Doppler effect[7]. However, the low speed measurement error of this technology is large, and the optical collimation lens used is optical fiber collimator, while the collimation distance of ordinary optical fiber collimator is about 30 mm[8-9]. This paper presents a new all-fiber vibration measurement system, as shown in Figure 1. The optical path system includes DFB laser, isolator, coupler, ring, collimator, acousto-optic modulator, etc. The circuit system includes photoelectric converter, amplifier, filter, acousto-optic modulation controller, signal acquisition and logic circuit devices, etc.

![Figure 1. Impact sensing and monitoring system based on all-optical fiber.](image)

For the contact mode, this paper proposes a high-capacity/ultra-high-speed fiber optic strain measurement system, as shown in Figure 2. DWDM technology and low reflectivity grating technology are used to improve the sensor capacity of a single fiber to meet the requirements of large-capacity optical fiber sensor array detection for spacecraft. The ultra-high speed demodulation of spacecraft optical fiber sensing is realized by means of non-mechanical regulation principle.

![Figure 2. Large capacity/ultra-high speed fiber impact sensing strain monitoring system.](image)
3. Results & Discussion

In Figure 2, the wavelength range of C+L wide band light source is 1520-1610nm. The pulse light passes through the circulator and is incident into 1000 optical fiber sensor arrays, which contain 40 groups of optical fiber sensors. Each group contains 25 grating $\lambda_1, \lambda_2, \ldots, \lambda_{25}$. After the pulsed light is reflected through 1000 grating sensors, it enters a wavelength division multiplexer (WDM), which divides the reflected light into 25 channels.

After passing through WDM, each optical path is divided into two optical paths by a 1:1 coupler. Take optical path 1 in Figure 2 as an example. One of the two channels of light divided into directly reaches the photodetector PD1-1 and passes through the amplifier 1-1 to obtain the voltage signal $V_{G1}$; the other passes through the edge filter to reach the photodetector PD1-2 and passes through the amplifier 1-2 to obtain the voltage signal $V_{F1}$. The ratio $V_{F1}/V_{G1}$ is a constant related to wavelength.

Figure 3 shows the schematic diagram of 90nm wideband light source incident fiber grating. When 90nm broadband light is transmitted in optical fiber, its characteristic parameter, which is wavelength, will be changed by the modulation of external factors such as strain and temperature. The fiber Bragg grating sensor is a wavelength modulated sensor, which can measure the strain and temperature by obtaining the change of the return wavelength $\lambda_i$.

Figure 4 shows the reliability demonstration diagram for the full alignment of 40 optical fibers. For grating with different reflectivity, due to the influence of crosstalk effect, the multiplexing number of grating is limited. Therefore, in order to continuously increase the multiplexing number of the system, the influence of crosstalk effect should be considered.

Assume that $I_0$ is the incident light intensity, $I_N$ is the reflected light intensity of the NTH TDM sensor, and $R$ is the reflectivity of the grating, then:

$$I_N = I_0 \times R(1 - R)^{2(N-1)}$$

(1)

The number of first-order reflected crosstalk intensity can be expressed as
\[ M = \frac{(N-1)(N-2)}{2} \]  

(2)  

Then the total intensity of the first order reflected crosstalk on N multiplexed gratings

\[ I_N = \frac{(N-1)(N-2)}{2} I_0 R^2 (1-R)^{2(N-2)} \]  

(3)  

In order to detect the system without the interference of the first order reflection crosstalk, it must satisfy.

\[ I_N > 10I_{N'} \]  

(4)  

Under different reflectivity (0.6-6%), the reusable grating capacity is shown in Figure 5.  
In the experiment, the grating with 1% reflectivity was selected, and the number of multiplexable reached 46 theoretically if the conditions were met $I_N > 10I_{N'}$. In order to keep the allowance, the multiplexable number was chosen to be 40.

Figure 5. Insertion loss diagram of a wavelength division multiplexer in 25 channels at bands 1520~1610.

Figure 5 shows the design of the WDM in the 1520~1610 band of 25 channels of insertion loss diagram. The wavelength division multiplexer divides the reflected light with 90nm bandwidth into 25 channels, and the bandwidth occupied by each channel is shown in Table 1.

| The light path number | Center wavelength/nm | Minimum wavelength that can be measured/nm | Maximum wavelength that can be measured/nm |
|-----------------------|-----------------------|------------------------------------------|------------------------------------------|
| 1                     | 1521.9                | 1520.4                                   | 1523.4                                   |
| 2                     | 1525.5                | 1524.0                                   | 1527.0                                   |
| 3                     | 1529.1                | 1527.6                                   | 1530.6                                   |
| 4                     | 1532.7                | 1531.2                                   | 1534.2                                   |
| 5                     | 1536.3                | 1534.8                                   | 1537.8                                   |
| 6                     | 1539.9                | 1538.4                                   | 1541.4                                   |
| 7                     | 1543.5                | 1542.0                                   | 1545.0                                   |
| 8                     | 1547.1                | 1545.6                                   | 1548.6                                   |
| 9                     | 1550.7                | 1549.2                                   | 1552.2                                   |
| 10                    | 1554.3                | 1552.8                                   | 1555.8                                   |
| 11                    | 1557.9                | 1556.4                                   | 1559.4                                   |
For the designed multi-channel WDM, the degree of isolation between channels is bigger than 30dB, which can meet the application requirements.

Based on the all-optical fiber vibration measurement system, high-speed impact tests were carried out. In the tests, high-frequency vibration information could be obtained in real time and accurately, as shown in Figure 6. In the future, the impact location will be accurately located by combining with the multi-point vibration measurement system.

|   | 1561.5 | 1560 | 1563 |
|---|--------|------|------|
| 13 | 1565.1 | 1563.6 | 1566.6 |
| 14 | 1568.7 | 1567.2 | 1570.2 |
| 15 | 1572.3 | 1570.8 | 1573.8 |
| 16 | 1575.9 | 1574.4 | 1577.4 |
| 17 | 1579.5 | 1578.0 | 1581.0 |
| 18 | 1583.1 | 1581.6 | 1584.6 |
| 19 | 1586.7 | 1585.2 | 1588.2 |
| 20 | 1590.3 | 1588.8 | 1591.8 |
| 21 | 1593.9 | 1592.4 | 1595.4 |
| 22 | 1597.5 | 1596.0 | 1599.0 |
| 23 | 1601.1 | 1599.6 | 1602.6 |
| 24 | 1604.7 | 1603.2 | 1606.2 |
| 25 | 1608.3 | 1606.8 | 1609.8 |

For the designed multi-channel WDM, the degree of isolation between channels is bigger than 30dB, which can meet the application requirements.

4. Conclusions
In this paper, a new type of large-capacity/high-speed fiber strain measurement device is proposed. The number of sensors on a single fiber is more than 1000, which can meet the detection needs of a large range of distribution on the spacecraft. The device is simple and easy, and has low technical requirements for grating engraving. At the same time, the device adopts the method of non-mechanical regulation principle to realize the ultra-high speed demodulation of fiber sensing. Compared with the current mechanical regulation method applied in orbit, the demodulation rate is increased by two orders of magnitude, which can realize the acquisition of high-frequency signal for spacecraft strain. For the untouched vibration measurement system, the proposed all-fiber measurement system for many detection points can accurately capture the vibration information of high-speed impact, which plays an important role in the positioning of high-speed impact.

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