Composite Shell Strain Detection for SRM Based on Optical Fiber Sensors

Zhang Lei, Chang Xin-Long, Zhang You-hong, Chen Xiang-dong
Xi’an Hi-Tech Institute, Xi’an, Shanxi 710025, China
lwzy_zl@163.com

Abstract. As a new passive sensor, fiber Bragg grating (FBG) sensors have provided a new idea for the SRM shell damage detection, which is to integrate the FBG sensor network in the material interior or to the surface to monitor the shell structure. However, it is difficult to embed the FBG sensor in filament wound composite material structure for the reason of large tension and high temperature in process of manufacture. Therefore we propose a new method that embed FBG sensor network between the composite shell surface and the thermal protective coating. The calibration of sensor is presented by tensile test and the strain transfer coefficient is gotten. It is certified by the hydrostatic test that the FBG sensors could precisely describe the strain variation and distribution of the composite shell and effectively improve the survival rate by embedding the FBG sensors between the composite shell surface and the thermal protective coating.

1. Introduction
As an important part of missile weapon system, the health status of Solid Rocket Motor (SRM) composite shell structures is of great concern to the system. At present, the shell of solid missile in service around the world is wide application of filament wound composite material structure which has lots of advantages such as light quality, lower cost and higher than strength and stiffness, corrosion resistance and good stability, etc. However, composite materials have heterogeneity, anisotropy and process discreteness, easily appear internal defects such as pores, layered in the process manufacturing. Due to the collision in the process of transportation, storage, environmental erosion, and aging factors, the shell may generate much defect such as fracture, layering, and even delamination. In recent years, optical fiber sensors [1-7] have shown greater benefits in the field of static and dynamic strain monitoring with respect to more traditional sensors, such as immunity to electromagnetic fields, durability, resistance to corrosion and multiplexing capability. Furthermore, their small sizes and compatibility with common composites materials make them easily embeddable inside the structure of solid rocket motors (SRM) without inducing significant weakening of the structure. However, the main research on damage detection all concentrated on the structure of laminated plates which is easy to embedded the FBG and the survival rate is high. Due to the filament wound tension and high temperature of curing during the course of manufacture, the embedded FBG sensors is easily overloaded and damaged[8]. Also, the Bragg spectrum may be distorted depending on the intensity and spatial distribution of the residual strain field and finally the strain transfer from the host material to the fiber core is different in the case of an embedded sensor rather than an adhesively bonded sensor. Another problem is that the location of the FBG sensors is difficult to determine in processing of fiber winding.
In this paper, we propose a new method that FBG sensor network was embedded between the composite shell surface and the thermal protective coating. The strain detection system to detect the
shell strain distribution under pressure and the feasibility of composite shell strain detection based on FBG sensors was verified by hydrostatic test of small scale SRM shell. This way of embedment effectively improve the survival rate of the FBG sensor.

2. Basic of FBG Operation

A fiber Bragg grating is a periodic modulation of the effective refractive index \( n_{\text{eff}} \) in the optical fiber core. Light travelling at the Bragg wavelength, \( \lambda_B \), which depends on the grating features, is reflected back by the grating itself and as a result it is missing in the transmission spectrum. The reflected spectrum is centered at the Bragg wavelength and depends on the mentioned effective index of refraction \( n_{\text{eff}} \) and on the Bragg period \( \Lambda \) of the grating, according to the following equation:

\[
\lambda_B = 2n_{\text{eff}} \Lambda
\]

which is the Bragg equation. By inscribing an array of FBG sensors with different grating periods in the same fiber, it is possible to monitor different locations on a structure. When a local deformation is present, the grating’s period varies and the reflected wavelength varies accordingly, allowing the detection of the local strain via the Bragg equation (1). The strain and the wavelength variations can be put in a one to-one relationship only in the case of unidirectional and uniform deformation, provided that the effect of the temperature on the Bragg wavelength is suitably compensated for.

3. FBG Sensors Embedded and Calibration

After the shell curing and molding, the FBG sensor arrays were arranged by means of surface paste on the shell surface. Then the thermal protective coating was sprayed evenly on the surface. In this way the sensor arrays were embedded between the shell and coating. When FBG sensors embedded between missile composite shell and coating, the adhesive and coating all will influence the strain transfer ratio of the sensor. Because the adhesive thickness is also difficult to precise control and so it is difficult to calculate by the strain transfer function of the strain transfer ratio of the sensor. In order to build a practical application of optical fiber sensing test system, and finally realize in the application of solid rocket motor, it is very necessary to calibrate relationship between the shift of FBG center wavelength and the strain of composite shell before the actual application.

3.1. Calibration method

The calibration test was completed by axial tensile test. Axial tensile specimens were made of glass fiber composites according to Chinese standard of P.R.C, GBT1447. The length of Bragg grating is 1.5cm. Stick the FBG by adhesive on the specimen surface along the tensile direction. Then the coating was evenly sprayed on the surface of specimen. High precision resistance strain gages used to measure the axial real strain was pasted on the other side of the specimen surface and ensure the paste direction in strict accordance with fiber grating direction. The demodulation system of the FBG in test is SM130 produced by MOI. The calibration test as figure 1 shown.

3.2. Test data processing and analysis

In the process of test, the high precision resistance strain gauge and fiber demodulation instrument were used to track measurement and record of strain gauge and data at the same time. Due to the large strain taken place on tensile specimen, the FBG demodulation instrument hasn’t demodulated the abnormal wave shape when the tensile strain reach 7932 με. The test finished by now. The strain gauge and fiber sampling frequency demodulation devices are set to 1 Hz. To calibration of sensor, need to get a grating center wavelength variation - strain curve. As the figure 2 shown, strain-time and wavelength-time data were depicted in a coordinate system. To calibration of sensor, we need to get a grating center wavelength variation-strain curve. A new coordinate system with the strain gauge measured strain values as X axes and the sensor demodulation instrument center wavelength variation as Y axes was established. Then the center wavelength variation of the sensor and strain curve was obtained, as shown in figure 3. The real strain measured by FBG and gauge measurement were compared, as shown in figure 4.
Figure 1. Calibration test

Figure 2. Strain-time and wavelength-time data in tensile test

Figure 3. Strain-wavelength variation curve

Figure 4. Comparison strain measured by FBG and resistance strain gauge

Linear regression analysis for data fitting was made by use of the mathematical tools Origin software, the strain-wavelength linear regression equation is obtained as follows:

\[ y = 0.001151x - 0.22748 \]

\[ R^2 = 0.99746 \]

The degree of fitting:

\[ S = \Delta \lambda / \Delta \varepsilon = 1.151 \text{ pm/\mu m} \]

Where \( \Delta \lambda \) is FBG center wavelength variation, \( \Delta \varepsilon \) is the strain variation. It can be conclude that the FBG sensor keep a good linearity and sensitivity.

4. Hydrostatic Test of Small Scale SRM Shell

In order to test the feasibility of the sensor network with the FBG embedded between composite and coating, a glass fiber filament wound scale SRM model embedded sensors was used to hydrostatic test. The length and radius of cylindrical section of the shell are \( r = 75 \text{ mm} \), and \( l = 160 \text{ mm} \), respectively. The staking sequences of 9 laminae (from inner to outer) is \([ (\pm 28^\circ)/(90^\circ) ] \). As the figure 5 shown, small scale SRM shell coated by thermal protective coating.
4.1. Sensors arrangement and hydrostatic test
The sensors arrangement are as follows: In the cylindrical section along the axial deploy a three series grating, along the hoop direction deploy a three series grating, then two quasi distributed sensor network has formed on the shell surface. As the figure 6 shown, the FBG sensor 1 #, 2 #, 3 # are along the axial direction, their wavelength is 1550.155 nm, 1555.102 nm and 1560.126 nm respectively, distance between each grating is 5 cm; 4 #, 5 #, 6 # are along the hoop direction, the wavelength of 1530.872 nm, 1535.728 nm and 1539.760 nm, distance between each grating is 5 cm also. After arrangement the sensor, the coating was evenly sprayed on the surface of the cylindrical section of the shell. After the coating fully cured, the FBG sensors were tested by using of demodulation instrument. We can see that the survival rate of FBG sensor effectively improve and reach 100%. In order to verify the test result, six high precision resistance strain gages were pasted near the location of the FBG on the surface of the shell, the test strain direction of strain gages are consistent with the FBG sensor.

The water pressure slowly increase from 0 to 5Mpa, keep the pressure for 10s. Then release the pressure gradually until extinction, record the process of centre wavelength and grating strain gauge measured strain values.

4.2. Test data processing and analysis
Due to the shell was knocked down accidentally in the process of hydrostatic test, an axial arrangement with FBG sensor and strain gauge were failure, at the end of the test only five sets of data were collected. Recording the test data, we can get the relationship between centre wavelength and time. According to the strain-wavelength linear regression equation (2), the relationship between strain measured by FBG sensors and time can be gotten. Figure 7 and Figure 8 respectively show strain measured by FBG and resistance strain gauge in the process hydrostatic test. In according to the comparison of the two figures, we can see that the trend of two sets of curves are basically identical.

Experimental results demonstrate the good agreement between the concentration strain filed provided by strain gauges and that provided by the FBG sensors network. However, the FBG sensor can be more precisely the change of strain on the shell than the resistance strain gauge. In the hydraulic testing, the hoop strain was bigger than axial strain in the cylindrical section. In the middle of cylindrical section the hoop strain is biggest than the strain of other section pasted sensors.
**Figure 7.** Strain measured by resistance strain gauge

**Figure 8.** Strain measured by FBG

### 5 Conclusion

In order to realize the strain monitoring of FBG sensors in SRM, a method of embedding FBG sensor between composite shell and the thermal protective coating is proposed. This method can effectively improve the survival of FBG sensor than embedding directly into the composite fiber of shell and achieves 100% survival in the Hydrostatic test. It is certified by the hydrostatic test that the FBG sensors could precisely describe the strain variation and distribution of the composite shell surface and the thermal protective coating. As a first step research for the development of health monitoring system for SRM, the capability of embedded FBG sensors network system in composite structures has been demonstrated in these experiments.

### References

[1] W. R. Habel, Reliable Use of Fiber Optic Sensors. In: Encyclopedia of Structural Health Monitoring, Eds: Boller C. etal., John Wiley & Sons (2009).

[2] Costiner S, Winston H A, Gurvich M R, Ghoshal A, Welsh G S, Butler S L, Urban M R, Bordick N. Optimal Sensor Fusion for Structural Health Monitoring of Aircraft Composite Components. United Technologies Research Center, 2011:1-9.

[3] Degrieck J, De Waele W, Verleysen P. Monitoring of fibre reinforced composites with embedded optical fibre Bragg sensors, with application to filament wound pressure vessels. NDT&E International 2001;34(4):289–96.

[4] Grant J, Kaul R, Taylor S, Myers G, Wilkerson C, Jackson K, et al. Distributed sensing of carbon-epoxy composites and filament wound pressure vessels using fiber-Bragg gratings. Proc SPIE 2002;4935:32–40.

[5] Kunzler M, Udd E, Kreger S, Johnson M, Henrie V. Damage evaluation and analysis of composite pressure vessels using fiber Bragg gratings to determine structural health. Proc SPIE 2005:5758:168–76.

[6] Ortyl Nicholas E. Damage evaluation and analysis of composite pressure vessels using fiber Bragg gratings to determine structural health. Proc SPIE 2005:6004.

[7] Kang DH, Kim CU, Kim CG. The embedment of fiber Bragg grating sensors into filament wound pressure tanks considering multiplexing. NDT&E Int 2006;39(2):109–16.

[8] Chang, Xinlong; He, Xiangyong; Hu, Jianghua; Li, Jinjun. Experimental research on embedded fiber Bragg grating sensors network for solid rocket motors health monitor[C]. Proceedings - The 1st International Conference on Intelligent Networks and Intelligent Systems, ICINIS 2008.