Response of FBG sensors embedded in SRM interface of combustor when subjected to tri-axial normal loadings

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Abstract: In this paper, polymer packaged fiber Bragg grating (FBG) sensors are installed inside of the combustor wall to monitor the health of solid rocket motor. The responses of sensor embedded in adhesive specimen composed of propellant, insulation and case when subjected to axial and unaxial tensile stress are investigated. The strain distribution and spectrum of FBG were simulated when the specimen suffered from different normal loadings by finite element method and computer simulation technology. The result is validated by axis and unaxis tensile test. It is shown that the proposed type of sensing system can measure the bond stress (the radial stress) in SRMs.

Keywords: solid rocket motor, FBG, optical sensors, interface

Classification: Optical systems

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1 Introduction

Rocket motors are one of the largest items that dictate missile system service life. Thus, structure health monitoring is of significant interest for the safety and reliability of solid rocket motors (SRMs) [1]. The ability to detect damage in SRMs will help enable timely, accurate, and reliable assessment of structural integrity, and thus will yield great cost savings and prevent catastrophic structural failures. Because SRMs are cooled from the cure temperature to an ambient temperature, radial stresses persist in the grain throughout its life. And SRMs can develop critical flaws that can cause catastrophic failure at ignition. There are three primary failure mechanisms: propellant aging, bore cracking, and delamination (debond) at the interfaces between the propellant, insulation, and case [2]. As the Fig. 1(a) shown, in regions of the grain where a highly triaxial stress state exists. Classical approaches used to predict and detect material degradation have been to develop aging models for predicting the state of a material, given an assumed or measured environmental history, and the use of non-destructive testing methods such as ultrasound and X-rays. Both approaches, as currently practiced, are inadequate to meet the needs of a real-time, self-sensing health monitoring system. Thus, in recent years efforts have been devoted to investigate an entirely new approach to meet the goal of self-sensing ordnance the use of embedded sensors [3]. Several types of embedded sensors are being investigated in the solid rocket motor community [4]. Bond line sensors are small pressure sensors used to measure the stress between the propellant and case. The sensors are used to detect the perturbation in the stress field due to the presence of damage. Among the several types of sensors that could be considered, electrical strain-gage-based bond stress sensors, which measure the normal stress between the grain and liner, have received the most attention, and it has been shown that they can have significant value in their ability to validate grain stress predictions [5, 6]. However, the need for electrical leads entering the motor presents safety concerns that may preclude this method except for laboratory applications. Optical fiber strain sensors [7, 8, 9], particularly Fiber Bragg grating (FBG) strain sensors, have also received some attention, optical sensors are considered as the preferable solution in such environments, due to their electromagnetic interference immunity and their inherent electrical and explosion safe characteristics. Furthermore, FBG are ideal for multiple sensor applications as many of these gratings can be employed either in series or in parallel. There are, however, several issues with fiber optics that need...
to be addressed and overcome before this technology can be used in general in SRMS. Fibers are typically made from brittle material such as glass. This results in being fragile and difficult to handle. This paper proposes a new method using fiber Bragg gratings by polymer packaging sensors for measuring the bond stress between the propellant and insulation. There are three advantages for using polymer packaging the FBG. Firstly, the FBG is so very brittle that the survival rate is difficult to guarantee in the embedding process. It needs special protection to prevent breaking. Secondly, the bubbles or impurities may be formed around the FBG in embedding process. They will generate stress concentration causing the spectrum peak splitting or chirp which provides an unambiguous indication of the strain, and it is difficult to interpret the results. Lastly, the bond stress is perpendicular the bond interface embedded FBG sensor. The lateral pressure tuning of FBGs suffers from the drawback of low lateral pressure sensitivity, narrow tuning range and stress induced birefringence. This can be achieved by coating or packaging the FBG with a material having low elastic modulus and very high Poisson’s ratio, which can effectively transfer the stress applied in one direction to the mutually perpendicular directions. In this paper, the FBGs coated by a wafers’ package of HTPB/TDI elastic mass, the structure diagram of sensor as the Fig. 1(b) shown.

![Fig. 1. (a) Stresses at grain-liner-case, (b) Structure diagram of sensor](image)

The spectral response of coated FBGs embedded in adhesive specimen subjected to axial and unaxial tensile stress are studied and presented. HTPB(hydroxyl-terminated polybutadiene) resin is a good binder in solid rocket propellant. It is characterized by low glass transition temperature, proper mechanical property after curing, age resistance, having very low stiffness and very high Poisson’s ratio value. It is thermally stable and retains room temperature characteristics across a wide temperature ranging from −40 to 70°C. As Fig. 2 shown, schematic diagram of a solid rocket motor and an array of four FBG sensors at the midplane of the motor. Optical sensors evenly distributed along the circumference of the motor at the propellant/insulation interface.
2 Principle

When the fiber is strained axially, the fiber elongates or compresses, changing the fiber gratating spectral period and the output spectrum goes to longer or shorter wavelengths, respectively. The condition of high reflection or Bragg condition, relates the reflected wavelength or Bragg wavelength, $\lambda_{B0}$, to the grating period, $\Lambda$, and the mean effective index of refraction, $n_0$. The most general relationship between strain and induced change in the reflected wavelength in a FBG (with the fiber axis parallel to the z direction) can be expressed by

$$\lambda_{B0} = 2n_0\Lambda$$  \hspace{1cm} (1)

However, a three dimensional state of strain prevails around a FBG embedded in the propellant/insulation interface. Various experimental studies have shown that the transverse load response of FBGs is entirely different from axial loading. When a FBG is subjected to non-negligible transversal strains, its optical response is generally affected. Thus, transversal strains essentially induce birefringence in the fiber core, which may lead to the separation of the initial Bragg peak into two distinct ones along two polarization axes. Consequently, Eq. (1) splits into the following relations along the two intrinsic polarization axes of the fiber,

$$\lambda_{By} = 2n_y\Lambda$$  \hspace{1cm} (2)

$$\lambda_{Bx} = 2n_x\Lambda$$  \hspace{1cm} (3)

Where $\lambda_{Bx}$, $\lambda_{By}$, $n_x$, $n_y$ are the reflected wavelength and effective indexes of refraction for the $x$ and $y$ polarization axes, respectively (with the fiber axis parallel to the $z$ direction). The change reflective index can be expressed:

$$\frac{\Delta n_x}{n_0} = -\frac{n_0^2}{2} [P_{11}e_x + P_{12}(e_y + e_z)]$$  \hspace{1cm} (4)

$$\frac{\Delta n_y}{n_0} = -\frac{n_0^2}{2} [P_{11}e_y + P_{12}(e_x + e_z)]$$  \hspace{1cm} (5)

Where $e_x$, $e_y$, $e_z$ are the principle strain components of the fiber core at any point P($x, y, z$) in the X,Y and Z direction, $n_0$ is the effective refractive index of the unstressed. $\Delta n_x$, $\Delta n_y$ are the effective refractive index X,Y polarization axes. The most general relationship between strain and induced change in the reflected wavelength in a FBG can be expressed by
\[
\frac{\Delta \lambda_{Bx}}{\lambda_{B0}} = \frac{\Delta n_x}{n_0} + \frac{\Delta \lambda}{\lambda}
\]  
(6)

\[
\frac{\Delta \lambda_{By}}{\lambda_{B0}} = \frac{\Delta n_y}{n_0} + \frac{\Delta \lambda}{\lambda}
\]  
(7)

Equation can be obtained by relation (4) (5)

\[
\frac{\Delta \lambda_{Bx}}{\lambda_{B0}} = e_x - \frac{n_0^2}{2} [P_{11}e_x + P_{12}(e_y + e_z)]  
\]  
(8)

\[
\frac{\Delta \lambda_{By}}{\lambda_{B0}} = e_y - \frac{n_0^2}{2} [P_{11}e_y + P_{12}(e_x + e_z)]  
\]  
(9)

Where \( P_{11}, P_{12} \) are photoelastic coefficient.

\[
\frac{\Delta \lambda_{Bx} - \Delta \lambda_{By}}{\lambda_{B0}} = \frac{n_0^2}{2} (P_{12} - P_{11})(e_x - e_y)  
\]  
(10)

one notices that the peak separation \( \Delta \lambda_{x} - \Delta \lambda_{y} \) only depends linearly on the transversal strains difference \( e_x - e_y \). When the induced birefringence is negligible (i.e. \( e_x \) and \( e_y \) are equal), a simplified equation can be obtained by averaging relations (8) (9),

\[
\frac{\Delta \lambda_{B}}{\lambda_{B0}} = e_z - \frac{n_0^2}{2} \left[ P_{12}e_z + \frac{1}{2}(P_{11} + P_{12})(e_x + e_y) \right]  
\]  
(11)

Assuming further that \( e_{x,y} = -ve_z \), where \( v \) is the Poisson’s ratio of the fiber, and Eq. (11) simplifies to

\[
\frac{\Delta \lambda_{B}}{\lambda_{B0}} = \left( 1 - \frac{n_0^2}{2} (P_{12} - v(P_{11} + P_{12})) \right)e_z = (1 - P_e)e_z  
\]  
(12)

where the new strainoptic constant \( P_e \) can be easily determined experimentally. This relation points out that the shift in wavelength of the Bragg peak is proportional to the applied axial strain. When it is uniform, shifts occur without modification of the initial spectrum shape and \( e_z \) is easily obtained from (12). However, it has been shown that a non-uniform strain distorts the shape of the reflection spectrum.

3 Finite element simulation

In order to simulate the loading condition of shell/insulation/Liner/propellant bonding system. A adhesive specimen is designed for rectangular adhesive specimen embedded optical sensor according to Chinese aerospace industry standard of P.R.C, QJ 2038. 1-2004. The adhesive specimen is composed of steel shell, two pieces of insulation, liner, block of HTPB propellant. The propellant cast and cured between two layers of liner bonded to NBR (nitrile-butadiene rubber) insulation, which had been bonded previously to steel plates and the optical sensor lie between insulation and propellant (Fig. 3(a)). Constant load experiment with different load magnitude and angles were performed,and the changing characteristics of FBG sensors were obtained.

Finite element simulation of the tensile test process was carried out to scrutinize the strain distribution on the FBG and thereby to compute the wavelength response characteristics. The simulation was carried out using commercial software ANSYS.
The schematic of the model and the coordinate system used is shown in Fig. 3(b). The central axis of the fiber is designated as Z axis and the direction perpendicular to the specimen shell plate is designated as the Y axis. The applied boundary conditions are as follows: For the upper shell plate, the degree of freedom is arrested as a fixed support, allowing the bottom shell plate to move in the loading direction. In order to simplify the calculation, the viscoelastic material only considers equilibrium modulus. The material properties used for the simulation is shown in Table I. To analyze the response of FBG subjected to stress in different direction, the following 3 case have been studied.

### Table I. Material properties

| Property       | Elasticity modulus, E (MPa) | Possion’s ratio, $v$ | Size (mm) | Photoelastic coefficient | $\Lambda$ (nm) | $\Delta n$ |
|----------------|-----------------------------|----------------------|-----------|--------------------------|-----------------|------------|
| Fiber grating  | $7.2 \times 10^4$           | 0.17                 | $10 \times 10^4$ | $0.125$ $P_{11} = 0.113$ $P_{12} = 0.252$ | 530.834         | $10^{-4}$  |
| Case           | $2.1 \times 10^5$           | 0.3                  | $40 \times 50 \times 3$ | $P_{12}$ | 0.113 | 530.834 | $10^{-4}$ |
| propellant     | 12.189                      | 0.49                 | $40 \times 50 \times 25$ | $P_{12}$ | 0.252 | 530.834 | $10^{-4}$ |
| Insulation     | 24.178                      | 0.49                 | $40 \times 50 \times 3$ | $P_{12}$ | 0.252 | 530.834 | $10^{-4}$ |
| Adhesive layer | 5000                        | 0.3                  | 0.05–0.5 | $0.05–0.5$ | 530.834 | $10^{-4}$ |
| Polymer coating| 4                           | 0.49                 | $4 \times 6 \times 1$ | $P_{12}$ | 0.252 | 530.834 | $10^{-4}$ |
| Metal plate    | $1.078 \times 10^5$         | 0.3                  | $40 \times 50 \times 0.2$ | $P_{12}$ | 0.252 | 530.834 | $10^{-4}$ |

*Fig. 3. (a) Adhesive specimen embedded FBG sensor, (b) The schematic of the model and the coordinate system*

Case 1: The loading direction is along Y-axis (axis tensile stress)
When the loading direction is along Y-axis (see Fig. 4(a)), the loading component direction are along Z-axis $P_z$ and X-axis $P_x$, $P_z = P_x = 0$. Fig. 4(b) shows the distribution of the strain at the three axis of the FBG with respect to the applied load. It could be seen that strain in the Z-direction $e_z$ is compressive in nature and its magnitude is very high compared to the compressive radial strains $e_x$ and $e_y$. At a load of 0.1 MPa, the magnitude of axial strain is $6.511 \times 10^{-3}$, whereas the radial strains in the X- and Y-directions are only $1.045 \times 10^{-4}$ and $1.047 \times 10^{-4}$,
respectively. This is crucial in connection to the requirement of superior axial strain for the center wavelength of the FBG to have improved sensitivity to the applied lateral load. Since the plane of the gratings is perpendicular to the axis of the fiber only the axial strain $\varepsilon_z$ can produce maximum gradient in the period of the grating during strain tuning. The shift in the center wavelength is calculated with respect to a center wavelength of 1550 nm. As the Fig. 4(c) shown, it can be seen that $\varepsilon_x$ and $\varepsilon_y$ are superimposed and shifts almost at the same rate with respect to the applied load. The difference between the two is so little, which is too negligible. According to the formula(10), it cannot cause apparent peak splitting. The FBG’s reflection spectra can be simulated by the software Optigrating. Fig. 4(d) shows strain corresponding optical spectral wavelength under different angles.

![Diagram](image)

**Fig. 4.** (a) The loading direction is along Y-axis, (b) Distribution of the strain at the three axis of the FBG with respect to the applied load, (c) Strain at the center of the FBG due to lateral loading, (d) Wavelength shifting of FBG under different magnitude stress

Case 2: The loading component direction is along X-axis and Y-axis.

As shown in Fig. 5(a), the specimen is subjected to a unaxis loading which has the components in X-axis and Y-axis direction, the Z-axis component is 0. The angle between the loading direction and Y-axis direction is $\alpha$. Fig. 5(b) shows the strain distribution at the axis of FBG when the specimen is subjected to the loading whose X-axis component and Y-axis component two values are both 0.1 MPa. In this case, the degree of $\alpha$ is 45°. We can see that the distribution of strain on three axis direction is the same as the case1 (as Fig. 4(b) shown), namely the loading component along X-axis direction has little influence on the distribution of strain.
on FBG. The response of FBG sensor is simulated at constant weight loading when α is 15°, 30°, 45°, 60° and 75°. Fig. 5(c) shows the variation of the strain at the axis of the FBG with respect to the different angles applied load. It is observed that $\varepsilon_z$ and $\varepsilon_y$ are superimposed and shifts almost at the same rate with respect to the applied load. The difference between the two is so little, it still cannot cause apparent peak splitting. The shapes of the reflection spectrum have little change compared with the initial. There is no reflection spectrum bandwidth broaden and peak spitted. Fig. 5(d) shows strain corresponding optical spectral wavelength under different angles. It can be seen that the absolute value of three axes’ strain $\varepsilon_x$, $\varepsilon_y$ and $\varepsilon_z$ are all decreasing with the increase of α. As a result, the wavelength drifts toward the increasing as the α increases.

Case 3: The loading component in three direction all exist. Analysis by Case 2 can be seen, the loading component along X-axis direction has little influence on the distribution of strain on FBG. When the specimen is subjected to a loading whose component in three directions all exist, this can be simplified that the specimen is subjected to a unaxis loading which has only the components in Y-axis and Z-axis direction, the X-axis component is 0 (see Fig. 6(a)). The angle between the loading direction and Y-axis direction is α. Fig. 6(b) shows the strain distribution at the center of the FBG due to lateral loading, (d) Wavelength shifting of FBG under different angle stress.

Fig. 5. (a) The loading component direction is along X-axis and Y-axis. (b) Distribution of the strain at the three axes of the FBG with respect to the applied load, (c) Strain at the center of the FBG due to lateral loading, (d) Wavelength shifting of FBG under different angle stress.

© IEICE 2017
DOI: 10.1587/elex.14.20170657
Received June 28, 2017
Accepted July 14, 2017
Publicized July 31, 2017
Copyedited August 25, 2017
the degree of $\alpha$ is 45°. It could be seen that the distribution strain in the Z-direction $e_z$ on the FBG approximates linear function. At the centre of FBG, the magnitude of axial strain is $-6.506 \times 10^{-4}$ whereas the radial strains in the X- and Y-directions are only $1.045 \times 10^{-4}$ and $1.047 \times 10^{-4}$, respectively. The response of FBG sensor is simulated at constant weight loading when $\alpha$ is 15°, 30°, 45°, 60° and 75°. Fig. 6(c) shows the variation of the strain at the axis of the FBG with respect to the different angles applied load. It can be seen that $e_x$ and $e_y$ are superimposed and shifts almost at the same rate with respect to the applied load. The difference between the two is still so little, it cannot cause apparent peak splitting. Fig. 6(d) shows strain corresponding optical spectral wavelength under different angles. The shapes of the reflection spectrum all broaden with the increase of the angle $\alpha$. The bandwidths value at −20 dB as the Table II shown.

| Table II. The bandwidths value at −20 dB in different angle |
|----------------|----------------|----------------|----------------|----------------|----------------|
| $\alpha$       | Original       | 15°            | 30°            | 45°            | 60°            | 75°            |
| Bandwidth at −20 dB (nm) | 0.44175 | 0.59775 | 0.846 | 1.026 | 1.19175 | 1.2705 |

Fig. 6. The loading component direction is along X-axis and Y-axis, (b) Distribution of the strain at the three axis of the FBG with respect to the applied load, (c) Strain at the center of the FBG due to lateral loading, (d) Wavelength shifting of FBG under different angle stress

According to analysis for the response of the sensor in above three cases, it can be concluded that the stress perpendicular to the bonding interface (the force in the Y-axis direction) affects the drift of the center wavelength of the sensor, the two are
inversely proportional to the linear relationship. The sensor is not sensitive to stress response in the X-axis direction and which can be negligible in the testing. And the stress in the axial direction of the fiber (the Z-axis direction stress) may causes a large stress gradient to appear on the grating because the strain distributes nonuniformly on the FBG. It results in the widening of the reflected wave of the FBG sensor. Take advantage of the FBG sensor response, we can locate the debonding in the SRM interface in Fig. 2. When debonding occurs between the sensors 1 and 2 positions, the interfacial adhesion stress changes with the change of temperature around the SRM. The amount of change in the bond stress at the 1 and 2 positions different from the amount of change in the adhesive stress at the 3 and 4 positions. When the defect is relatively large, the position near debonding of the sensor will form a large strain gradient caused by stress in the direction of the grating, then the sensor reflection wave shape will appear widening phenomenon.

4 Experiments

The FBG sensing system used in this experiment is shown in Fig. 7(a). Stepwise stress tensile tests were made to validate the response of the sensors embedded.

As the Fig. 7(b) shown, the cycle loading and unloading experiment were done with three cycles, maximum loading is 35 N and the magnitude of stepwise loading is 7 N. A set of graphs of stress-peak wavelength of FBG sensor under axial and unaxial cycling loadings for the double plate test specimen were obtained.

As the Fig. 8(a) shown, peak shift with respect to applied load in axis tensile test. The curves appear downward tendency after every cycle result for the character of viscoelastic for HTPB solid propellant. This suggests that the specimen in the process of loading and unloading experiment the interface bond stress change taken place which can be measured by the center wavelength of FBG. It is very useful to determine the quality of bonding interface in the long term health monitoring of SRMs. Fig. 8(b) shows the relationship between the center wavelength of FBG and tensile stress when tensile stress direction has a angle between the Y-axis. In this experiment the angle is 39°. It is the same as case3 which loading component direction is along z-axis and y-axis. In the experiment, the component of loading in Z direction is so little that we cannot observe the shapes of the
reflection spectrum broaden. However, with the increase of tensile stress, the spectrum will eventually appear broadening phenomenon.

In order to find out the relationship between the axial tensile data and the non-axial tensile data, the mean values of the FBG center wavelengths under the same stress are obtained for the two experimental data. The relationship of average center wavelength between tensile stress and comparison with analytical value can be shown as the Fig. 8(c). The wavelength-stress curve can be shown by in four oblique lines. It can be seen that the absolute value of the line gradient of analytical are larger that of the test. The main reason for this is that the materials such as propellant, polymer coating, Insulation and adhesive layer are high-molecular polymer which have the properties of viscoelastic materials. The viscoelasticity of material whose elasticity modulus decrease with time when the stress is constant. The relation between elasticity modulus and time can be expressed by prony format:

\[ E(t) = E_\infty + \sum_{i=1}^{n} E_i \exp \left( -\frac{t}{t_i^E} \right) \]  

Where \( E(t) \) is the relaxation modulus, \( E_\infty \) is the equilibrium modulus, \( t_i^E \) relaxation times for each Prony component, \( E_i \) is relaxation kernel elastic moduli. The viscoelastic material’s elasticity modulus for simulation is the equilibrium modulus \( E_\infty \) which is less than real modulus in the tensile test. According to the sensor strain transfer model, when the elastic modulus of each layer decreases, the strain of the grating increases, which leads to the absolute value of the line gradient of analytical

![Fig. 8.](image-url)
are larger than that of the test. As the Table III shown, the linear fitting \( y = a + bx \) of relationship of average center wavelength between tensile stress has been carried out. It can be seen that the linearity is up to 0.99, which shows there is a good linear relationship between the average center wavelength of FBG and tensile stress. Where \( b \) value represents the center wavelength variation with load increment, the ratio of two is 0.777 which just equal to the \( \cos 39^\circ \). A conclusion can be drawn that the variation of center wavelength is only related to the loading’s component of Y axis when the shape of spectrum doesn’t apparent significant broadening.

| Test    | Parameter A | Parameter B | Linearity  |
|---------|-------------|-------------|------------|
| Axial   | 1540.508    | −2.37401    | 0.99094    |
| Unaxial | 1540.540    | −1.84368    | 0.99654    |

### 5 Conclusion

In this paper, the strain distribution of the adhesive specimen under different direction forces are simulated by finite element method, and the response of FBG spectrum are simulated. The results show that the design of the FBG sensor center wavelength can effectively reflect the change of the interface bonding stress (the component in the Y-axis direction). The sensor is not sensitive to the stress in the X-axis direction. However, the FBG spectrum will broaden when a large stress gradient is in Z-axis direction. According to the arrangement of sensors in Fig. 2 FBG sensors evenly distributed along the circumference of the motor at the propellant/insulation interface, we can determine the approximate position of the defect by the change of FBG center wavelength which change with the variation of bond stress. When there is a large stress gradient in circumferential direction, it can be reflected from the reflection spectrum.

### Acknowledgments

The paper is financially supported by the National Scientific Support program of China (Grant No. 51605480).