New Method of Temperature and Strain Decoupling Based on Directivity of Fiber Bragg Grating Sensing

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Abstract. Fiber Bragg Grating (FBG) has been widely used in temperature and strain measurement. Its center wavelength drift is affected by both temperature and strain. The influence of temperature and strain on center wavelength should be decoupled when measuring. In this paper, the sensing characteristics of FBG which pasted at different angles were simulated and analyzed, and it was found that FBG sensing for strain has strong directivity. A dual FBG composite construction based on the directivity of FBG sensing was proposed. Two FBGs were at an Angle of 62°. One FBG was sensitive to both temperature and strain, and the other was only sensitive to temperature. The structure can realize the decoupling of temperature and strain, and it doesn’t depend on feature of cantilever beam. It was verified by experimental analysis that the decoupling result was good by utilizing the combined FBG structure, and decoupling was realized easily.

Keywords. Fiber Bragg Grating, directivity of sensing, composite construction, temperature and strain decoupling.

1. Introduction
Fiber Bragg Grating (FBG) possesses some remarkable advantages over the conventional electrical sensors, such as resistance to electromagnetic interference, high reliability, low cost, multiplexing capabilities [1]. It is extensively applied in temperature and strain measurement of aerospace field, mechanical equipment, civil engineering and so on. Its center wavelength will be changed with temperature and strain, so it can measure temperature and strain simultaneously. Therefore, the influence of temperature and strain on FBG’s center wavelength should be decoupled first [2]. Similarly, the influence of temperature on FBG’s center wavelength should be eliminated in strain measurement to ensure that the change of center wavelength depends on strain only.

Many researches on temperature and strain decoupling have been done. Some scholars realized the decoupling of temperature and strain by pasting two FBGs on the upper and lower surfaces of the cantilever beam and so they were under opposite strain and the same temperature [3-5]. Xiong [6] used five FBGs and crossbeam elastomer structure to achieve a self-decoupling and realized temperature self-compensation measurement of three-dimensional force at the wrist of the device. Besides, Xiong [7] proposed that the prestretching and fixation of the double grating could obtain better temperature compensation effect and stability. Jiang [8] cascaded Mach-Zehnder interferometer with FBG to achieve simultaneous measurement of transverse pressure and temperature parameters. Yan [9] proposed a large range strain sensor based on FBG with temperature sensitization and strain reduction. Kang [10] monitored the wavelength at the valley of transmission spectrum of dual-core
fiber and the wavelength drift of transmission spectrum of fiber grating in real time and realized the
decoupling of temperature and strain double measurement.

Most of present studies used the characteristics of a specific elastic element for decoupling, so the
specific elastic element should be packaged in FBG sensor. As a result, the size of FBG sensor is
bound to be limited, which restricts the application of FBG in some special applications where the size
and weight of sensors are required to be small enough.

In this paper, the directivity of FBG sensing was analyzed, and a new method of temperature and
strain decoupling based on FBG sensing directivity was studied. In the method, the decoupling
principle didn’t rely on the characteristic of specific elastic components any more.

2. FBG Sensing Theory

2.1. Sensing Theory of FBG under Axial Strain

When FBG is illuminated by a spectral broadband optical source, a narrow spectral band is reflected.
The reflected band is centered at the Bragg wavelength \( \lambda_B \), given by equation (1).

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

(1)

where \( n_{eff} \) is the effective refractive index of the optical fiber and \( \Lambda \) is the periodicity of the created
modulation.

If FBG is stretched and exposed to temperature variations simultaneously, the change of \( \lambda_B \) caused
by temperature \( \Delta T \) and strain \( \varepsilon \) can be described by equation (2).

\[
\Delta \lambda_B / \lambda_B = (1 - P_t)\varepsilon + (\alpha_f + \xi)\Delta T
\]

(2)

where \( P_e, \alpha_f, x \) are the Elastic-optic coefficient, thermal expansion coefficient and thermal optical
coefficient respectively.

2.2. Sensing Theory of FBG under Nonaxial Strain

It is emphasized that equation (2) is only applicable to the case where FBG is just subjected to axial
strain. The relative variance of \( \lambda_B \) should be calculated by equation (3) if FBG is under transverse
strain [11].

\[
\frac{\Delta n_x}{\Delta n_y} = \frac{\eta_{eff}^2}{2E} \left[ \frac{1}{P_{11} - 2\nu P_{12}} \left( 1 - \nu \right) P_{12} - \nu P_{11} \right] \left[ \frac{1}{P_{11} - 2\nu P_{12}} \left( 1 - \nu \right) P_{12} - \nu P_{11} \right] \times \left[ \frac{\sigma_x}{\sigma_y + \sigma_z} \right]
\]

(3)

where, \( E \) is the elastic modulus, \( P_{11}, P_{12} \) are the elastic-optical coefficients of the fiber, and \( \sigma_x, \sigma_y, \sigma_z \)
are the stress components acting on FBG perpendicular to the strain direction, parallel to the strain
direction and the fiber axis respectively.

![Figure 1. Sketch map of \( \theta \).](image)

When an isotropic elastic element is strained or compressed, not only axial strain but also
transverse strain will be generated. If the axial direction of FBG which is pasted on the elastic element
is the same as the axial strain direction of element, the influence of transverse strain of elastic element
can be ignored because the transverse strain sensitivity of FBG is much lower than that of axial strain.
If there is an angle \( \theta \) between axial direction of FBG and axial strain direction of element, as shown in
figure 1, the actual strain acting on FBG should be determined both by the axial strain and transverse strain of the elastic element, as shown in equation (4), where the strain transfer effect of the glue layer is ignored. By substituting equation (4) into equation (2), the approximate calculation method of FBG’s wavelength drift can be obtained, as in equation (5).

\[ \varepsilon = \varepsilon_x \cos \theta + \varepsilon_y \sin \theta \]  

\[ \Delta \lambda_b / \lambda_b \approx (1 - P_c)(\varepsilon_x \cos \theta + \varepsilon_y \sin \theta) + (\varepsilon_f \cos \xi \sin \theta + \varepsilon_f \sin \xi \cos \theta) \Delta T \]  

3. Simulation Analysis of FBG Sensing Directivity

The simulated model was shown in figure 2, including cantilever beam, mass, glue and fiber. The size of model was shown in table 1. All fiber was embedded in the glue. The parameters of the model were listed in table 2.

![Figure 2. Simulated cantilever beam and fiber model.](image)

### Table 1. Size of simulated model (mm).

| Cantilever beam | Mass | Glue | Fiber |
|-----------------|------|------|-------|
| length=60       | diameter=8 | length=12 | length=12 |
| maximum width=24| height=4   | width=0.4 | diameter=0.125 |
| thickness=1     | thickness=0.2 |          |       |

### Table 2. Parameters of simulated model.

|                        | Cantilever | Mass | Glue | Fiber |
|------------------------|------------|------|------|-------|
| Density \( \rho \) (kg/m\(^3\)) | 7850       | 7850 | 1100 | 8960  |
| Poisson ratio \( \mu \)     | 0.28       | 0.28 | 0.35 | 0.35  |
| Modulus of Elasticity E(GPa) | 205        | 205  | 3.3  | 110   |

\( \theta \) was changed from 0° to 180°, and step was 2°. Static load was applied on the upper surface of mass. The strain of the fiber’s center with different \( \theta \) was shown in figure 3. It can be found from figure 3 that the strain varied with \( \theta \): (1) The sensitivity is greatest when \( \theta=0° \), and it decreases with the increase of \( \theta \). (2) The sensitivity is closed to zero when \( \theta=62° \). (3) The strain is negative when \( \theta \) is between 62° and 90°, which indicates the direction of strain is opposite. (4) The sensitivity curve is symmetric about \( \theta=90° \).
Then, a dynamic load (frequency: 10Hz) was instead of the static load. And $\theta_1$ was fixed at 0° and $\theta_2$ was 62°. The strain of fiber under two different $\theta$ was shown in figure 4. Similar to the case of static load, the sensitivity is closed to zero when $\theta=62^\circ$.

4. Experimental Analysis of Temperature and Strain Decoupling

It can be found by simulation analysis that FBG has a strong sense of direction. The sensitivity of the fiber is the highest when $\theta=0^\circ$, and negligible when $\theta=62^\circ$. Based on this conclusion, a temperature and strain decoupling method based on the directivity of FBG sensing was proposed.

In experiments, an FBG composite structure which including two FBGs was proposed. Two FBGs were pasted on the same surface of the equal strength cantilever beam. FBG1 whose initial central wavelength was 1540.22 nm is pasted axial along the cantilever beam, and FBG2 whose initial central wavelength was 1534.916 nm has an Angle of 62° with FBG1. In order to reduce the temperature difference of each point on the surface of the cantilever beam, the positions of two FBGs were as close as possible. The free end of the cantilever beam was loaded under static load by weight. The temperature was changed by a heating device. The incident broadband spectrum was provided by a broad band light source (Agilent 83438A), and the reflected spectrum was obtained by a spectrometer (YOKOGAWA AQ6370D). Experimental devices except broadband light source and spectrometer were shown in figure 5.

The drifts of two FBGs' center wavelength were shown in figure 6. The blue one was initial value without loading and heating, the other one was under 600g loading and heating. It can be found that the wavelength change of FBG1 is much larger than that of FBG2. Because the wavelength of FBG1 was affected by temperature and strain simultaneously, while the wavelength of FBG2 only changed with temperature, as in equation (6).
\[
\begin{align*}
\Delta \lambda_{B1} / \lambda_{B1} &= (1 - P_e) \varepsilon + (\alpha_f + \xi) \Delta T \\
\Delta \lambda_{B2} / \lambda_{B2} &= (\alpha_f + \xi) \Delta T
\end{align*}
\tag{6}
\]

Equation (7) which is derived from equation (6) depends on strain only.

\[
\Delta \lambda_{B1} / \lambda_{B1} - \Delta \lambda_{B2} / \lambda_{B2} = (1 - P_e) \varepsilon
\tag{7}
\]

The data of experiments was extracted and analyzed, as shown in table 3. Figure 7 showed the curve between the strain and the loaded weight mass. It proved that the decoupling linearity was good.

**Table 3.** Analysis of two FBGs’ wavelength change.

| No loading, T0 | 200g, T1 | 400g, T2 | 600g, T3 |
|---------------|---------|---------|---------|
| \(\lambda_{B1}\) (nm) | 1540.22 | 1540.488 | 1540.844 | 1541.048 |
| \(\Delta \lambda_{B1} / \lambda_{B1}\) | 0 | 1.74 \times 10^{-4} | 4.05 \times 10^{-4} | 5.38 \times 10^{-4} |
| \(\lambda_{B2}\) (nm) | 1534.916 | 1535.184 | 1535.356 | 1535.284 |
| \(\Delta \lambda_{B2} / \lambda_{B2}\) | 0 | 1.02 \times 10^{-4} | 2.40 \times 10^{-4} | 2.87 \times 10^{-4} |
| \(\Delta \lambda_{B1} / \lambda_{B1} - \Delta \lambda_{B2} / \lambda_{B2} \) | 0 | 0.72 \times 10^{-4} | 1.65 \times 10^{-4} | 2.51 \times 10^{-4} |
| Calculated strain | 0 | 0.923 \times 10^{-4} | 2.115 \times 10^{-4} | 3.218 \times 10^{-4} |
Figure 7. Curve between the strain and the loaded weight mass.

5. Conclusions
In this paper, the directivity of FBG sensing was simulated, and a dual FBG composite structure which can realize temperature and strain decoupling was proposed based on the directivity of FBG sensing. The conclusions are as follows:

1. FBG has strong sensing directivity for both static strain and dynamic strain. When FBG's axial direction is consistent with the strain direction, the sensing sensitivity is the strongest. With the increase of the angle between FBG and strain direction, the sensing sensitivity decreases continuously and is approximately 0 at 62°, and then increases in the opposite direction.

2. When the angle between FBG axial direction and strain direction is 0°~180°, FBG sensor sensitivity is symmetric about 90°.

3. It was proved by experiment that the FBG composite structure in which two FBGs at an Angle of 62° each other can realize temperature and strain decoupling well and the procedure was simple. To a certain extent, it can make up for the deficiency of temperature difference between two FBGs when they are pasted at different positions in other decoupling methods.

4. In principle, the combined FBG structure can also be used for strain and temperature measurement of other mechanical structures with known strain directions too.

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