Research on Double Parameters Measurement Technology Based on Optical Fiber Bragg Grating

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Abstract. Double parameters measurement technology of pressure and temperature is presented in this paper based on Optical Fiber Bragg Grating (FBG.). The device of FBG double parameters measurement technology based on equal intensity beam is designed, which can measure the pressure and temperature at the same time. Experimental research and error analysis indicate that cross sensitivity between stress and temperature of fiber grating can influence less measuring results. The smaller measuring range is, the less the error of stress and temperature caused by cross sensitivity is.

1. Introduction
Optical fiber grating is a kind of fiber passive device, and recently it is one of most quickly developed. The appearance of the fiber grating, makes many complicated complete all optical communication and fiber sensor network possible, develops the applied range of fiber technology greatly. Recently, Optical fiber grating based on stress and temperature sensor is a new type sensing structure based on Fiber Bragg Grating (FBG) technology. It is successful in monitoring and abstracting multiple objective information in engineering structure, such as monitoring on-line stress, strain, temperature and crack and so on.

But cross sensitivity problem between strain and temperature leads to error in measuring result, this is one of bottle-neck problems restricting the application of FBG sensing technology. Since 1993, people have started to pay attention to this problem, and there are many projects for the cross sensitivity problem of FBG sensor. For example, combining reference FGB approach, chirp fiber grating approach, dual-wavelength superposition FGB approach, twin-core approach and so on. These methods have its merits and faults, but they are difficult to realize. FBG double parameters measurement method of equal intensity beam is proposed in this paper. It is suitable to have popular application in engineering practice, because its characters: convenient, easy-using, credibility, low cost, wide application and so on.

2. Sensing principle of FBG
The reflecting wavelength in FBG is:

$$\lambda_n = 2\Delta n_{\text{eff}}$$

(1)

In Equation (1), $n_{\text{eff}}$ ---- effective refractive index of fiber core
$\Lambda$ ---- grid pitch of grating.
From coupling theory, just when light-wave that satisfies Bragg can be reflected by fiber grating, calculate differential Equation (1):

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

(2)

From Equation (2), \( n_{\text{eff}} \) or \( \Lambda \) changes, the reflecting central wavelength will change correspondingly. The basic principle of FBG sensing is shown as follows: The changes of temperature, stress or other measured physical quantities around grating can lead to the variety of \( \Lambda \) or \( n_{\text{eff}} \). So the displacement variation of FBG central wavelength is \( \Delta \lambda_B \). The variation of measured physical quantities can be gained by means of detecting the displacement of grating wavelength.

3. **Research on FBG double parameters measurement technology based on equal intensity beam**

When variation of stress and temperature simultaneously function, the offset of FBG central wavelength is:

\[
\Delta \lambda_g = K_e \Delta \varepsilon + K_T \Delta T
\]  

(3)

In Equation (3), \( K_e \) and \( K_T \) separately present the coefficients of strain and temperature sensitivity of two gratings. When stress and temperature change at the same time, the variation of pressure or temperature can not be distinguished just by the variation of signal Bragg wavelength, this is cross sensitivity of fiber grating. The cross sensitivity of fiber grating influences the application of fiber grating in the field of sensor badly. According to the characteristics of strain sensor, single fiber double gratings structure based on cantilever is proposed in the paper, to achieve the purpose of simultaneous measurement of stress and temperature.

Schematic diagram of structure of equal intensity cantilever is shown as figure 1. This structure can reduce the system error caused by the incertainty of the position of FBG.

![Figure 1. Structure of equal intensity cantilever.](image)

Schematic diagram of double parameters measuring device of equal intensity beam is shown as figure 2. At different places of a fiber, read in two gratings with different wavelength, and place the two gratings to corresponding sides of projecting beam. When the beam is applied load, the upper and the lower of the beam are compressed or pulled, that is to say, pulling force and pressure force are generated. Correspondingly, grating central wavelength will move to long wave and short wave individually. So, change of the force makes the central wavelength of the two gratings displaced in different directions. But the change of the temperature makes the central wavelength of the two gratings displaced in the same direction.

When variation of stress and temperature simultaneously function, the offset of FBG central wavelength is:

\[
\Delta \lambda_{g1} = K_{e1} \Delta \varepsilon + K_{T1} \Delta T
\]

\[
\Delta \lambda_{g2} = K_{e2} \Delta \varepsilon + K_{T2} \Delta T
\]  

(4)
In equation (4), \( K_{e1}, K_{e2} \) — the coefficients of strain sensitivity of two gratings
\( K_{T1}, K_{T2} \) — the coefficients of temperature sensitivity of two gratings

The matrix form of central wavelength variation of fiber grating is:

\[
\begin{bmatrix}
\Delta \lambda_{g1} \\
\Delta \lambda_{g2}
\end{bmatrix} =
\begin{bmatrix}
K_{e1} & K_{T1} \\
K_{e2} & K_{T2}
\end{bmatrix}
\begin{bmatrix}
\Delta \varepsilon \\
\Delta T
\end{bmatrix}
\]  \( (5) \)

The variation of reflecting wavelength of the two Bragg gratings caused by stress and temperature can be measured in the experiment. So the variation of measured pressure and temperature can be gained.

4. Experimental Research

The experimental device of stress and temperature simultaneous measuring is show as figure 2. The fiber used in lab is single mode optical fiber, and choose FBG-SLI demodulator produced by Co. Micron Optics in the USA as FBG wavelength demodulating system. The ray form broadband luminous source entering the two gratings through the fiber and the reflected light returning to the demodulator after coupler, the central wavelength of the measuring grating will change. The central reflected wavelength of the two gratings individual is \( \lambda_{g1}=1537.272 \text{nm} \) and \( \lambda_{g2}=1562.580 \text{nm} \). Relation between wavelength and stress and fitting line and fitting a straight line is shown as figure 3. When increase the stress, the central wavelength of grating 1 will become longer, while the one of the grating 2 will become shorter.

The date fitting indicates that sensitivity coefficients of grating 1 and 2 are 0.188nm/kg and -0.207nm/kg individually. The change of temperature makes the central wavelengths of the two
grating vary in the same direction, and the sensitivity coefficients of temperature are $0.01071\text{nm/°C}$ and $0.01089\text{nm/°C}$ individually.

So Equation (5) can be transferred as following equation:

$$\begin{bmatrix}
\Delta \lambda_{B1} \\
\Delta \lambda_{B2}
\end{bmatrix} =
\begin{bmatrix}
0.188 & 0.01071 \\
-0.207 & 0.01089
\end{bmatrix}
\begin{bmatrix}
F \\
\Delta T
\end{bmatrix} \quad (6)$$

During the experiment, when the value of force is $0.1\text{kg}$, the ambient temperature is $20\text{°C}$, the data we measured using Equation (6) is: the value of force is $0.0992\text{kg}$, and the temperature change is $0.2\text{°C}$. When the value of force is $0.2\text{kg}$, the ambient temperature is $30\text{°C}$, the data we measured is: the value of force is $0.1983\text{kg}$, and the temperature change is $9.74\text{°C}$. The theoretical arithmetic and experimental result are consistent basically.

5. Error Analysis and Conclusion

5.1. Error Analysis

In case of the range of temperature changes is limited, that’s to say in the range of temperature changes the Elasto-Optical coefficient and Poisson ratio of the material are constant. So the cross sensitivity between stress and temperature is:

$$K_{sT} = (K_T \kappa - 2 p_0 \xi) \lambda_B \quad (7)$$

In Equation (7), $p_0$----effective Elasto-Optical coefficient, $\xi$----Thermo-Optical coefficient.

At the same place of a fiber, read in two Bragg gratings with different wavelength. Because the thermo-optical coefficient and Elasto-Optical coefficient are relative to wavelength, the two coefficients of the two Bragg gratings with different wavelength are different. Stress and temperature are taken simultaneously to the two gratings, consequently simultaneous measurement of stress and temperature is achieved. When the wavelengths of the two Bragg gratings are: $\lambda_{B1}=1300\text{nm}$, $\lambda_{B2}=850\text{nm}$, sensitivity coefficients of stress and temperature are:

$$K_{s1}=0.96\text{pm/με} \quad K_{s2}=0.59 \text{ pm/με}$$
$$K_{T1}=8.72\text{pm/°C} \quad K_{T2}=6.30 \text{ pm/°C}$$

So:

$$K_{sT} \bigg|_{\lambda=1300} = 2.31 \times 10^{-6} \text{ pm/με.°C}$$
$$K_{sT} \bigg|_{\lambda=850} = 0.62 \times 10^{-6} \text{ pm/με.°C}$$

Suppose absolute errors of the change of the stress and temperature are $\delta(\Delta\varepsilon)$ and $\delta(\Delta T)$, equations set of error solution about the change of stress and temperature is as followed:

$$\begin{cases}
0.96\delta(\Delta\varepsilon) + 8.72\delta(\Delta T) - 2.31 \times 10^{-6} \Delta\varepsilon \Delta T &= 0 \\
0.59\delta(\Delta\varepsilon) + 6.30\delta(\Delta T) - 0.62 \times 10^{-6} \Delta\varepsilon \Delta T &= 0
\end{cases} \quad (8)$$

From equations set(8), absolute errors of the stress and temperature are:

$$\begin{cases}
\delta(\Delta\varepsilon) \approx 7.90 \times 10^{-6} \Delta\varepsilon \Delta T \\
\delta(\Delta T) \approx 0.77 \Delta\varepsilon \Delta T
\end{cases} \quad (9)$$

The error analysis of cross sensitivity between stress and temperature indicate that when the measurement range of the stress is $0\text{°C} \sim 100\text{°C}$ and $0\sim 1\%$: the relative error of stress is $0.079\%$, the relative error of temperature is $0.77\%$.

5.2. Conclusion

(1)Double parameters measuring technology of FBG can realize the simultaneous measurement of stress and temperature. (2)Ignoring cross sensitivity between stress and temperature of fiber grating
can less influence measuring results. The smaller measuring range is, the less the error of stress and
temperature caused by ignoring cross sensitivity is. (3) The measuring error of stress is less than error of
temperature caused by cross sensitivity.

This research not only establishes theory foundation, but also provides new measuring though and methods, for oversize bridge, building structure, oil will, railway, highway, tunnel, mine and so on, to implement the long-standing stress distribution monitor and long-term safety monitoring.

References
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