Cubic fitting method of wavelength shift of optical fiber grating temperature sensor and a temperature measuring device

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Abstract. The center wavelength movement of fiber grating reflecting is not strictly linear relationship with the measured temperature due to the influence of grating materials, fiber materials, packaging and other factors. This makes the fiber Bragg grating temperature sensor produce error. In order to improve the accuracy of temperature measurement, the more mature method is to use the conic fitting method to correct the error. This method has good temperature measurement accuracy in the medium-low temperature region (-20.0~80.0°C). But the error of the medium-high temperature region (80.0~140.0°C) increases gradually. In this paper, the cubic fitting method of wavelength shift is proposed and a temperature measuring device is developed by using this method. The method selects the center wavelength of the reflected light at the temperature of 0°C as the reference wavelength and The measured temperature is fitted with the cubic polynomial of the shift $\Delta \lambda$ between the reflected wavelength and the reference wavelength. The temperature measurement experiment shows that this method improves the temperature measurement accuracy of the medium-high temperature zone under the premise of calibration in the medium-low temperature zone.

1. Introduction
The fiber grating temperature sensor has the advantages of compact structure, small size, anti-electromagnetic interference, non-electricity, etc., which makes it have high application value in the field of high voltage, strong interference, strong corrosion, explosion-proof and temperature sensing, in electricity, petroleum, Chemical, coal, construction and other occasions have been widely used [1-5]. At present, the fiber grating temperature sensor technology is still developing and improving. Its package form [6-7], wavelength demodulation method [8-10], precision correction [11], etc. are still being improved and developed, making the fiber grating temperature sensor has been further improved in terms of temperature conduction characteristics, wavelength demodulation sensitivity, and temperature range.

The principle diagram of fiber grating temperature sensor is shown in Figure 1:
When a beam of broad-spectrum light passes through a fiber grating, wavelengths that satisfy the Bragg condition will produce reflections, and the remaining wavelengths continue to propagate through the fiber grating. The spatial density of the grating determines the center wavelength of the reflected light, and gratings of different densities will reflect light of different center wavelengths. When the temperature of the grating changes, the spatial density of the grating also changes, and the center wavelength of the reflected light also moves accordingly. The ambient temperature can be calculated by detecting the center wavelength of the reflected light [12]. At present, the temperature characteristics of fiber gratings are relatively clear. The thermo-optic coefficient and thermal expansion coefficient of the grating are not constant, but have a nonlinear relationship with the measured temperature [12]. For the conventional packaged grating temperature sensor, due to the influence of fiber material, grating material, package and other factors, the central wavelength shift of the reflected light of the grating is also nonlinearly related to the measured temperature. Therefore, after the fiber grating temperature sensor demodulates the center wavelength, the measured temperature needs to be corrected according to the nonlinear relationship. At present, the fiber grating temperature measuring device generally uses the conic fitting method to correct the error [13]. The temperature error of the method in the medium-low temperature region (-20.0~80.0℃) can reach 0.1℃. The conic fitting formula is:

$$\lambda = aT^2 + bT + c$$

In the formula, $\lambda$ is the wavelength of the reflected wave, $T$ is the measured temperature, $a$, $b$ and $c$ are constants and require actual calibration.

2. Wavelength shift cubic fitting method

In this paper, through a large number of experiments on the temperature characteristics of fiber gratings, it is found that the conic fitting correction method is generally calibrated in the medium-low temperature regions, so the conic fitting correction method has better precision in the medium-low temperature regions, but in the medium-high temperature region(80.0~140.0℃), the error can reach 8.0℃, and the error still shows a nonlinear increase trend. In order to further improve the temperature measurement accuracy in the medium-high temperature regions, according to the nonlinear increase of temperature error, a cubic fitting correction method for wavelength shift is proposed. The method takes the center wavelength of the reflected light at a temperature of 0℃ as the reference wavelength. The measured temperature is fitted with a cubic polynomial of the reflected wavelength shift from the reference wavelength $\Delta\lambda$. The temperature measurement experiment shows that the method improves the temperature measurement accuracy of the medium-high temperature zone under the premise of calibration in the medium-low temperature zone, and the temperature error of the medium-high temperature zone falls below 2.0℃. The formula for the cubic fitting method of wavelength shift is:

$$T = k_0 + k_1\Delta\lambda + k_2\Delta\lambda^2 + k_3\Delta\lambda^3$$

In this formula, $T$ is the measured temperature, $\Delta\lambda$ is the wavelength shift relative to the reflection wavelength of a certain reference, $k_0$, $k_1$, $k_2$ and $k_3$ are constants and require actual calibration. Taking the center wavelength $\lambda_0$ of the reflected wave at 0℃ as the reference wavelength, then:
In this case, the fitting formula (2) becomes:

\[ T = k_1 \Delta \lambda + k_2 \Delta \lambda^2 + k_3 \Delta \lambda^3 \]  

In this formula, \( T \) is the measured temperature, \( \Delta \lambda \) is the wavelength shift of the reflected wave with respect to 0℃, \( k_1, k_2 \) and \( k_3 \) are constants, which require actual calibration.

3. Temperature measuring device

The LE-TMS-16 fiber grating temperature measuring device was developed. The fitting method was solidified in the device through software programming. The device can switch 1×16 optical path, and each fiber can be connected in series with 16 temperature measuring gratings. A total of 256 temperature measurement points can be detected, and a large-capacity temperature measurement requirement is satisfied by a single device. Figure 2 is a schematic structural view of the LE-TMS-16 fiber grating temperature measuring device, including a CPU board, an OS board, an ASE board, and the fitting method was solidified in the device through software programming. The device can switch 1×16 optical path, and each fiber can be connected in series with 16 temperature measuring gratings. The wavelength demodulation module and the light source are welded on the ASE board. The CPU sends an optical path switching command to the OS board through the control bus. The OS board sequentially switches 1 to 16 optical fibers. When switching to a certain fiber, the optical fiber turns on the incident light source and enters the light. Propagating along the optical fiber, the reflected light of the grating is also returned through the optical path, and the CPU sends a demodulation command to the wavelength demodulation module on the ASE board through the control bus, and reads out the center wavelength of the demodulated 16 gratings through the data bus, according to The wavelength data calculates the ambient temperature of the current 16 rasters, and stores and displays them; after the calculation is completed, the CPU issues the next switching command to the OS board to process the next fiber, and so on.

4. Temperature measurement experiment and analysis

Set up the temperature calibration system shown in Figure 4. The system consists of high-precision constant temperature oil tank (type: HWC-Y), fiber grating (type: T-04), fiber grating temperature measuring device (type: LE-TMS-16) composition. The temperature adjustment range of the constant temperature oil tank is -20.0~140.0℃, and the fiber grating probe is packaged by Shandong Linkotech Electronic Co., Ltd using its own process.
Table 1. Measured data of a fiber grating.

| Temperature (℃) | Reflective wavelength (nm) | Δλ (nm) |
|-----------------|---------------------------|---------|
| -20.0           | 1557.595                  | -0.190  |
| -10.0           | 1557.683                  | -0.096  |
| 0.0             | 1557.785                  | 0.000   |
| 20.0            | 1557.978                  | 0.193   |
| 30.0            | 1558.077                  | 0.292   |
| 40.0            | 1558.175                  | 0.390   |
| 50.0            | 1558.272                  | 0.488   |
| 60.0            | 1558.382                  | 0.597   |
| 70.0            | 1558.488                  | 0.703   |
| 80.0            | 1558.598                  | 0.813   |
| 90.0            | 1558.703                  | 0.918   |
| 100.0           | 1558.819                  | 1.034   |
| 110.0           | 1558.935                  | 1.150   |
| 120.0           | 1559.050                  | 1.265   |
| 140.0           | 1559.300                  | 1.515   |

According to the measured data of the medium-low temperature zone (-20.0~80.0℃) in Table 1, the coefficients of the conic fitting method are calculated as:

\[ a = 4.17 \times 10^{-6}, \quad b = 9.58 \times 10^{-3}, \quad c = 1557.785 \]

Substituting formula (1) gives:

\[ \lambda = 4.17 \times 10^{-6} T^2 + 9.58 \times 10^{-3} T + 1557.785 \] (4)

Using the same method, according to the measured data of the medium-low temperature zone (-20.0~80.0℃), the coefficient of the cubic fitting method of wavelength shift is calculated as:

\[ k_1 = 104.53, \quad k_2 = -4.26, \quad k_3 = -2.02 \]

Substituting formula (3) gives:

\[ T = 104.53 \Delta \lambda - 4.26 \Delta \lambda^2 - 2.02 \Delta \lambda^3 \] (5)

The temperature values and actual errors calculated according to the fitting formulas (4) and (5), respectively, are shown in Table 2:
Table 2. Temperature calculation results.

| Actual temperature (℃) | Temperature calculated by conic fitting method (℃) | Error (℃) | Temperature calculated by cubic fitting method (℃) | Error (℃) |
|------------------------|-----------------------------------------------|-----------|-----------------------------------------------|-----------|
| -20.0                  | -20.0                                         | 0.0       | -20.0                                         | 0.0       |
| -10.0                  | -10.1                                         | 0.1       | -10.1                                         | 0.1       |
| 0.0                    | 0.0                                           | 0.0       | 0.0                                           | 0.0       |
| 20.0                   | 20.0                                          | 0.0       | 20.0                                          | 0.0       |
| 30.0                   | 30.1                                          | 0.1       | 30.1                                          | 0.1       |
| 40.0                   | 40.0                                          | 0.0       | 40.0                                          | 0.0       |
| 50.0                   | 49.8                                          | 0.2       | 49.7                                          | 0.3       |
| 60.0                   | 60.7                                          | 0.7       | 60.5                                          | 0.5       |
| 70.0                   | 71.2                                          | 1.2       | 70.7                                          | 0.7       |
| 80.0                   | 82.0                                          | 2.0       | 81.1                                          | 1.1       |
| 90.0                   | 92.1                                          | 2.1       | 90.8                                          | 0.8       |
| 100.0                  | 103.3                                         | 3.3       | 101.3                                         | 1.3       |
| 110.0                  | 114.4                                         | 4.4       | 111.5                                         | 1.5       |
| 120.0                  | 125.2                                         | 5.2       | 121.3                                         | 1.3       |
| 140.0                  | 148.7                                         | 8.7       | 141.6                                         | 1.6       |

It can be seen from the comparison of temperature error that the error value of the conic fitting method in the medium-high temperature region gradually increases, reaching 8.2℃ at 140.0℃, and exhibits a nonlinear relationship. The maximum error of the wavelength shift cubic fitting method in the medium-high temperature region is 1.6℃. Figure 5 shows the error comparison of the two correction methods. It can be seen from the figure that compared with the conic fitting correction method, the accuracy of temperature measurement by the wavelength shift cubic fitting correction method is significantly improved.

5. Conclusion
Aiming at the nonlinear increase of the error of the fiber grating temperature sensor conic fitting correction method in the medium-high temperature region (80.0~140.0℃), this paper proposes a cubic fitting correction method for wavelength shift and develops a temperature measuring device. The temperature experiment shows that this method effectively eliminates the nonlinear error. Basing on
using the medium-low temperature region data for coefficient calibration, the temperature measurement accuracy of the cubic fitting method is close to 1% in the medium-high temperature region (80.0~140.0°C) within the experimental range. The method is directed to a conventional packaged fiber grating temperature sensor. For a specially packaged sensor (e.g., a stress compensation package), the adaptability of the method requires further testing and verification.

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