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Investigation on Temperature Sensitivity of Fiber Bragg Grating Sensor under Global Temperature Variations Experience

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Abstract. An experiment was developed to relate the wavelength shifts resulting from temperature changes of fiber Bragg grating (FBGs) to the thermal expansion coefficients. The range of the temperature is set from -60 ℃ to 100 ℃ as the simulation of outer space temperature environment and the experiment results show that the primary wavelength shift of this sensor due to temperature changing is more precise with the secondary polynomial fitting than the theory relatively linear fitting. Consequently, the reason of the difference between the theoretic and the experiment calculation has been analyzed.

1. Introduction

Fiber Bragg grating (FBG) technology is a promising measurement concept for future sensor system applications. It has been extensively proposed recently and utilized especially in monitoring the aerospace structures and materials health condition [1,2]. Compared with many other sensors, such as PZT [3], ICMS, the FBG [4] sensors have many advantages of being lightweight and flexible. In general, the response of FBGs are determined by coupling effect of strain and temperature, and the primary wavelength shift is linear for a broad range of average strain [5], however, for the temperature response of FBGs the main wavelength changing is much more complicated. There are a lot of researches on FBGs temperature sensitivity based on theory and experiment analysis. Wolfgang Eche et al [6]. proposed a distributed sensor network system consisting 12 FBGs to monitoring the structural health of the X-38 spacecraft undergone the temperature range from -40℃ to 200℃ and the strain range of -1000με to 3000με.

In this paper, considering the FBGs temperature sensitivity independently in experiment, then the influence of strain effect is excluded, so the FBGs is in the stress-free state. When the FBGs sensors is under cryogenic temperatures, the FBGs temperature sensitivity becomes more nonlinear. Furthermore, the primary wavelength shifting with the temperature increasing per 5℃ performs better in secondary polynomial fitting than the theory relatively linear fitting. The paper consists two parts, the section II shows the origination of the experiment design, and the section III shows the detail discussion of the experiment results.

2. Experiment design

In this concept, shown in figure 1, Bragg wavelength-shifts are measured to determine temperature effects that act on the grating section. This study building the FBG temperature sensitivity detection experiment platform, contains two major segments as a temperature control system and an optical sensing system (SM125). To simulate the outer spacecraft temperature circumstances, the rang of temperature is set from -60℃ to 110℃ and the rate of its growth is 5℃. To acquire the temperature sensitivity, the temperature control of a temperature box, the four FBG sensors are parallel placed in it under unstressed state. Moreover, an optical sensing system (SM125) are used here to get the reflectivity response of the FBG sensor under different temperatures.

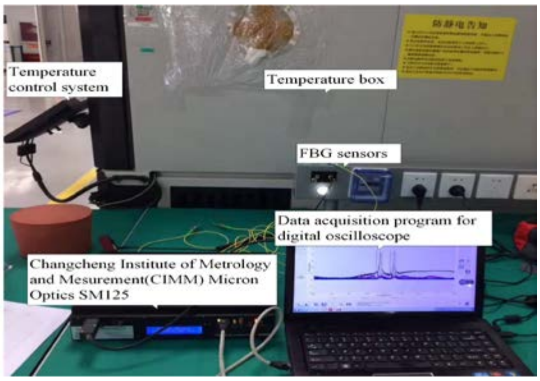


Figure 1. The experiment setup for FBG sensor temperature sensitivity detection system

3. Result and Discussion

The response signal assessed from experiment can be seen in the following figure 2. The lateral axial presents the wavelength and the longitudinal shows the FBG reflectivity spectrum under different temperatures, 0℃,5℃. Obviously, the primary wavelength shift to the longer wavelength with the temperature increasing.

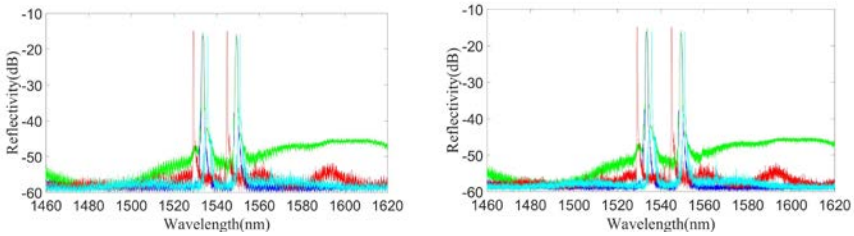
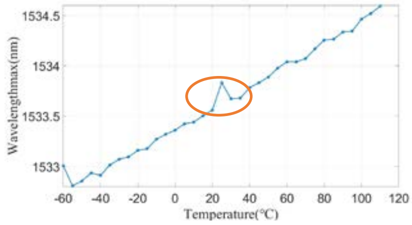
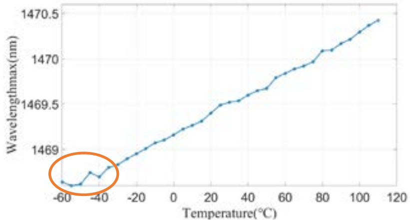


Figure 2. The reflectivity spectrum under temperatures. (a) in the 0℃; (b) in the 5℃.

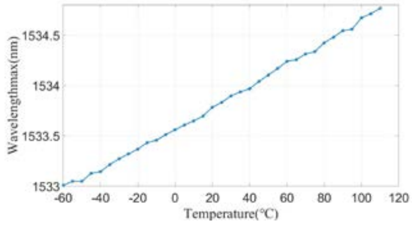
To analysis the relationship between the temperature characteristic primary wavelength shifting and the temperature changing under extreme environment. The features were obtained by extracting from the FBG reflectivity spectrums under the Temperature range from -60℃ to 110℃, and the gradient is 5℃. Then, there are 35 groups experiment data can be processed in this test for each grating position. As mentioned before, the four FBG sensors with eight grating are placed in the temperature box to eliminate the random error. The processed results can be seen in the figure 3, and the axial lateral is the temperature and the longitudinal shows the primary wavelength.



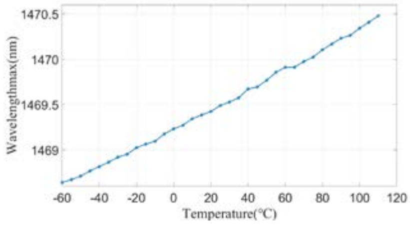
(a) The first grating of the CH1



(b) the second grating of the CH1



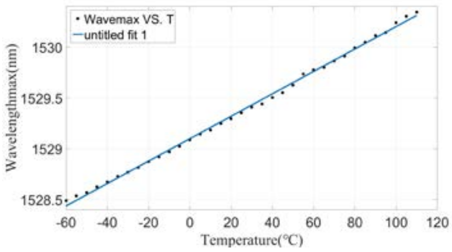
(c) The first grating of the CH2



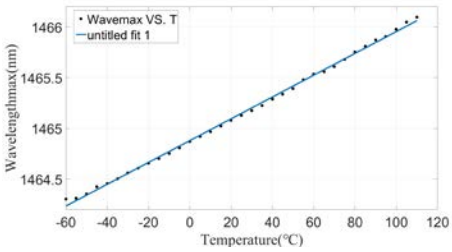
(d) the second grating of the CH2

Figure 3. The primary wavelength changing under different temperature.

The cycles presented in the figure 3. (a) and (b) clearly shows the singularity in wavelength shifting with temperature increasing. These wavelengths shifting may appear randomly for the reason that the other FBGs do not show the same performance. So, the FBG3 and FBG4 are used to analysis the sensitivity coefficient, what's more, in other parts of the diagram, the variation curve between the primary wavelength shifting and the temperature are not satisfied the one-variable linear regression, shown in figure 4. Then, the coefficient of them may not be equal to the theoretical calculation [7] constant coefficient 0.01nm/°C. The error between the experiment coefficient and the theory is result that when the material of fiber grating expands with heat and contracts with cold [8], it appears unusual that the fiber optical and mechanical properties changed experienced different temperature stages.



(a) the first grating position of the CH3 data



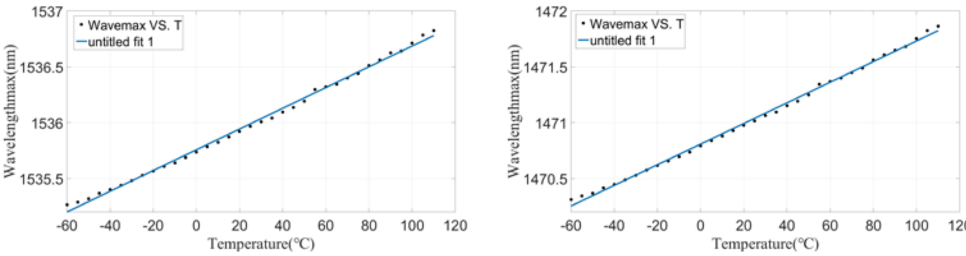
(b) the second grating position of the CH3 data

Figure 4. Linear regression fitting results between primary wavelength and the temperature in CH3

Table 1. The function and the evaluation indicators of the fitting results

Grating position 1	Grating position 2
F (x) = 0.01074x + 1465	F (x) =0.01075x + 1466
SSE： 0.0176	SSE： 0.0177
R-square： 0.9982	R-square: 0.9983
RMSE： 0.02315	RMSE: 0.02316

In the following, we operate the linear and quadratic fitting between the primary wavelength and the temperature. To evaluate the performance of two fitting methods, the three indicators [9] such as, the sum of squares due to error (SSE), Coefficient of determination(R-square) and the Root mean squared error (RMSE) are chosen here to quantitative the fitting performance. The fitting results diagram show the quadratic model fits more successfully than the linear model, shown in figure 5, and the details can be seen in the following tables 1 (CH3) and table 2 (CH4).



(a) the first grating position of the CH4 data (b) the second grating position of the CH4 data

Figure 5. Linear regression fitting results between primary wavelength and the temperature in CH4

Table 2. The function and the evaluation indicators of the fitting results

Grating position 1	Grating position 2
F (x) = 0.00923x + 1472	F (x) = 0.00922x +1471
SSE：0.01931	SSE: 0.01932
R-SQUARE：0.9974	R-square: 0.9975
RMSE: 0.0241	RMSE: 0.0242

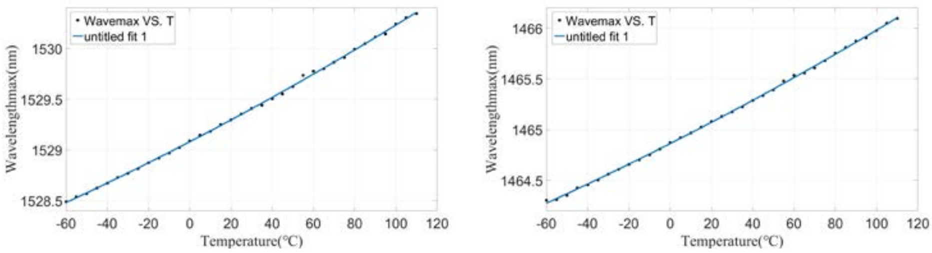
The tables show the linear regression result of the measured Bragg wavelength versus temperature. The theory temperature sensitivity of the FBG is 0.01nm/℃, however the experiment data fitting results are not equal to it with shifting left and right side. Moreover, by calculating the relative error, the results as follows:

$$\delta_2 = \frac{0.01075-0.01}{0.01} \times 100\% = 7.5\% \tag{1}$$

$$\delta_3 = \frac{0.01-0.00923}{0.01} \times 100\% = 7.7\% \tag{2}$$

Moreover, the temperature ranging from 45℃ to 100℃, the coefficients is not following the linear calculating result. When the temperatures are below -40℃, the curve is almost nonsmoothed, i.e., showing fluctuate temperature sensitivity.

In order to choose the beat fitting method and to solve the singularities in the prementioned linear fitting. The quadratic fitting method is proposed here to compare with the theory ideal method. The processing result about CH3 (shown in figure 6) and CH4 (shown in figure 7)can be seen in the following table 3 (CH3) and table 4 (CH4).



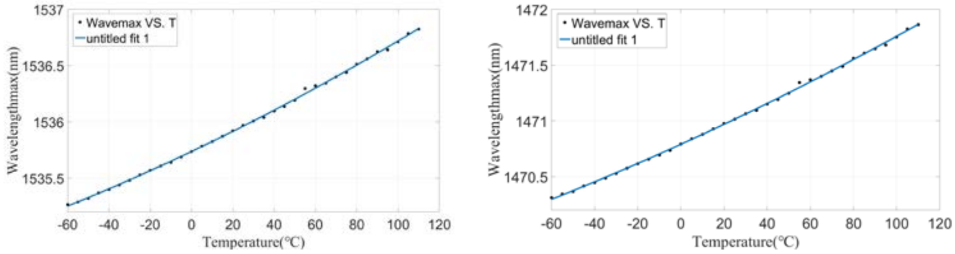
(a) the first grating position of the CH3 data (b) the second grating position of the CH3 data

Figure 6. The quadratic regression fitting results between primary wavelength and the temperature in

CH3

Table 3. The function and the evaluation indicators of the fitting results

Grating position 1	Grating position 2
$\mathbf{F(X) = 0.000009514 * X^2 + 0.01055 * X + 1529}$	$F(X) = 0.000009513 * X^2 + 0.01056 * X + 1529$
SSE: 0.006015	SSE: 0.006016
R-square: 0.9994	R-square: 0.9993
RMSE: 0.01371	RMSE: 0.01372



(a) the first grating position of the CH4 data (b) the second grating position of the CH4 data

Figure 7. The quadratic regression fitting results between primary wavelength and the temperature in CH4

Table 4. The function and the evaluation indicators of the fitting results

Grating position 1	Grating position 2
F (x) = 7.132e-06$* \boldsymbol{X}^2$ +0.01016 $* \boldsymbol{X}$ + 1534	F (x) = 7.131e-06$* X^2$ +0.01017 $* X$ + 1534
SSE: 0.009737	SSE: 0.009735
R-square: 0.999	R-square: 0.999
RMSE: 0.01744	RMSE: 0.01743

In the above discussion about the theoretical linear fitting method and the quadratic fitting methods for CH3 and CH4 data processing. Comparing the three indexes proposed here, the quadratic method has a better performance than the theoretical method. Meanwhile, according to the linear fitting of the wavelength offset and the temperature in curve, it is found that the linear relationship between them is an approximate function, and the constant temperature sensitivity coefficient represents the average of the temperature sensitivity coefficient in a certain temperature range. When the temperature increases over 45°C, the temperature sensitivity coefficient of FBG increases quickly along with the gradually rise of temperature, then, the quadratic relation used to fit the relative primary wavelength drift and temperature has a better effect than linear fitting method.

The reason for the difference between the theoretical calculation value and the experiment value in FBG temperature sensitivity is that the theoretical values are obtained by the mechanical parameters of the fiber grating material. However, in experiment, the original mechanical parameters such as the refractive index and the temperature coefficient have changed after under the temperature difference alternately. Then the temperature sensitivity coefficient which mostly based on the above two fiber parameters will be changed. In practice, if the FBG sensors are used to accurately measure temperature, it is not appropriate to calculate the FBG temperature sensitivity coefficient by using the

FBG material mechanical parameters, moreover, the specific temperature sensitivity coefficient should be determined based on experiment.

4. Conclusions

In this paper, the FBG response signals under different temperature values have been processed to define the temperature sensitivity of the sensor. Comparing the theoretical linear fitting methods, the quadratic fitting model performs better that have the smallest SSE and RMSE, what's more, the R-square is the biggest. Through analysis the error between the linear fitting and the experiment quadratic fitting results, the reason for the difference is that the FBG materials expands with heat and contracts with cold when the fiber grating sensing the temperature gradient. And the FBG reflectivity signal has been changed with the FBG parameters refractive index and the temperature coefficient changed.

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