Temperature-insensitive fiber Bragg grating tilt sensor

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A temperature-insensitive optical fiber tilt sensor is presented. The sensor scheme uses a prestrained fiber Bragg grating to sense the strain, which depends on the tilt angle. To compensate for the temperature effect, materials that have different linear thermal expansion behaviors are used for implementation of the sensor body. The differentiation in the linear thermal expansion would then cause a counter effect to the original temperature effect. Experimental tests show an accuracy of $0.167^\circ$ in tilt angle measurement. A temperature stability better than $0.33^\circ$ over the temperature range from 27 °C to 75 °C is demonstrated. The resolution 0.0067° in tilt angle measurement is achieved by using our preliminary sensor with a dimension of $16 \times 5 \times 5$ cm$^3$. © 2008 Optical Society of America

1. Introduction

Tilt sensors (also known as inclinometers) are required for measuring the angular deflection of an object against a reference plane or line. They are frequently used in the field of aviation (e.g., monitoring for aircraft landing) and civil engineering (e.g., monitoring the inclination of towers and bridge holders). They can also apply to platform levering, boom angle indication, slope angle measurement, etc. Most conventional tilt sensors are of an electronic type, transforming the inclination into electric signals through a magnetic effect [1,2] or capacitive effect [3]. These electronic tilt sensors can achieve a measurement resolution in the order of 0.001° with an accuracy of 0.15°. Optical interferometry was also applied to the tilt angle measurement with about the same resolution [4].

Fiber Bragg gratings (FBGs) have been widely used as sensors for the measurement of temperature, stress/strain [5–7], pressure [8], force [9], acceleration [10], and tilt angle [11–13]. FBGs can provide a compact sensitive means for electromagnetic-interference-free measurement, and can apply to wavelength multiplexing schemes for multipoint measurement. As tilt sensors, FBGs can be configured in pendulum schemes, in which a strain is induced to shift the Bragg wavelengths of the FBGs. Experimental results for temperature-independent measurement of tilt angle variation were reported [11–13] by using such pendulum schemes. These schemes were designed to use two FBGs for eliminating the temperature effect in measuring tilt angle variation in one-dimensional direction. These pendulum-based FBG tilt sensors compare well with the aforementioned non-FBG types because they can offer measurement accuracy and resolution in the same order as those for the non-FBG types. Here, we present a different scheme for a tilt angle measurement, in which only one prestrained FBG is employed to obtain temperature independence in one-dimensional measurement. The paper is organized as follows. Section 2 first describes the operational principle of the FBG tilt sensor, and then the theoretical background of the temperature compensation. Experimental results are shown in Section 3. Then Section 4 concludes this paper.

2. Basic Theory of the Tilt Sensor

The proposed sensor is depicted in Fig. 1, where an FBG is anchored at its two ends (marked by A and B in the figure) between an iron ball and a polyvinyl chloride (PVC) cylinder. The PVC cylinder is fixed at one end onto the inner surface of the aluminum box.
For \(|\theta| \leq 20^\circ\), \(\Delta \lambda\) can be used for linearly calibrating the tilt angle with a maximum error no larger than 2%. However, the accuracy in measuring the tilt angle may strongly be affected by the environmental temperature.

The principle of operation of the proposed temperature-compensated sensor scheme is described as follows. When temperature rises, the iron ball, aluminum box, and PVC cylinder expand longitudinally. The expansion of both the iron ball and the PVC cylinder exerts a compressive strain on the FBG, while the expansion of the aluminum box generates an extensile strain. Because the PVC [with the coefficient of thermal expansion (CTE) \(\sim 78 \text{ ppm}^\circ\text{C}\)] expands more than the aluminum (with the CTE \(23.7 \text{ ppm}^\circ\text{C}\)), the FBG may suffer from a compressive strain, and induce a blueshift in its Bragg wavelength. (Note that the FBG is pretrained when configured into the sensor scheme.) Such a blueshift can be deliberately tailored to match the inherent redshift due to the temperature rise by adjusting the length of the PVC cylinder. Figure 2 shows the experimental sensor scheme with length legend. Here the PVC cylinder goes through a hole made at the end-face wall of the aluminum box, and is fixed by screwing both sides of the PVC cylinder. The length of the PVC cylinder, \(L_1\), can be adjusted by using this mechanism. The reason for the adjustment is that there is slight variation in the CTE of the PVC material from the nominal value given by the handbook.

The required length \(L_1\) for compensating for the temperature effect on the FBG is determined by the
following equation (noting that \(Lt\) is equal to \(L1 + L2 + L3\)):

\[
(L1 \times \alpha_1 + L3 \times \alpha_3 - Lt \times \alpha t)0.0012 \times 10^{-9}/L2 = 0.01 \times 10^{-9}.
\]

(3)

Here, \(\alpha_1, \alpha_3,\) and \(\alpha t\) are, respectively, CTEs of PVC, iron, and aluminum; the numbers \(0.0012 \times 10^{-9}\) and \(0.01 \times 10^{-9}\) account for the strain sensitivity (m/strain) and temperature sensitivity (m/°C), respectively, of the FBG.

3. Experimental Results

In our preliminary experiment, \(L2\) is 3 cm, \(L3\) (the radius of the 357 g iron ball) is 2.25 cm. We substitute these lengths and the coefficients \(\alpha_1 = 78.1 \text{ ppm/°C}, \alpha_3 = 12.3 \text{ ppm/°C}, \alpha t = 23.7 \text{ ppm/°C}\) in Eq. (3) to find \(L1 = 2.24 \text{ cm}\). We then adjust \(L1\) to be 2.3 cm for our experiment. The FBG used in the experiment originally had the Bragg wavelength of 1564.32 nm and prestrained by an increase of 1.2 nm. Figure 3 shows the Bragg wavelength (measured at 27 °C) versus \(|\theta|\), the absolute value of the tilt angle, for the cases of \(\theta > 0\) and \(\theta < 0\). The case for \(\theta > 0\) was done by raising the left end of the aluminum box, i.e., the end marked by (A) in Fig. 2, while the case for \(\theta < 0\) corresponds to raising the end marked by (B). For \(\theta > 0\), the Bragg wavelength increases with the tilt angle; while for \(\theta < 0\), the Bragg wavelength decreases with the angle in the range \(|\theta| < 15°\). Both variations are quite linear. In each line, the circles (filled squares) correspond to the results with increasing (decreasing) \(|\theta|\). The results prove high linearity and repeatability.

To prove the temperature independence of the proposed sensor, we put the sensor in a temperature-controlled box and measured the Bragg wavelength as the temperature rose from 27 °C to 75 °C. Figure 4 shows the measured Bragg wavelengths at various temperatures when the sensor box (i.e., the aluminum box) maintained a horizontal position (i.e., at \(\theta = 0\)). A maximum variation of 0.02 nm (i.e., within ±0.01 nm) in the Bragg wavelength was observed in this temperature range. We then tilted the sensor box and carried out the measurement for \(\theta = \pm 5°\) and \(\theta = \pm 10°\). Figure 5 shows four Bragg wavelength variations with respect to temperature for \(\theta = 5°\) (---), \(\theta = -5°\) (-----), \(\theta = 10°\) (-----) and \(\theta = -10°\) (--------), respectively. Note that the sensor box was tilted in the temperature-controlled box by raising the (A) end to obtain a positive \(\theta\) and by raising the (B) end for a negative \(\theta\). It can be seen from Fig. 5 that the Bragg wavelength varies within a span of 0.04 nm (i.e., ±0.02 nm) for each case, when the temperature changes in the range as indicated. In comparison, an uncompensated FBG would have a Bragg wavelength shift of 0.48 nm for the temperature rise.

Although conventional electronic tilt sensors have a relatively small dimension, the dimension of the proposed FBG sensor is about the same as the previous optical counterparts. The proposed sensor has a dimension of \(16 \times 5 \times 5 \text{ cm}^3\). The dimension of the sensor in [4] is \(11 \times 13 \times 2.15 \text{ cm}^3\); the sensor in [11] has a dimension larger than \(9.8 \times 9.8 \times 4.7 \text{ cm}^3\); the sensor in [12] has a diameter of 16 cm and a height of several cm; the sensor in [13] has a length of larger than 12.8 cm and a diameter of several cm.

4. Discussion

The measurement sensitivity is estimated to be 0.06 nm/degree from Fig. 3. The maximum discrepancy in the measurement results (shown in Fig. 3)
when the tilt angle increases from 0° to 15° and decreases from 15° to 0° is ±0.01 nm, corresponding to an accuracy of ±0.167° [which is obtained as (±0.01 nm)/(0.06 nm/degree)]. The resolution of our wavelength interrogator is 0.0004 nm, corresponding to a resolution of 0.0567° [=0.0004 nm/(0.06 nm/degree)] for the tilt angle measurement. The performance can be improved by using a heavier ball. The thermal error of ±0.02 nm in the Bragg wavelength shift corresponds to an error of ±0.33° in tilt angle.

To see the measurement sensitivity at different temperatures, we show in Fig. 6 the Bragg wavelengths for θ = 0°, 5°, and 10° at the temperature of 55 °C. It can be seen that the measurement sensitivity may change a little bit at other different temperatures. It should be noted that the measurement error is deduced here in a straightforward manner. A more rigid theoretical analysis based on the work in [5] would demonstrate more accurately how well the proposed measuring technique will actually work. Here we estimate the maximum measurement error resulting from the thermal instability and the error in wavelength reading. In using the previous model to analyze our sensor, however, it is noted that only the Bragg wavelength shift (i.e., Δλ) is measured to recover the measurand, i.e., the tilt angle θ. It can be seen next that such an analysis gives almost the same prediction for the measurement error as the previously estimated, which is ±0.33°. Ideally, the Bragg wavelength shift is written as λ = λ₀ + δλ, where λ and θ are expressed in nm and degree, respectively; the numeral 0.06 comes from the measurement sensitivity (which is in nanometers per degree). In present case, it is reasonable to assume that there exists an error in measuring λ and a recovering error in θ. Therefore one can write

\[ \lambda = \lambda_0 + \delta \lambda = K \Delta T + 0.06(\theta_0 + \delta \theta), \]

where λ₀ and θ₀ are, respectively, true values of λ and θ (i.e., λ₀ = 0.06θ₀); δλ and δθ represent, respectively, the error in λ and θ; K (in nm per °C) is a parameter to introduce the thermal instability of the sensor within the temperature change ΔT. From the experimental results shown in Figs. 4 and 5, the value of KΔT should be located within ±0.02 nm, i.e., |KΔT| ≤ 0.02 nm for the temperature range from 27 °C to 75 °C. The error δθ in recovering the tilt angle is then found as

\[ \delta \theta = (\delta \lambda - K \Delta T)/0.06. \]

The maximum error in θ can therefore be expressed as

\[ |\delta \theta|_{max} = (|\delta \lambda|_{max} + |K \Delta T|_{max})/0.06. \]

In the experiment, |δλ|_{max} and |KΔT|_{max} are 0.0004 nm and 0.02 nm, respectively, the former being the resolution of the wavelength interrogator used. Thus, the maximum error in tilt angle would be ±0.34°, which is quite close to the previously predicted, i.e., ±0.33° (because the error induced by the thermal effect dominates).

5. Conclusion

We have presented a new FBG tilt sensor, which uses composite materials to compensate for the temperature effect. A blueshift in the Bragg wavelength is

![Fig. 6. Measured Bragg wavelengths for θ = 0°, 5°, and 10° (see the circles) at the temperature of 55 °C.](image-url)

Table 1. Relative Performance of Current Tilt Angle Measurement Systems

<table>
<thead>
<tr>
<th>System</th>
<th>Accuracy (degree)</th>
<th>Resolution (degree)</th>
<th>Temperature Instability (degree)</th>
<th>System Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>[2]</td>
<td>0</td>
<td>0.005–0.05</td>
<td>±0.14 (for 0° tilt)</td>
<td>Electronic</td>
</tr>
<tr>
<td>[3]</td>
<td>0.15 (for ±30°)</td>
<td>0.02</td>
<td>±0.5 (for 5° tilt)</td>
<td>Electronic</td>
</tr>
<tr>
<td>[4]</td>
<td>0.0026 (for 2°)</td>
<td>0.004 (for 17°)</td>
<td>±0.04 (over 100 °C range)</td>
<td>Optical</td>
</tr>
<tr>
<td>[11]</td>
<td>±0.1</td>
<td>0.007</td>
<td>±0.13 (for 30 °C–70 °C)</td>
<td>Optical (using FBG)</td>
</tr>
<tr>
<td>[12]</td>
<td>±0.13</td>
<td>0.02</td>
<td>0.3% of a tilt angle (for 10 °C–60 °C)</td>
<td>Optical (using FBG)</td>
</tr>
<tr>
<td>[13]</td>
<td>±0.06</td>
<td>0.002</td>
<td>±0.06 (for 23.6 °C–26.6 °C)</td>
<td>Optical (using FBG)</td>
</tr>
<tr>
<td>The proposed</td>
<td>±0.167 (over ±15°)</td>
<td>0.0067 (over ±15°)</td>
<td>±0.167 (for 0° tilt) 27 °C–75 °C</td>
<td>Optical (using FBG)</td>
</tr>
</tbody>
</table>

*Data unavailable.*
produced to counterbalance the inherent thermally induced redshift as the surrounding temperature rises. To compare the performance between the proposed sensor and previous works, we list in Table 1 the measurement accuracies, resolutions, and temperature instabilities that are achieved. The proposed FBG sensor is almost as accurate as those in [3] and [12], while it provides a resolution as good as those current state-of-the-art sensors can offer. The temperature stability of the proposed sensor can also compete with some current sensors.

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