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Thermal effects of fiber sensing coils in different winding pattern considering both thermal gradient and thermal stress

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ABSTRACT

By studying the temperature gradient and thermal stress of the difference-winding interferometric fiber optic gyroscope (IFOG) sensing coils, the improvement of the IFOG's temperature performance is realized. A new turn-by-turn quantization thermal-induced bias error model including the traditional "pure Shupe effect", elastic strain interactions and elasto-optical interactions are established. Compared with the traditional "pure Shupe effect" model, the experimental results show that the new model can more fully describe the thermal effect of the coils. Based on the temperature and stress distribution models mentioned above, the effects of the fiber coils with the quadrupolar (QAD) winding pattern, octupolar winding pattern and cross winding pattern on the temperature performance of IFOG are simulated under the same temperature gradient, respectively. The results show that the elastic strain and the elasto-optical effect must be considered when calculated the thermal-induced bias error of the fiber coil. Furthermore, we also come to the conclusion that cross-winding coil of the IFOG have more wonderful temperature performance than the fiber coil with quadruple winding and octupole-winding.
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1. Introduction

Interferometric fiber optic gyroscope (IFOG) has been evaluated as the new solid-state inertial rotation sensor, with the properties of high reliability, low cost, strong impact resistance, wide dynamic range [1,2]. The performance of the sensitive coil in the IFOG affects directly the precision of the IFOG. As we all know, the thermal-induced drift is one of major factors impairing the coil performance [3,4]. A typical IFOG coil consists of multilayer winding of optical fiber with a large number of turns, and the winding quality of the fiber coil affects directly the thermal performance of the IFOG. To evaluate and improve the quality of the fiber coil, novel winding patterns are proposed, such as QAD winding pattern, octupolar winding pattern and cross winding pattern [5–10]. Most researchers have gone into investigation of the "pure Shupe effect" in the fiber coil with different winding [11–15], while have given less attention to the nonreciprocity phase shift induced by the thermal stress [16–20] with the different winding.

To the best of our knowledge, this is the first report about the coils' temperature performance considering of both thermal gradient and thermal stress with different winding. In order to describe more accurately thermal-induced drift phase in an IFOG fiber coil, a two-dimensional (2-D) heat-conduction model with an accuracy of turns is introduced. Moreover, by the 2-D model, the temperature distribution and thermal stress in the fiber coil can be obtained and a general discretization thermal-induced bias error expression can also be deduced. By using the bias error expression, the quantitative analysis of the thermal-induced shift of the coil with QAD winding pattern, octupolar winding pattern and cross winding pattern could be realized.

2. Theory

At first, the "pure Shupe effect" [3] is introduced for a description of the thermal in a Sagnac interferometer. The phase ϕ of a wave propagating in a piece with fiber of length l is shown in Eq. (1).

$$\phi(l) = \beta_0 nl + \beta_0\left(\frac{\partial n}{\partial T}\Delta T + n\alpha\Delta T\right)l \tag{1}$$

where β_0 is the free space propagation constant, n is the refractive index of the fiber, ΔT is the temperature change, $\partial n/\partial T$ is the temperature coefficient and α is the thermal expansion coefficient of the fiber. However, varying temperature can cause the change of mutual extrusion pressure between the fiber coating and silica fiber, which resulted in the extrusion on the silica fiber and subsequently the change of the fiber length l corresponding to the elastic deformation and the change of the fiber refractive index

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corresponding to the elasto-optical effect [21–26]. So it is necessary to take into account the nonreciprocal phase shift which is caused by the elastic strain and the elasto-optical effect [27–28]. The difference of thermal expansion between coating and glue materials of the coil at different temperature is obvious. When temperature rises or drops, the thermal stress of the silica fiber will change. Here, we take a l length typical fiber in a fiber coil as example. Once the fiber coil temperature varies, the pressure acting on the silica fiber will also change. Then, pressure causes the length and the refractive index of the fiber changing. The following Eq. (2) describes the phase shift with changing pressure.

$$\Delta\phi(l) = \beta\Delta l + l\Delta\beta = \beta l\frac{\Delta l}{l} + l\frac{\Delta\beta}{\Delta n}\Delta n \tag{2}$$

assuming $\beta \approx n\beta_0$, $d\beta/dn \approx \beta_0$, $\Delta l/l \approx \varepsilon_z$, Eq. (2) can be rewritten as Eq. (3).

$$\Delta\phi(l) = \beta_0 \ln \varepsilon_z + \beta_0 l\Delta n \tag{3}$$

where ε_z is the longitudinal strain of the fiber and Δn is the refractive index variation of the fiber. In the fiber coil, it can be considered approximately that the thermal-induced pressure in the fiber only exists in the transverse direction. According to the linearly polarized light theory and the theory of elasticity, the change of fiber refractive index induced by thermal stress can be described in Eq. (4).

$$\Delta n = -\frac{1}{2}n^2\left(P_{11}\varepsilon_x + P_{12}\varepsilon_y + P_{12}\varepsilon_z\right) \tag{4}$$

where P_{11} and P_{12} are photoelastic coefficients, ε_x, ε_y and ε_z are the horizontal transverse strain, vertical transverse strain and longitudinal strain, respectively. The relationship between stress and strain in three orthogonal directions is shown in Eq. (5).

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \varepsilon_{yz} \\ \varepsilon_{zx} \\ \varepsilon_{xy} \end{bmatrix} = \begin{bmatrix} 1/E & -\nu/E & -\nu/E & 0 & 0 & 0 \\ -\nu/E & 1/E & -\nu/E & 0 & 0 & 0 \\ -\nu/E & 1/E & 1/E & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/G & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/G & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/G \end{bmatrix} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \sigma_{yz} \\ \sigma_{zx} \\ \sigma_{xy} \end{bmatrix} \tag{5}$$

where $\sigma_i (i = x, y, z)$ and $\sigma_j (j = yz, zx, xy)$ are normal and shear stresses in three orthogonal directions, $\varepsilon_i (i = x, y, z)$ and $\varepsilon_j (j = yz, zx, xy)$ are linear and shear strains in three orthogonal directions, ν is Poisson's ratio, E is modulus of elasticity, and G is the shear modulus of elasticity. Considering the silica fiber length much longer than the silica fiber cross-section diameter of the fiber coil, the longitudinal stress can be ignored [19,29]. Therefore, the stress σ can be expressed in Eq. (6).

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \sigma_{yz} \\ \sigma_{zx} \\ \sigma_{xy} \end{bmatrix} = \begin{bmatrix} -P(T) \\ -P(T) \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{6}$$

where $P(T)$ is the thermal stress value. A new Eq. (7), which stands for the change of phase shift caused by changing thermal-induced pressure, can be obtained by integrating Eqs. (2)–(6).

$$\Delta\varphi(l) = \beta_0\frac{2\nu n}{E}\Delta P(T)l + \beta_0\frac{n^3}{2E}\left[(1-\nu)p_{11} + (1-3\nu)p_{12}\right]\Delta P(T)l \tag{7}$$

where $\Delta P(T) = P(T_t) - P(T_0)$. Taking into account the elastic strain and elasto-optical effect, Eq. (1) can be expressed completely as Eq. (8).

$$\phi(l) = \beta_0 nl + \beta_0\left(\frac{\partial n}{\partial T}\Delta T + n\alpha\Delta T\right)l + \beta_0\left\{\frac{2\nu n}{E} + \frac{n^3}{2E}\left[(1-\nu)p_{11} + (1-3\nu)p_{12}\right]\right\}\Delta P(T)l \tag{8}$$

Integrating both partial waves in the Sagnac interferometer with their respective time dependency leads to the Sagnac phase. Eq. (8) can be written as Eq. (9).

$$\Delta\phi(t) = \frac{\beta_0}{c}\int_0^L\left[\left(\frac{\partial n}{\partial T} + n\alpha\right)\dot{T}(l,t)\right](L-2l)dl + \frac{\beta_0}{c}\int_0^L\left[\frac{2\nu n}{E} + \frac{n^3}{2E}\left((1-\nu)p_{11} + (1-3\nu)p_{12}\right)\right]\dot{P}(T(l,t))(L-2l)dl \tag{9}$$

where L is total length of the fiber, $\dot{T}(l,t)$ is temperature change rate at position l, and $\dot{P}(T(l,t))$ is pressure change rate at position l. This result (Eq. (9)) can be extended further to describe the apparent rotation rate error (shown in Eq. (10)) [7].

$$\Omega_E(t) = \frac{n}{DL}\int_0^L\left[\left(\frac{\partial n}{\partial T} + n\alpha\right)\dot{T}(l,t)\right](L-2l)dl + \frac{n}{DL}\int_0^L\left\{\frac{2\nu}{E} + \frac{n^2}{2E}\left[(1-\nu)p_{11} + (1-3\nu)p_{12}\right]\right\}\dot{P}(T(l,t))(L-2l)dl \tag{10}$$

where D is the effective diameter of the fiber coil. In Eq. (10), the 1st term describes thermal-induced bias error and the 2nd term describes thermal stress-induced bias error.

In order to calculate the total thermal-induced rate error $\Omega_E(t)$ quantificationally, it is necessary to discretize the coil. To increase efficiency, the thermal symmetry of optical fiber coils is considered. The three-dimensional (3-D) model can be simplified to two-dimensional (2-D) model. The total L length fiber is divided into M layers and each layer contains N turns, total optic fiber turns is MN. Then Eq. (10) is rewritten to get a numerical value expression (Eq. (11)).

$$\Omega_E(t) = \frac{n}{DL}\sum_{i=1}^{MN}\left(\frac{\partial n}{\partial T} + n\alpha\right)\dot{T}(l_i,t)\left(L-2l_i\right)dl_i + \frac{n}{DL}\sum_{i=1}^{MN}\left\{\frac{2\nu}{E} + \frac{n^2}{2E}\left[(1-\nu)p_{11} + (1-3\nu)p_{12}\right]\right\}\dot{P}\left(T\left(l_i,t\right)\right)\left(L-2l_i\right)dl_i \tag{11}$$

where l_i is the starting point coordinates of ith turn fiber, dl_i is the length of ith turn fiber, $\dot{T}(l_i,t)$ is temperature change rate of ith turn fiber, and $\dot{P}(T(l_i,t))$ is pressure change rate of ith turn fiber.

3. Simulation and experiment

Fig. 1 shows the partial section of the fiber coil and the geometric parameters of the fiber coil are derived from our QAD-wound IFOG products. Different winding patterns of the fiber coil are shown in Fig. 2, which indicates the winding direction and position of each turn. Fig. 2(a–c) represented the QAD winding pattern, octupolar winding pattern and cross winding pattern, respectively. And the layer number of each optical coil model is 40, and each layer has 68 loops. A L length fiber is circled from the midpoint, using color-coded circles to distinguish each side of the coil fiber. The red arrow and blue arrow indicate the winding direction to each side of the optical fiber, respectively. The yellow

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