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Reduction of the Shupe effect in interferometric fiber optic gyroscopes: The double cylinder-wound coil

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ABSTRACT

For the first time, we introduce a novel double-cylinder winding method for reducing the Shupe effect in interferometric fiber optic gyroscopes (IFOGs). Simulation by finite element method (FEM) is performed to calculate the dynamic temperature distribution of fiber coils, which can obtained thermal-induced rate errors in IFOGs with cross-wound coil and double cylinder-wound coil respectively. Simulation results reveal that thermal-induced rate errors in IFOGs by both winding methods can be substantially reduced under the same variable temperature conditions, but the latter has a simpler winding technology. This study is promising for reducing the temperature fragility of IFOGs.

1. Introduction

The Shupe effect [1] is well known as a main contributor to the signal drift in interferometric fiber optic gyroscopes (IFOGs), which is exposed to a change in temperature. A standard solution to the problem is to wind a coil in such a manner that lengths of fiber which are equidistant in phase from the center of the interferometer are positioned so as to be as close together as possible. Therefore, most researchers are committed to investigate the winding methods for fiber coil [2–8], and some advanced winding methods have been investigated, such as quadrupolar (QAD) winding [2], octupole winding [3], cross winding [4] and cross-over-free winding [5]. The cross winding may be the most efficient winding method in terms of thermal error suppression. However, the technological process complexity of the fiber coil with cross winding cannot be ignored. Recently, a multi-loop reversible thermal control system of time-variant temperature fields has been proposed as an alternative to suppress thermal-induced error of IFOGs [9,10]. But the size, the weight, and the cost of IFOGs will be increased inevitably. Comparatively, the temperature error compensation method is a purely mathematical approach which can guarantee the precision of IFOGs just by establishing the error model based on IFOGs' temperature characteristics to compensate errors by software without extra facilities and equipment. But the purely mathematical approach needs masses of prior data, which limits its practical application [11–13].

In our previous studies, a new designed heat-off spool which meshes with cross-wound fiber coil is proposed and results show that this method can effectively improve the IFOGs' temperature performance [14]. Meanwhile a novel two-dimensional (2-D) heat-conduction model is established by our research team and it is concluded that the cross-wound coil of IFOGs has a more wonderful temperature performance than that with quadruplar or octupolar winding pattern [15]. But it is difficult to implement the cross winding technology in practice because the alternating layer pair geometry tends to produce great winding flaws. Therefore, we need to redesign an operable and simple winding method so that the winding process can not only overcome the alternating layer pair geometry flaw problems but also keep the greatest degree spatial symmetry length for fiber coil. It is critical that the winding method can keep the greatest degree spatial symmetry length for fiber coil. If optical fiber segments are equal distance apart from the coil center, and the fiber coil is given with an up and down plane symmetric temperature field, the total thermal-induced phase shift could vanish. After a detailed mechanism analysis, we propose a simple double-cylinder winding method. However, based on the winding characteristic, the double-cylinder coil itself is not capable of solving problem caused by the drastic temperature field fluctuations. We might be able to use the new designed heat-off spool [14] to maintain the up and down plane symmetric temperature distribution for the fiber coil with this simple

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winding method. This scheme may be promising which can make complicated matter simplified.

2. Theory

Based on the aforementioned analysis, a novel double-cylinder winding is proposed in this paper as illustrated in Fig. 1(b), meanwhile Fig. 1(a) shows the cross winding pattern. Comparing Fig. 1(a) with (b), the common point is that both sides of the fiber coil midpoint in each layer are symmetrically distributed. Therefore, both winding methods could achieve the greatest degree spatial symmetry for fiber coil. However, Fig. 1(a) shows interleave winding complexity of cross winding pattern, while Fig. 1(b) describes a simple cylinder winding process. In Fig. 1, the red arrow and blue arrow indicate the winding direction to each side of optical fiber, respectively. The yellow rectangle section, big hollow circle section (the gray) and small circle section (the white or blue) in Fig. 1 represent glue material, coating and silica fiber core of the fiber coil, respectively.

Generally, the phase ϕ of a wave propagating in a piece of fiber length l is shown in Eq. (1) [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. Considering the angular error over the whole fiber length, the nonreciprocal phase shift $\phi(t)$ induced by the Shupe effect can be expressed as Eq. (2).

$$\Delta\phi(t) = \frac{\beta_0}{c}\int_0^L\left[\left(\frac{\partial n}{\partial T} + n\alpha\right)\dot{T}(l, t)\right](L - 2l)dl, \tag{2}$$

where L is total length of the fiber, and $\dot{T}(l, t)$ is the temperature change rate at position l.

Sagnac interferometers are used for rotation detection. Then, the phase difference is related to L, D (loop diameter) and the measurand Ω (rotation rate of the loop about its axis) through Eq. (3).

$$\Delta\phi(t) = \frac{2\pi LD}{\lambda_0 c}\Omega, \tag{3}$$

As a rule, the $\partial n/\partial T$ value is approximately equal to 10^{-5}/°C, and $n\alpha$ has a smaller magnitude than $\partial n/\partial T$, so $n\alpha$ can be ignored. Eqs. (2) and (3) yields the apparent rotation rate error induced by thermal transients as Eq. (4).

$$\Omega_E(t) = \frac{n}{DL}\int_0^L\left(\frac{\partial n}{\partial T}\dot{T}(l, t)\right)(L - 2l)dl, \tag{4}$$

Considering the structure characteristics of the cross-wound coil and double cylinder-wound coil, both have a wonderful axial symmetry. Therefore, in order to raise efficiency, the three-dimensional (3-D) model can be simplified to two-dimensional (2-D) model. Based on the approach given by Mohr F. [16], a numerical expression of $\Omega_E(t)$ is shown in Eq. (5).

$$\Omega_E(t) = \frac{n}{DL}\sum_{i=1}^{MN}\left(\frac{\partial n}{\partial T}\dot{T}(l_i, t)\right)(L - 2l_i - dl_i)dl_i, \tag{5}$$

where l_i, dl_i, and $\dot{T}(l_i, t)$ indicate the starting point coordinates, the length, and temperature change rate respectively of ith turn fiber, and MN is the total loop number of the fiber coil.

3. Simulation and experiment

It is clear to see from Fig. 1(b) that the double-cylinder winding coil itself is not capable of solving problem caused by the axial temperature gradient fluctuations. Meanwhile the cross winding method is also sensitive to the axial temperature gradient. Therefore, for better comparing the temperature performance of both winding methods, the sensitivity of axial temperature gradient should be decreased firstly. As we know, air is a good thermal insulating material if convection is cut off by the exterior and interior packing. A suitable heat-off spool [14] based on this theory is proposed by our research team as illustrated in Fig. 2.

3.1. Heat-off spool

As you can see from Fig. 2, the outer shield is used to equalize the surface temperature by smoothing the local heat sources, which break the asymmetry of heat flows. The shield is made of an alloy-al material with a high thermal conductivity. The air layer with low thermal conductivity arranged within the outer shield also serves as a shield of the other kind: it prevents the thermal waves from penetrating into the coil, thus reducing the rate of temperature change throughout the coil volume. As a second shield, air can be employed, exhibiting low thermal conduction. In

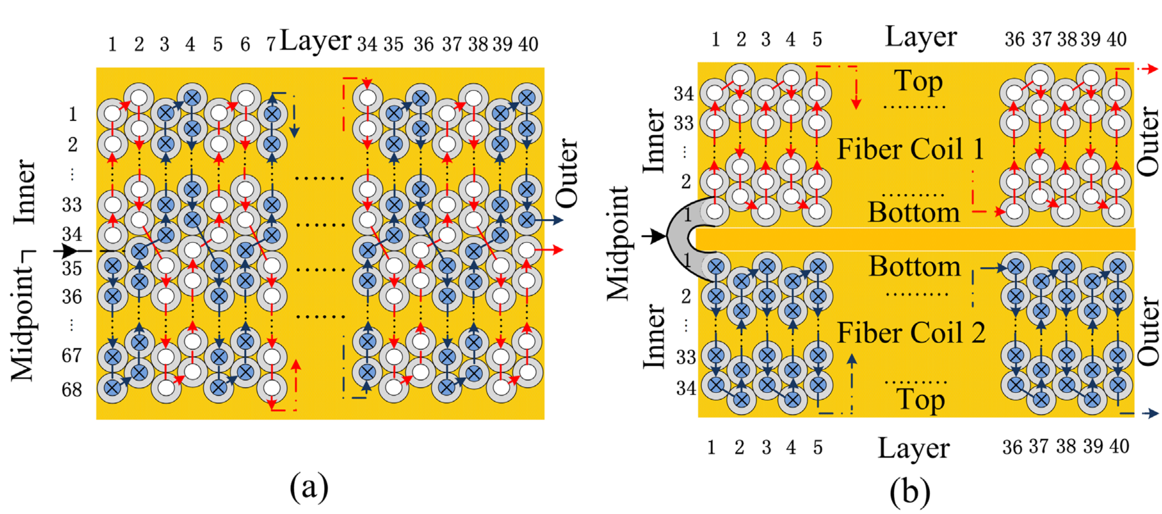

Fig. 1. (a) Cross winding pattern, and (b) double-cylinder winding pattern. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)