Bias phase and light power dependence of the random walk coefficient of fiber optic gyroscope

Jian Mi (米 剑)[1], Chunxi Zhang (张春熹)[2], Zheng Li (李 铮)[1], and Zhanjun Wu (邬战军)[2]

[1]*School of Electronic Engineering, Beihang University, Beijing 100083*

[2]*School of Instrument Science and Opto-Electronic Engineering, Beihang University, Beijing 100083*

Received February 16, 2006

Taking account of shot noise, thermal noise, dark current noise, and intensity noise that come from broad band light source, the dependence of the random walk coefficient of fiber optic gyroscope (FOG) on bias phase and light power is studied theoretically and experimentally. It is shown that with different optical and electronic parameters, the optimal bias phase is different and should be adjusted accordingly to improve the FOG precision. By choosing appropriate bias phase, the random walk coefficient of the aim FOG is reduced from 0.0026 to 0.0019 deg./h$^{1/2}$.

OCIS codes: 130.2790, 060.2370, 060.2800.

Although much research has been done on fiber optic gyroscope (FOG)[1], the precision parameter bias stability of this kind of sensors is limited to 0.01 deg./h up to now in China. The same parameter of Honeywell HPFOG is 0.0003 deg./h[2]. And this is the highest level product as we know. Any improvement based on this is difficult and meaningful.

The precision of FOG is limited by its noise level and the involved signal processing technology. The random walk coefficient (RWC) parameter represents the precision of FOG and describes the noise level of the system. To improve the precision is to depress the noise and increase the useful signal. Lefver[3] have pointed out that the precision of FOG is related with the bias phase and describes the relationship by a simple formula that just consideres the shot noise, it is better that the bias phase is set nearly to ±180°.

Well in practice, the bias phase dependence of RWC is not as clearly as it has been described in the Ref. [3]. The RWC is somehow dependent on both light power and bias phase. In daily application, the bias phase is usually set to 90° to get the best sensitivity. Although there is someone who wants to change the location of bias phase to restrain the noise, but the optimal bias phase is difficult to be located. In this letter, the bias phase and light power dependence of precision of FOG are confirmed. If all the needed optical and electronic parameters are acquired, the optimal bias phase can be calculated accurately.

Since the RWC reflects the noise level of FOG, to improve the precision of FOG we must improve the signal-to-noise ratio (SNR) of FOG. The detected signal SNR of FOG can be described by

$$\mathrm{SNR_d} = i_\mathrm{d}^2/i_\mathrm{n}^2, \tag{1}$$

where i_d is the detected current which is in direct proportion to the light power, i_n is the unwanted current that comes from various noises. However the SNR of FOG is not the detected signal SNR, because the rotation signal does not come from the light power, but come from the change of light power that induced by rotation speed. The rotation speed SNR of FOG is

$$\mathrm{SNR} = [i'_\mathrm{d}(\phi_\mathrm{b})]^2/i_\mathrm{n}^2, \tag{2}$$

where ϕ_b is the bias phase. $i'_\mathrm{d} = \eta P_\mathrm{d}$, η is the responsibility of the opto-electronic detector, and P_d is the light power that is described by

$$P_\mathrm{d} = P_0\left[1 + \cos\left(\Delta\phi_\mathrm{S} + \phi_\mathrm{b}\right)\right], \tag{3}$$

where $\Delta\phi_\mathrm{S}$ is Sagnac phase and considered to be zero here. P_0 is the total light power that arrives at the detector. So we have

$$i'_\mathrm{d}(\phi_\mathrm{b}) = \eta P_0 \sin\left(\phi_\mathrm{b}\right). \tag{4}$$

The most common used receiver in FOG is PIN-FET detector. The main noises of PIN-FET are thermal noise, shot noise, dark current noise, and intensity noise that come from broad band light source. There is no generation-recombination (GR) noise in PIN-FET detector. With the high frequency modulation and demodulation, $1/f$ noise is eliminated also. So we have

$$i_\mathrm{n}^2 = \overline{i_\mathrm{T}^2} + \overline{i_\mathrm{sn}^2} + \overline{i_\mathrm{in}^2}, \tag{5}$$

where i_T is thermal noise current, i_sn is shot noise current, i_in is intensity noise current, respectively. Thermal noise current comes from the inside resistance of PIN-FET, and can be described by

$$\overline{i_\mathrm{T}^2} = \frac{4K_\mathrm{B}T\Delta f}{R_\mathrm{L}}, \tag{6}$$

where K_B is the Boltzmann constant 1.38×10^{-23}. T is the absolute temperature. R_L is the inside resistance of PIN-FET. Δf is the detecting frequency band width. Shot noise is the terminal noise that comes from the statistical characteristic of photon and electron stream. Shot noise cannot be terminated by any method, unlike other kind of noise. Shot noise current is described by

$$\overline{i_\mathrm{sn}^2} = 2e\left(i_\mathrm{d} + i_\mathrm{s}\right)\Delta f, \tag{7}$$

where i_d is the dark current, i_s is the detected current, $e = 1.6 \times 10^{-19}$ C is the single electron charge . Intensity noise comes from the random beat of the different wavelengths of the broad band light source. Intensity noise current is

$$\overline{i_{\mathrm{in}}^2} = i_{\mathrm{s}}^2 \Delta f / \Delta \nu, \tag{8}$$

where $\Delta\nu$ is the spectral width in frequency that can be calculated by $\Delta\nu = c\Delta\lambda/\lambda^2$. c is the light speed in vacuum. $\Delta\lambda$ is the integral spectral width of light source. λ is the mean wavelength of light source.

With all the variable parameters being considered, the SNR of FOG is

$$\mathrm{SNR} = \frac{\eta^2 P_0^2 \sin^2(\phi_{\mathrm{b}})}{(2ei_{\mathrm{s}} + 2ei_{\mathrm{d}} + 4K_{\mathrm{B}}T/R_{\mathrm{L}} + i_{\mathrm{s}}^2/\Delta\nu)\,\Delta f}, \tag{9}$$

where $i_{\mathrm{s}} = \eta P_0 [1 + \cos(\phi_{\mathrm{b}})]$, so Eq. (9) becomes

$$\mathrm{SNR} = \eta^2 \sin^2(\phi_{\mathrm{b}}) \cdot \left\{ \left(\frac{2e\eta[1+\cos(\phi_{\mathrm{b}})]}{P_0} + \frac{2ei_{\mathrm{d}}}{P_0^2} + \frac{4K_{\mathrm{B}}T/R_{\mathrm{L}}}{P_0^2} + (\eta[1+\cos(\phi_{\mathrm{b}})])^2/\Delta\nu \right) \Delta f \right\}^{-1}. \tag{10}$$

The dependence of SNR on the bias phase and light power is not easy to be confirmed. Figure 1 shows the SNR described by Eq. (10), all the parameters are the real data of the experimental FOG. They are $\eta = 0.94$ A/W, $i_{\mathrm{d}} = 3$ nA, $T = 300$ K, $R_{\mathrm{L}} = 1$ kΩ, $\Delta\lambda = 30$ nm, $\lambda = 1550$ nm, $\Delta\nu = 3.75 \times 10^{12}$ Hz, and Δf is normalized to 1 Hz.

From Fig. 1 we can see that when the bias phase is fixed, the SNR of FOG increases with the light power increasing. But to some level the SNR does not increase with the light power and tends to be saturated. This is because that under that condition the intensity noise is higher than other noise and is directly proportional to light power. When the light power is fixed, the peak of SNR appears between 90° and 180° and is closed to 180° under higher light power.

In order to make the bias phase and light power dependence of SNR clear, we select four different curves of SNR as shown in Fig. 2. The four curves are calculated with four different light powers of 5, 20, 35, and 60 μW respectively. From Fig. 2 we can see clearly that the peak of SNR is determined by light power. The location of the peak of SNR is just the optimal bias phase. With the increase of light power, the optimal bias phase moves to 180°. For example, the optimal bias phase is near 100° and 145° under 5- and 35-μW light powers respectively. It is better to set the bias phase nearly to 180°. But when the light power is low, the optimal bias phase is far from 180° and just near 90°. It will not increase but decrease the SNR to set the bias phase nearly to 180° arbitrarily under this condition. The effect of bias phase to SNR is more distinct if there is higher light power. When the light power is 35 μW the best SNR under optimal bias phase is 4 times more than the SNR with usual bias phase of 90°. If the bias phase is under 100°, the SNRs under 35- and 60-μW light powers are nearly equal. So it cannot utilize the noise restraint advantage of high light power. With the optimal bias phase, the SNR under 60-μW light power is nearly two times than that under 35 μW-light power.

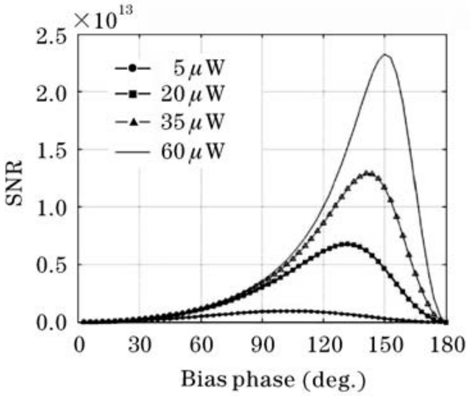

Fig. 2. Bias phase dependence of SNR for different light powers.

According to the above theoretical analysis, we can improve the SNR of FOG and consequently increase the precision by choosing optimal bias phase. In experiment, as FOG has the same optical and electronic parameters as the theory. And the highest light power we can acquire is 20 μW. Then in Fig. 2 the optimal bias phase of this FOG is near to 135°. The output data of the FOG under 90° and 135° bias phases are shown in Fig. 3. The noise band under 135° bias phase is clearly narrower than that under 90° bias phase. The RWCs under two bias phases are 0.0019 and 0.0026 deg./h$^{1/2}$, respectively. The RWC ratio of 90° bias phase to 135° bias phase is 1.37. However from Fig. 2 we can see that when the light power is 20 μW the SNR ratio of 135° bias phase to 90° bias phase is 2.05. This is because that there is following relation of RWC and SNR[4]

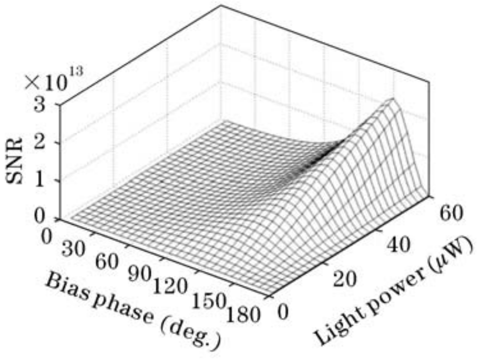

Fig. 1. Bias phase and light power dependence of SNR.

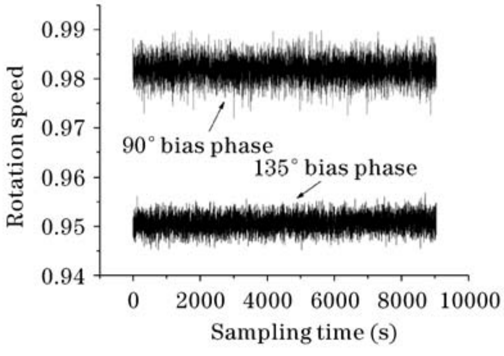

Fig. 3. Fiber optic gyro output with different bias phases.

$$\text{RWC} = k\sqrt{1/\text{SNR}}, \tag{11}$$

where k is the static coefficient related to the FOG. So we must extract the SNR to get the RWC. Extract 2.05 we get 1.42 which is very near to the measured RWC ratio 1.37. So the theory is accordant with the experiment.

In summary, we have proposed a practical method to enhance the precision of FOG just by selecting appropriate bias phase. Although it is well known that the bias phase can affect the FOG precision, the practical bias phase dependence of FOG precision is indistinct. And how to choose the optimal bias phase is unclear also. Taking account of related practical noise, we make it clear and effective. And it is also proved that the precision of FOG is dependent on both bias phase and light power. It is no use only to increase the light power without selecting optimal bias phase. The experiment proved that the theoretical analysis is accurate. By selecting optimal bias phase, the RWC of the aim FOG is reduced from 0.0026 to 0.0019 deg./h$^{1/2}$. If the light power increases to 60 μW, by selecting optimal bias phase the SNR of the aim FOG can increase nearly 4 times, and consequently the RWC can reduce to 0.001 deg./h$^{1/2}$.

J. Mi's e-mail address is mijian_cn@sohu.com.

References

1. V. N. Listvin and V. N. Logozinskii, J. Commun. Technol. Electron. **50,** 679 (2005).
2. S. J. Sanders, L. K. Strandjord, and D. Mead, in *Proceedings of OFS'2002* **1,** 5 (2002).
3. H. Lefevre, *The Fiber Optic Gyroscope* (Artech House, Boston London, 1993).
4. W. K. Burns, R. P. Moeller, and A. Dandridge, IEEE Photon. Technol. Lett. **2,** 606 (1990).