

Research on Signal Integrity of Optical Fiber Gyroscope North-seeker Sensor

Xu Xiaofei¹² Yang Chongzhu¹

(¹School of Automation, Beijing Information Science and Technology University, Beijing, 100192, China;

²School of Electronic and Information Engineering, Beijing Jiaotong University, Beijing, 100044, China.)

E-mail: 18910782910@163.com

Abstract: To overcome the deviation and develop the signal integrity of inertial technology sensor, a rapid pre-orientation method based on angular detecting was put forward and built the calculating model through analyzing the output characteristics of the miniature FOG north seeking in continuous rotary, which analyzed kinds of factors and improved more precision of advanced north seeking. Firstly, according to the sensitivity of interference, the method was established different filter pretreatment and post-treatment; Then, the output error had been reduced by using high speed acquisition consistent with the inherent frequency of FPGA and DSP; Finally, these experiments datas were designed and conducted to different error factor by the processing nonlinear least square method. Analysis and experiment results showed that the proposed method could achieve north seeking sensor at any initial erecting north angle maximum error can be controlled within 5%.

1. Introduction

Fiber optic gyro north seeker sensor was widely applied in aerospace, mining, large underground engineer^{[1]-[3]}, not only high precision, fast speed, strong anti-interference, but also full autonomy. At present, there were the research of fiber optic gyroscope technology, equipped with high precision and fast north seeking mode, from some countries, such as the United States Litton company, Japan AGP-1, and Russia and some Western European countries. North seeking process generally includes the full range of rapid pre-orientation, initial phase and limiting, integral stages and so on^{[4]-[12]}. Now, there were also more considerable research effect on FOG north seeker from many domestic universities and research institutes, such as Tsinghua University, the 15 hospital, 618 aerospace aviation Corporation and Academy, and so on. As a result of technical secrecy and other reasons, there was scarce group of Beihang University and some research institutes, which had the ability to explore higher-precision in the field of FOG north seeker, and design to reach 0.01~1°/h, and meet the requirements of mass production.

Sagnac effect was a common effect of light propagation of optical rotation loop relative to inertial space, which two features of the light propagation finally is converge to the same point detection in the opposite the direction, and the equal originating light from the same source in the same closed optical path^{[13]-[19]}. FOG was a high accuracy inertial rotation sensor based on the Sagnac effect, and FOG north seeker was designed and carried out main mechanical environment vibration detection



experiments with high resolution and sensitivity. The north seeker sensor was used on gyro sensitive component of the earth's rotation rate on the carrier reference axis to calculate the mathematical novel angular velocity sensor between reference axis and north direction of the carrier.

2. The Theory of North Seeker Sensor

2.1 FOG basic scheme

As the key part of the fiber optic gyro north seeker, Fiber optic gyro was researched to focus on improving precision and load capacity, to achieve efficiently the precision geolocation. The Sagnac effect was the theoretical propagation rule of light waves in an inertial space of fiber optic gyroscope, considering the effect of time delay.

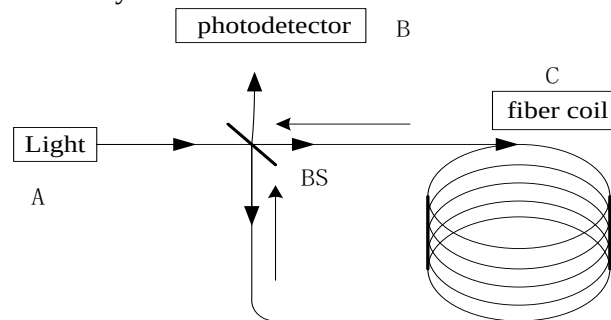


Figure.1 The signal diagram of fiber optic gyro

Figure.1 showed the working principle of fiber optic gyroscope, and there were comprised of four components as light source A, optical detector B, optical fiber coil C, semi transparent mirror BS. When two beams moved through the lens, repeated the process. Due to the effect, there was the variable ΔL named optical path difference (OPD), then the phase difference $\Delta\phi$ would be produced, and the interference spot on light detecting device B had light and shade changes, which the light interference intensity had changed. This phenomenon could be expressed as equation (1):

$$I_D = I_0(1 + \cos\Delta\phi) \quad (1)$$

In the equation(1), the average intensity I_D was the output light of the light detector B, the average intensity I_0 was the incident light, and the Sagnac phase shift $\Delta\phi$ was caused by the rotation of the fiber coil.

Since the phase difference $\Delta\phi$ couldn't be measured directly, which was converted into optical power to be detected the change of the light intensity from the optical detector B. The Sagnac phase shift $\Delta\phi$ could be get from the output of the function relation between I_D and I_0 , as shown in equation (2):

$$\Omega = \frac{\lambda c}{2\pi L D} \Delta\phi = \frac{\lambda c}{2\pi L D} \left[\arccos\left(\frac{I_D}{I_0} - 1\right) - \phi_m \right] \quad (2)$$

In the equation (2), the total length of the optical path was L, the diameter of the optical fiber coil was D, the speed of light was C, the wavelength of the light source was λ , the initial compensation phase was ϕ_m .

2.2 The process of FOG north seeker sensor

Fiber optic gyro north seeker was a kind of device to find the north through the sensitivity of the earth's angular velocity. The vector projection relation for north finding was shown in the Figure.2. The equation(3) established the projection relations between the earth's rotation angular velocity and the north direction (X axis of carrier coordinate system):

$$\omega_N = \omega_e \cos L \quad (3)$$

Here, ω_N was the projection value between the earth's rotation angular velocity and the north direction (X axis of carrier coordinate system), L was real latitude.

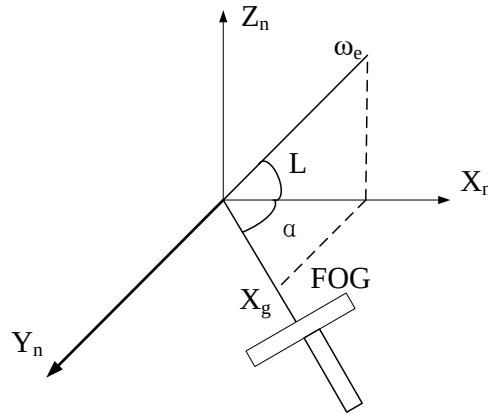


Figure.2 Angular velocity projection diagram

The fiber optic gyroscope could detect and have the component of the earth rotation angular, as shown in equation (4), which established the projection relations between the earth's rotation angular velocity component (X axis of carrier coordinate system) and the sensitive axis of the fiber optic gyro, and α was included angle :

$$\omega = \omega_N \cos \alpha \quad (4)$$

Here, ω was sensing value of gyro sensitive axis.

So the relation was established between the included angle α and the sensing value of the component of the earth rotation angular through experiment by deducing from the equations (3) (4) (5).

$$\alpha = \arccos \frac{\omega}{\omega_N} = \arccos \frac{\omega}{\omega_e \cos L} \quad (5)$$

Here, the smaller angle α and the higher demand for the sensitivity of the gyro, so the North Finder would lose the ability to find the north at North Pole.

Based on the function between angle rate output of the FOG and the location of gyro north finder, the rotation θ_i was substituted the equation (4), and deduced the equation (6), when the fiber gyro sensitive axis was rotated within the range of 360, then the i th angle was $\alpha + \theta_i$ between sensitive axis and the north direction, as followed in the equation (6).

$$\omega_i = \omega_0 + k\omega_e \cos L \cos(\alpha + \theta_i) + \varepsilon(t_i) \quad (6)$$

Here, ω_i was the gyro output, ω_0 was gyro zero bias, K was the scale factor of fog, $\omega_e = 15.041^\circ / h$ was the earth's rotation rate, L was the carrier of the geographic latitude, θ_i was angle between the FOG sensitive axis and initial sensitive axis, $\varepsilon_i(t)$ was random noise.

$$\begin{bmatrix} \omega_1 \\ \omega_2 \\ \vdots \\ \omega_n \end{bmatrix} = \begin{bmatrix} 1 & -\sin\theta_1 & \cos\theta_1 \\ 1 & -\sin\theta_2 & \cos\theta_2 \\ \vdots & \vdots & \vdots \\ 1 & -\sin\theta_n & -\cos\theta_n \end{bmatrix} \begin{bmatrix} \omega_0 \\ k\omega_e \cos L \sin\alpha \\ k\omega_e \cos L \cos\alpha \end{bmatrix} + \begin{bmatrix} \varepsilon(t_1) \\ \varepsilon(t_2) \\ \vdots \\ \varepsilon(t_n) \end{bmatrix} \quad (7)$$

Here, $A = k\omega_e \cos L \cos\alpha$, $B = k\omega_e \cos L \sin\alpha$, then:

$$\omega_i = \omega_0 + A \cos\theta_i - B \sin\theta_i + \varepsilon(t_i) \quad (8)$$

At first, the measured datum were pretreated by distribution periodicity, and then construct three different error function while processing nonlinear least square method parameter estimation [14-21]. The A and B value could be deduced by a method of iteration for multi-dimensions least square, and the included angle α could be identified and deduced by frequency domain maximum likelihood

method and least square method.

$$\alpha = \arctan \frac{\hat{B}}{\hat{A}} \quad (9)$$

The mean value from N repeated measurements was given as follow:

$$\bar{\alpha} = \frac{1}{N} \sum_{i=1}^N \alpha_i \quad (10)$$

Here, α_i was the i th North azimuth value measured by FOG north seeking system.

In order to find out the degree of coincidence of the north seeking the results, there was the σ_r precision value as the follow equation to express N repeatability error:

$$\sigma_r = \sqrt{\frac{1}{N-1} \sum_{i=1}^N (\alpha_i - \bar{\alpha})^2} \quad (11)$$

Here, adjust FOG sensitive axis to find A, the correct given north value, then get the average of X measurements after N times north seeking, so C expressed the accuracy value.

$$C = \bar{X} - A \quad (12)$$

The performance of a north seeking in calorific value determination was usually evaluated by the precision and accuracy of its determinate result, and E_s showed as follow.

$$E_s = \sqrt{\sigma_r^2 + \frac{N}{N-1} \cdot C^2} \quad (13)$$

3. Improving the precision of FOG north seeker sensor

According to the need of the project, adopt the F98M IFOG's realization, which the angle rate is $0.3''/s$, and output positive and negative pulse signal, as show in Figure.3. At the time, the geographic latitude of the laboratory was $39.9888^\circ N$, and the earth's rotation speed was about $15.041^\circ/h$. The parameters which had important influence on the performance of continuous rotary north seeking were studied, such as the motor speed and base tilt, graduation factor and the sampling rate.

(1) The motor rotational speed and base tilt influence

The motor rotational speed was direct effect on the sampling frequency impression to decide the precision result of north seeking. The more quick speed added the more error of the sampling frequency impression, and prolong the more time, so it would lead to the time dependence output error of the north seeking. The influence relation between the north seeking precision and motor rotational speed was showed in Figure.3:

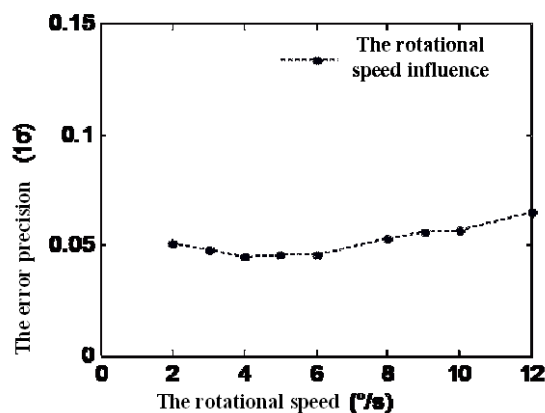


Figure.3 The influence relation between the precision and speed

As show in Figure.3, there was the maximum precision of the north seeking result, when the motor rotational speed was $6^\circ/s$ at the time.

The deviation influence of base tilt had be important factor of the measurement angular error,

which was also made by the vibration disturbance. It was effectively weaken the vibration interference signal by increasing the base quality and processing the multiplier and low-pass filtering, when the north seeking was continuous rotary and calculating.

(2) Graduation factor setting

The graduation factor of fiber optic gyro had an important influence on the precision of north seeking rotary, which need be calibrated before each experiment. The FOG's waveform was oscillograph display, as show in Figure.4, which the sampling period was T . The graduation factor calibration of the FOG was shown in the follow equation (14):

$$K = \frac{|C_+ - C_-|}{T\omega} \quad (14)$$

Here, K was the graduation factor calibration; C_+ was positive pulse, and C_- was negative pulse; ω was the average angular velocity measurement period T , which can be obtained from equation (14) derivation. The graduation factor of the system was $10014^{\circ}/s$ at the temperature range of -40°C to 60°C .

(3) The sampling rate influence

The sampling rate decided the precision result of north seeking, which was more consistent with the desired value of the motor set speed, the better precision result. The influence relation between the north seeking precision and the sampling rate was showed in Figure.5, which was processed from experiment data analysis, data pretreatments and polynomial segment fitting.

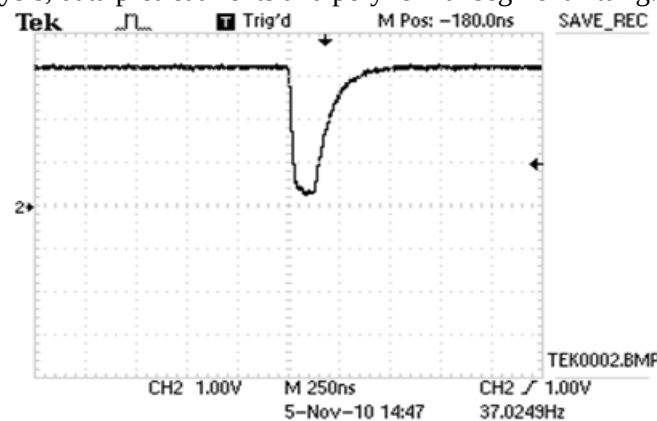


Figure.4 The positive and negative pulse of FOG's output

4. The precision of FOG north seeker

The process design for pretreatment precision was presented in section3, and an adaptive filter was designed and effective for data processing precision, which the result was showed in Figure.5. Then the upper computer received the FOG data weighted processing with FPGA and tilt data weighted processing with DSP, which was displayed the north seeking results after the operation of North-seeking algorithm.

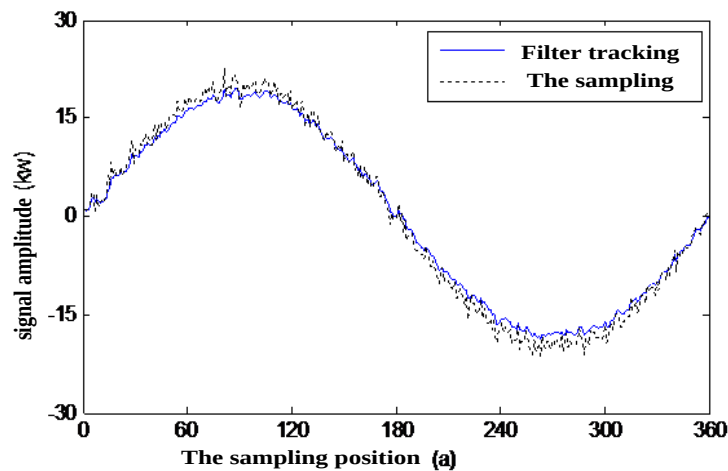


Figure.5 The filtering method for noise suppression

The designed data processing flow of north seeker was showed in the Figure.5. As the north seeking optimized results were showed in the Table.1:

Table.1 The data processor based on least square method

Order	init/(°)			
	30	60	120	180
1 2 3 4 5 6 7 8 9	30.35	60.31	120.33	180.16
	30.13	60.26	120.03	179.82
	29.98	59.85	119.85	180.23
	30.06	60.02	120.12	180.18
	29.82	59.82	119.83	179.80
	29.88	60.16	120.18	180.02
	30.38	59.79	119.82	180.20
	30.23	59.92	120.09	179.88
	29.69	60.22	120.20	179.92
Precision	23.81%	20.31%	18.23%	17.31%

Due to a degree of directional instability, the precision of the north seeking was between 0.1-0.3, and the smaller the initial north angle could be, the lower the precision of north seeking could be. Next step, there were many kinds of factors to develop a very thorough analysis flow and improve the precision of FOG north seeker.

5. Conclusion

This paper summarized the design result of FOG automatic fast-north-seeking system for location navigator, dealing with principle of system combination hardware and software, as well as error analysis. Besides the hardware support of FPGA and DSP high speed acquisition, software had been developed the core of north seeking during the system adjustment. Firstly, according to the sensitivity of interference, pre-treated method was established different processor, which was put forward and built the calculating model through analyzing the output characteristics of the miniature FOG north seeking in continuous rotary. Then, on consistent with the inherent frequency, there were analyzed kinds of factors and improved more precision of north seeker. Finally, experiments data were designed and conducted to different error function while processing nonlinear least square method. Analysis and experiment results showed that the proposed method could achieve north seeking at any initial erecting

north angle maximum error within 5%.

In summary, wide-area real time and precise positioning had attracted much attention recently in such application fields as optical engineering, micro-assembly, precision measurement, medical science, biology, semiconductor industry and aerospace. Next step, the main approach to realize higher accuracy FOG north seeker, was researching the intelligent data processor on the continuous rotary omni-bearing sampling scheme.

References

- [1] Lu Zhenli, Xie Yafei, Xu Huigang et al. Knowledge presentation by the MNSM-based controller for swimming motion of a snake-like robot[J].HIGH TECHNOLOGY LETTERS,2018,24(1):103-112
- [2] Li Guangsheng, Chou Wusheng. Semantic categorization of indoor places using CNN for mobile robot exploration [J]. HIGH TECHNOLOGY LETTERS,2018,24(2):125-133
- [3] KeKe Duan, DengHua Li, RenZhong Pei. Study on the Error of Four-Position North Seeking System Based on the single Axis Fiber Optic Gyroscope[J]. Advanced Materials Research Vols, 2012, 503(504): 1158-1163.
- [4] Denghua, Li, Keke, Duan. 1-3 piezocomposition for vibration accelerometer applications.[J]. Ferroelectrics, 2014, 466(1): 86-91.
- [5] Renzhong, Pei, Denghua, Li, Keke, Duan. Tilt error analysis and compensation for two-position north determining scheme in FOG north-seeker[J]. Applied Mechanics and Materials, 2012, 249(250): 175-179.
- [6] G.Pavlat,Challenges in the Development of the IFOG,AIAA Guidance, Navigation,and Control Conference and Exhibit,Austin,Texas,2003:11-14.
- [7] Jayesh H Kotecha, Petar M Djuric,Gaussian Particle Filtering .IEEE Transaction on Signal Processing,2003,51(10):2592-2601.
- [8] S.J. Sanders, L.K. Strandjord, D. Mead. Fiber optic gyro technology trends - a Honeywell perspective[C]//Optical Fiber Sensors Conference Technical Digest, 2002: 5-8.
- [9] ROMMEL N. Functional principle and technical concept of the high-precision surveying gyroscope GYROMAT2000[C]//Symposium Gyro Technology. Stuttgart,Germany,1994:8.0-8.31.
- [10] R.B. Morrow, D.W. Heckman. High precision IFOG insertion into the strategic submarine navigation system[C]//Position Location and Navigation Symposium, IEEE, 1998: 332-338.
- [11] D.E. Allen, S.M. Bennett, J. Brunner, et al. All-fiber gyroscope for land navigation[J]. Proceedings of SPIE, 1995(2510): 28-36.
- [12] R.B. Dyott, S.M. Bennett, D. Allen, et al. Development and commercialization of open loop fiber gyros at KVH industries[C]//15th Optical Fiber Sensors Conference Technical Digest, 2002: 19-22.
- [13] T. Tanaka, Y. Igarashi, M. Nara, et al. Automatic North Sensor Using a fiber-optic Gyroscope[J]. Applied Optics, 1994, 33(1): 120-123.
- [14] Z.J. Zhang, J.Y. Sun, K.Y. Wu. Error analysis and test study of fiber optic gyroscope north-finder[J]. Proceedings of SPIE, 2005, 5634(2): 611-618.
- [15] R.M. Rogers. Applied Mathematics in Integrated Navigation Systems[M]. second edition. Virginia: American Institute of Aeronautics and Astronautics, 2003: 105-112.
- [16] S.J. Sanders, L.K. Strandjord, D. Mead. Fiber optic gyro technology trends - a Honeywell perspective[C]//Optical Fiber Sensors Conference Technical Digest, 2002: 5-8.