第23卷 第3期
2010年3月

传感技术学报
CHINESE JOURNAL OF SENSORS AND ACTUATORS

Vol.23 No.3
Mar. 2010

# Online RWE Monitoring Based on Cross-Correlation Method for IFOGs in Space Applications*

*LI Min** , *ZHANG Chunxi*, *SONG Ningfang*, *JIN jing*, *LIN Song*

(*School of Instrument Science and Opto-electronics Engineering*, *Beijing University of Aeronautics and Astronautics*, *Beijing* 100191, *China*)

**Abstract**: Random Walk Error (RWE) is one of the most sensitive errors in interference fiber optic gyroscopes (IFOGs) for space applications. Based on the optical component parameters that degrade in space irradiation environment and the IFOG physical model, forward path gain (FPG) is confirmed as the feature characterizing deterioration of RWE. According to the cross-correlation identification theory, an online FPG extraction method with pseudo random binary signals(PRBS) injection is proposed. The correlativity between the forward path output, square-wave reference signal and square-wave modulated PRBS are analyzed, and the results show that the extraction process can identify the FPG effectively without disturbing IFOGs' normal working cycles. The prerequisite of the method is discussed and the hardware realization in IFOG is introduced. An IFOG gamma ray radiation experiment was carried out to verify the method and the results shows that the FPG identification process can reveal 75% deterioration of RWE.

**Key words**: IFOG; space applications; RWE; forward path gain; cross-correlation

**EEACC: 7230E; 7630**

# 空间应用光纤陀螺随机游走误差在线监测方法*

李 敏*,张春熹,宋凝芳,金 靖,林 松

(北京航空航天大学仪器科学与光电工程学院,北京 100191)

**摘 要**:随机游走误差是光纤陀螺空间应用中最受影响的误差之一。在分析陀螺器件在辐照环境下的失效模式以及陀螺模型的基础上,得到了前向通道增益是随机游走误差性能劣化的特征量的结论。依据相关辨识理论,提出了前向通道增益的在线监测方法,并在FPGA中得到了实现。通过将伪随机二进制码叠加在阶梯波中,并与方波调制伪随机二进制码解调得到前向通道增益;计算伪随机辨识信号与方波信号的相关性,该方法不会影响陀螺的正常工作。通过光纤陀螺辐照模拟实验验证了该方法的有效性,结果表明辐照过程中辨识得到的前向通道增益能够反映出随机游走误差75%的劣化。

**关键词**:光纤陀螺;空间应用;随机游走误差;前向通道增益;互相关

**中图分类号:V241.4** **文献标识码:A** **文章编号:1004-1699(2010)03-0383-05**

Benefited from the particular advantages of the Interference Fiber Optic Gyroscope (IFOG), it has been applied widely in space explorations. The well-known example is the application of LN-200 in "Clementine" in 1994[1], which was the first IFOG utilization in aerospace navigation. Astrix serials IFOGs of Ixspace co. have been used in space exploration projects such as PLEIADES, AEOLUS, and PLANCK[2].

Bias, random walk error (RWE) and scale factor are the most important characteristics of IFOGs[3]. Bias is a long-period random process, RWE is a short-period fluctuation, and scale factor is a proportional coefficient that relates the input and the output signal. They are also very susceptible to space radiation environment[4-6], and the deterioration of these characteristics may cause failures of IFOGs.

The on-line calibration of bias and scale factor is a most mature procedure at NASA's Goddard Space Flight Center[7]. Nevertheless, the on-line monitoring of RWE requires special tools of analysis, and the on-orbit RWE is an important factor that influences the performance of gyro-based attitude determination systems[8].

---

**项目来源**:国家863高科技计划资助(2007AA04Z436)

**收稿日期**:2009-09-16 **修改日期**:2009-11-24

The basic noise sensitivity of an IFOG is specified by the RWE performance, which is a rate angle white noise spectral density usually given in deg/h$^{1/2}$. RWE is an important parameter that characterizes the optical gyros[9].

Generally, Allan Variance method is used to model the error components of inertial sensors including random walk error[10]. By its very nature, the Allan Variance is an off-line method and the precondition for the method is that the handled noise should be stationary[8]. In recent years, methods and procedures were brought out to realize the on-orbit RWE characterization for gyros during the Post Launch Test (PLT) period[11]. A state-space based computation method was also advanced to model on-line RWE[12]. Most of those methods focus on analyzing the noise from the viewpoint of data. And the prerequisite of these methods is that the angular rate should first be removed from the IFOGs' output. In this way, other sensors such as star trackers on the spaceships are used as a reference, and their precision and working stability play a key role to these methods.

In the present work, we propose a novel method to monitor the on-line RWE performance. This paper begins with the analysis of space environment sensitive component parameters, and confirms that the forward path gain (FPG) is the feature to characterize the RWE. And the cross-correlation method is brought out for the on-line FPG estimation in section two. In section three hardware realization is discussed. An irradiation experiment is used to validate the method in section four. Finally, the conclusions and discussion are presented in section five.

## 1 Feature of RWE in Space Environment

The basic noise sensitivity of an IFOG is specified by the RWE performance, which is a rate angle noise spectral density usually given in deg/h$^{1/2}$. In a radiation-free environment, contributions to the RWE include photon shot noise, excess intensity noise in the source, detector and electronics noise, and quantization noise of the D/A converter in the closed-loop system. While in space applications, the most significant effect of radiation is an increase in photon shot noise due to a decrease in the transmission of the fiber resulting in less power on the detector. A falloff of the source power or detector sensitivity also increases the shot noise. A listing of the most sensitive degraded physical parameters that affect RWE performance in an IFOG is in table I[4].

Table 1 IFOG space sensitive component parameters

| Component | Degraded Parameter |
|---|---|
| Source | Output power |
| Fiber | Attenuation |
| Detector | Responsivity |

All those radiation-affected parameters can be reflected in the model of IFOGs[3] as shown in Fig. 1.

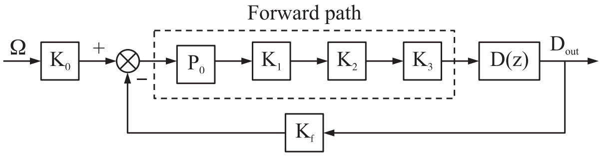


Fig. 1 IFOGs dynamic model

Where, $K_0$ is the Sagnac scale factor, $\frac{2\pi LD}{\lambda c}$, L is the fiber length , D is the diameter of the fiber coil and $\lambda$ is the wavelength; $\Omega$ is the input angular rate; $P_0$ is the light power from the source; $K_1$ is the gain of the optical transmission system, including the fiber coil, integrate optic circuit, and coupler; $K_2$ is the responsivity of the detector; $K_3$ is the gain of the pre-amplifier circuit; $D(z)$ is the square-wave demodulation block; $D_{\text{out}}$ is the IFOG's output. $K_f$ is the feedback gain.

The radiation-relevant parameters listed in table 1 are included in the forward path of the closed-loop system, which is enclosed in the dashed in figure 1. And the forward path gain is defined as,

$$\text{FPG} = P_0 \times K_1 \times K_2 \times K_3 \tag{1}$$

If the FPG decreases, the RWE deteriorates correspondingly and it is the main reason for the deterioration. The FPG can be viewed as the feature of RWE in the space environments.

## 2 Feature Extraction Based on Cross-Correlation Method

### 2.1 Cross-correlation ethod[13]

For single input and single output systems (SISO), its dynamic attribute in time domain is described as,

$$y(t) = \int_0^\infty g(\sigma)x(t-\sigma)\,\mathrm{d}\sigma \tag{2}$$

Where $g(\sigma)$ is the impulse response function of the system, $x(t)$ and $y(t)$ are the input and the output of the system separately.

The cross-correlation of $x(t)$ and $y(t)$ can be written as,

$$R_{xy}(\tau) = \int_0^{\infty} g(\sigma) R_{xx}(\tau - \sigma) \mathrm{d}\sigma \tag{3}$$

If the input $x(t)$ is the white noise, and its cross-correlation can be expressed as,

$$R_{xx}(\tau - \sigma) = \begin{cases} 1 & \tau = \sigma \\ 0 & \tau \neq \sigma \end{cases} \tag{4}$$

Then the formula(3) can be rewritten as,

$$R_{xy}(\tau) = Kg(\tau) \tag{5}$$

Where $K$ is the intensity of the signal $x(t)$.

That is, if the input of the SISO system is white noise, and then the cross-correlation of the input and the output signals give the impulse response of the system.

This theoretical result requires the ability to generate white noise as an input perturbation to the system. A simple compromise is to approximate white noise through use of pseudo random binary signal (PRBS) perturbations. And the PRBS can be easily generated but is periodic and deterministic. The data length for one period of an $n$-bit maximum length PRBS is given by $M = 2^n - 1$, and the signal itself has only two possible values: $\pm e$.

### 2.2 Forward Path Gain Extraction via Cross-correlation

As Fig. 2 is shown, the forward path in the solid lines and the forward path gain identification process is in the dashed lines. The forward path can be viewed as an SISO unit and the PRBS identification signal is injected to the feedback path combined with the normal working signals. The forward path gain identification is accomplished via the cross-correlation between the square-wave modulated PRBS signal and the forward path output signal.

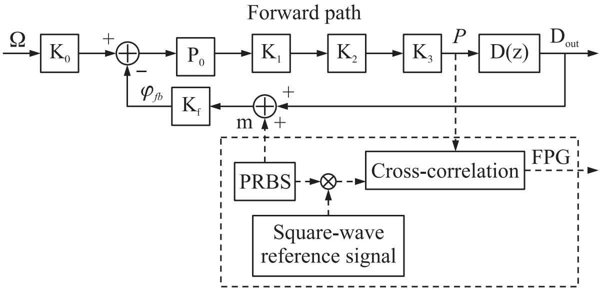


Fig. 2　FPG estimation schematic

The feedback signal $\varphi_{fb}$ can be expressed as,

$$\varphi_{fb}(n\tau) = K_f \times [D_{out}(n\tau) + m(n\tau)] \tag{6}$$

Where $\tau$ is the transit time of the fiber coil, $D_{out}(n\tau)$ is the closed-loop feedback digital values at the $n\tau$ time, $m(n\tau)$ is the PRBS signal, and $n = 1, 2, \cdots$.

The signal P is expressed as[3],

$$P(n\tau) = \mathrm{FPG} \times \sin[\varphi_S(n\tau) + \varphi_{fb}(n\tau) + \varphi_M(n\tau)] \tag{7}$$

For square wave modulation,

$$\varphi_M(n\tau) = \begin{cases} +\dfrac{\pi}{2} & n = 2k \\ -\dfrac{\pi}{2} & n = 2k - 1 \end{cases} \quad k = 1, 2, \cdots \tag{8}$$

So $P$ can be rewritten as,

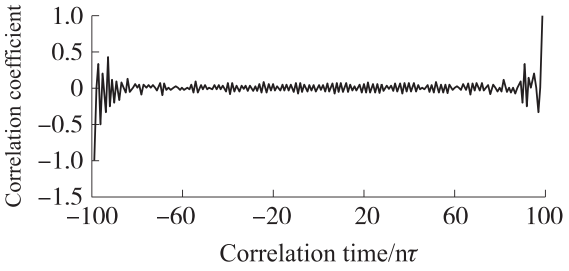
$$P(n\tau) = \begin{cases} \mathrm{FPG} \times \sin[\varphi_S(n\tau) + \varphi_{fb}(n\tau)] & n = 2k \\ -\mathrm{FPG} \times \sin[\varphi_S(n\tau) + \varphi_{fb}(n\tau)] & n = 2k - 1 \end{cases} \tag{9}$$

Ideally, for stable closed-loop IFOGs, the value of $[\varphi_s(n\tau) + K_f \times D_{out}]$ is zero and the intensity of the PRBS decides the linearity of the sin function, and here we suppose that the identification process does not ruin the linearity. Then the above formula can be rewritten as,

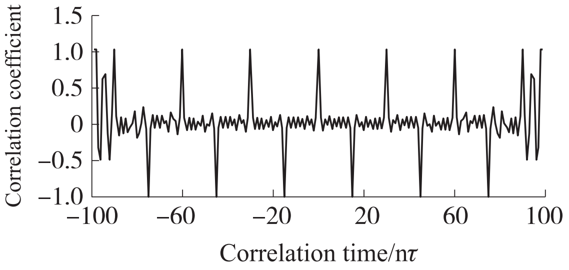
$$P(n\tau) = \begin{cases} \mathrm{FPG} \times [\varphi_s(n\tau) + K_f \times \\ \quad D_{out}(n\tau) + K_f \times m(n\tau)] & n = 2k \\ -\mathrm{FPG} \times [\varphi_s(n\tau) + K_f \times \\ \quad D_{out}(n\tau) + K_f \times m(n\tau)] & n = 2k - 1 \end{cases} \tag{10}$$

The forward path output $P$ is a composite of normal working signals, which is demodulated with the square-wave reference signal, and FPG identification signal, which is demodulated with square-wave modulated PRBS. So the correlativity between the square-wave reference signal, square-wave modulated PRBS decides the feasibility of the method.

The correlativity analysis is shown in figure 3 and the period of PRBS is 15. Fig. 3-a shows that the correlativity of square-wave reference signal and square-wave modulated PRBS is about 0.03, Fig. 3-b reveals that the cross-correlation between square-wave modulated PRBS and forward path output is correlated as white noise. So the FPG can be identified online via the correlation method without disturb the normal working cycles of IFOGs.



(a) Cross-correlation of square-wave reference and square-modulated PRBS



(b) Cross-correlation of forward path output and square-modulated PRBS

Fig. 3

### 2.3 Prerequisite of the Method

From formula (10) we can see that the result of the cross-correlation method is expressed as,

$$\mathrm{FPG}_{idn} = P_0 \times K_1 \times K_2 \times K_3 \times K_f \tag{11}$$

That is the identified FPG includes the feedback path gain $K_f$, which will disturb the identification result if it is not constant. For high performance IFOGs special techniques have been used to stabilize $K_f$[14]. Under such conditions, the identified result only reflects changes from forward path.

## 3 Hardware Realization

Our proposed procedure for FPG identification in hardware is summarized in Fig. 4, which is realized in FPGA. The solid lines show the normal working flows of IFOGs and the dashed lines show how the identification works. An 1023 period PRBS is generated in the PRBS generator block and injected to the feedback path combined with the normal working signals. The output of forward path is shifted to FPGA and directed to two blocks, one is square-wave demodulation block with angular rate as its output and the other is cross-correlation block with FPG gain as its result. In the cross-correlation block, the generated PRBS is firstly modulated by the square-wave signal and cross-correlation is calculated with the forward path output.

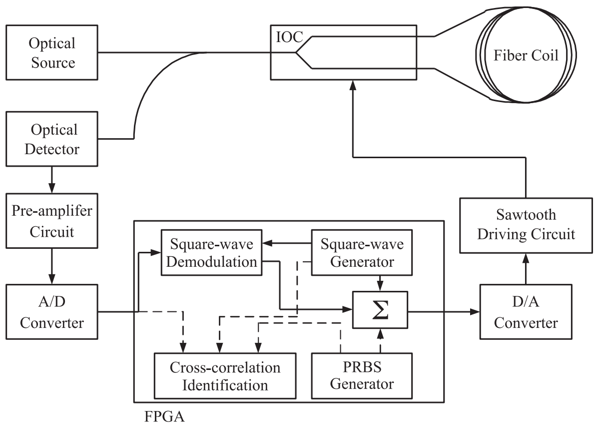


Fig. 4 Hardware realization of FPG identification

## 4 Experiment Verification

An IFOG with a superfluorescent light source (SFS) irradiation experiment was carried out to verify the cross-correlation method. The experiment radiation source is gamma ray under the condition of 0.1 rad/s and accumulative dose 20 krad. The experiment setup is shown in Fig. 5, and digital output of the IFOG and the FPG identification result were collected. Optical Power from the light source was monitored by the Optical Power Meter.

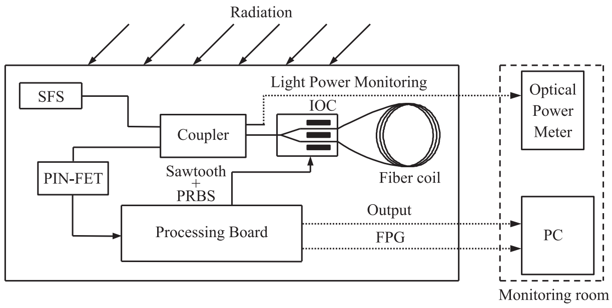
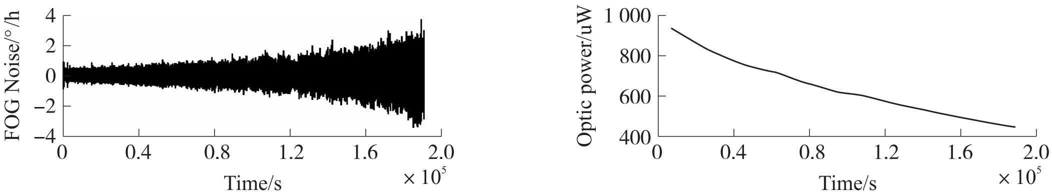


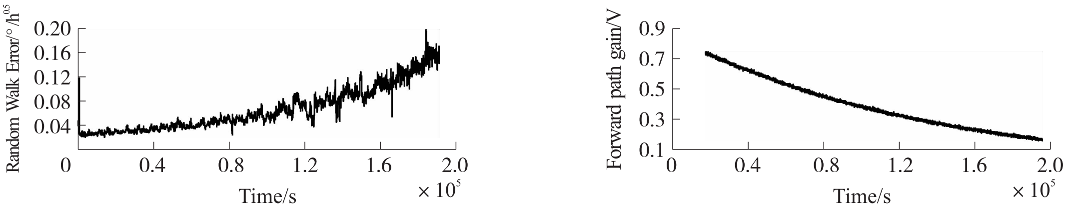
Fig. 5 Radiation experiment setup

The results of the experiment were shown in Fig. 6. Fig. 6-a shows the IFOG noise output, and figure 6-b reveals the optical power attenuation from SFS light source was about 3.5 dB. RWE degraded from $0.02°/h^{0.5}$ to $0.17°/h^{0.5}$. and the identified FPG changed from 0.74 V to 0.12 V. RWE deteriorated about 8 times and the FPG identified result decreased about 6 times which could reflect about 75% deterioration of RWE, and the remained RWE deterioration resulted from other irradiated-induced noise sources[7]. The lines in fig. 6-b and fig. 6-d were closely correlated indicating that a falloff of the optical power possibly was the main factor responsible for the RWE deterioration.



(a)IFOG noise output

(b)Optical power during radiation



(c)RWE during radiation

(d)FPG identification result

Fig. 6 Gamma radiation experiment and identification results

## 5 Conclusion and discussion

The present paper deals with the on-line RWE monitoring of IFOGs in space applications. The conclusion is that FPG is the feature of RWE deterioration in space applications and the cross-correlation method can online identify the feature of RWE deterioration based on theoretical analysis. And the experiment result shows that the identified FPG can reveal about 75% deterioration of RWE.

As shown in Fig. 3, the cross-correlation is nonzero and small disturbance will be brought to the IFOG output during the identification process, which need further research.

### Reference

[1] Sorensen T C, et al. The Clementine Mission-A 10-Year Perspective. J. Earth Syst. Sci , 2005, 114(6): 645 −668.

[2] Willememot E, et al. From Space to Underwater: Fiber Optic Gyro Multiuse Technology. Underwater Intervention International Conference, 2004, New Orleans, USA.

[3] LEFEVRE H C. The Fiber-optic Gyroscope[M]. London: Artech House, 1993.

[4] Richard H. Boucher, Warren F. Woodward, Terrence S. Lomheim et al. Proton-Induced Degradation in Interferometric Fiber Optic Gyroscopes[J]. SPIE Vol. 2482. 1996: 955 −976.

[5] Jin Jing, Song Ningfang, Li Min. Three-cluster Fiber Optic Gyroscope for Satellite[J]. Journal of Beijing University of Aeronautics and Astronautics, 2006, 32(11): 1385 −1389. (in Chinese)

[6] Xiao Wen, Liu De-Wen, Liu Yang. Effects of Polarization-Maintaining Fibre Degrading on Precision of Fibre Optic Gyroscopes in Radiation Environment [J]. CHIN. PHYS. LETT., 2008, 25 (4): 1224 −1226.

[7] Hashmall J A, Rowe J, Sedlak J. Spacecraft Attitude Sensor Calculation From On-orbit Experience[C]. Digital Avionics Systems Conference, 1997, 2(26): 8.4 −1 −8.4 −8.

[8] JI Wei, LI Qi. Research on Signal Analysis and Processing of FOG [J]. Chinese Journal of Sensor and Actuators, 2007, 20(4): 847 −852. (in Chinese)

[9] Zhang Guicai. The Principles and Technologies of Fiber-Optic Gyroscope[M]. Beijing, National Defense Industry Press, 2008. (in Chinese)

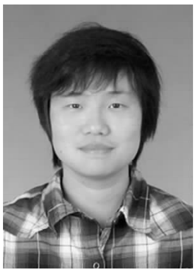
[10] Naser El-Sheimy, Haiying Hou, Xiaoji Niu. Analysis and Modeling of Inertial Sensors Using Allan Variance[J]. IEEE Transactions on Instrumentation and Measurement, 2008, 57(1): 140 −149.

[11] Quang M. Lam, Nick Stamatakos, Craig Woodruff, et al. Gyro Modeling and Estimation of Its Random Noise Sources [A]. AIAA-2003-5562 AIAA Guidance, Navigation, and Control Conference and Exhibit[C]//Austin, Texas, Aug., 2003: 11 −14.

[12] Jason J. Ford, Michael E. Evans. Online Estimation of Allan Variance Parameters [J]. Journalof Guidance, Control, and Dyanmics, 2000, 23(6): 439 −444.

[13] Hou Yuan-bin, Wang Mei, Wang Li-qi. System Identification and Matlab Simulation[M]. Beijing: Science Press, 2004. (in Chinese)

[14] Wang Yan, Zhang Chun-xi, Liu Zheng-pin. All Digital Closed-loop Fiber Optic Gyroscope with the Second Feedback Loop[J]. Piezoelectrics & Acoustooptics, 2005, 27(4): 14 −17. (in Chinese)



**李 敏**(1979 −),女,博士研究生,主要从事空间光纤传感器的故障机理、故障诊断和可靠性研究,limin11@263.net;

**张春熹**(1965 −),男,教授,博导,主要从事光电子器件、光纤传感和惯性导航等方面的研究.