Vol 17 No 2, February 2008
1674-1056/2008/17(02)/0573-05
Chinese Physics B
© 2008 Chin. Phys. Soc.
and IOP Publishing Ltd

Space radiation effect on fibre optical gyroscope control circuit and compensation algorithm

Zhang Chun-Xi(张春熹), Tian Hai-Ting(田海亭)†, Li Min(李 敏),
Jin Jing(金 靖), and Song Ning-Fang(宋凝芳)

School of Instrumentation Science & Opto-electronics Engineering, Beijing University of Aeronautics & Astronautics, Beijing 100083, China

(Received 21 December 2006; revised manuscript received 8 August 2007)

The process of a γ-irradiation experiment of fibre optical gyroscope (FOG) control circuit was described, in which it is demonstrated that the FOG control circuit, except for D/A converter, could endure the dose of 10krad with the protection of cabin material. The distortion and drift in D/A converter due to radiation, which affect the performance of FOG seriously, was indicated based on the elemental analysis. Finally, a compensation network based on adaptive neuro-fuzzy inference system is proposed and its function is verified by simulation.

Keywords: space radiation, fibre optical gyroscope, compensation network
PACC: 0760, 6170, 4281P

1. Introduction

Owing to the particular advantages for space applications, the fibre optical gyroscope (FOG) technology has been used widely in satellites and spacecrafts. This comes from its very high performance: it has no moving parts, but has a very high angular resolution, long lifetime and high reliability, and good behaviour in vacuum as well. Products of FOG can be easily adapted to different performance targets; and its cost is competitive.[1]

Space is a complex and dynamic environment, and FOG is affected by orbital location, time, solar activity, and geomagnetic field strength. Space radiation environment has serious effects on spacecraft electronics. And the failure of satellite electronic components due to the natural space radiation has been a hot point since the early 1960s when high altitude nuclear tests increased the radiation levels in the Van Allen belts. Of primary concern in spacecraft design is the analysis of these encounters during a FOG lifetime, evaluating their impact on the reliability of parts and materials for spacecraft.[2] Many space application researches have explored the optical part of FOG. From the experiments, many data had been obtained.[3]

This paper is composed of six sections. In section 2, space radiation environment is generally described. In section 3, result of a γ-ray radiation experiment is shown in detail. There is an analysis of the D/A converter distortion and drift in section 4. A D/A converter distortion and drift compensation network (DADDCN) based on adaptive neuro-fuzzy inference system (ANFIS) are proposed with the basic architecture included in section 5, and finally conclusion is given in section 6.

2. An overview of space radiation environment

The near-earth space environment has three major components: a) trapped radiation belts containing electrons and protons, b) transient radiation from solar flare activity, and c) cosmic rays from deep space.[4] The trapped charge radiation belts, called Van Allen belts, consist primarily of electrons and protons trapped by the magnetic field lines around the earth.[5] The trapped radiation belts consist of inner and outer zones which are separated at a distance of 21 earth radii near the equator. The flux in the outer zone is about an order of magnitude greater than that of the inner zone and the electron energies are higher. At about 3 earth radii, the proton energy is about 40MeV and at 4 earth radii about 8MeV.[5] The most intense radiation environment in low earth orbit is called the South Atlantic Anomaly (SAA). Because of the inverse altitude relation for proton energy, the protons in the SAA are of higher flux and energy.

†E-mail: tsatnt@gmail.com

For a satellite in low earth orbit with an inclination that passes through the SAA, nearly all the accumulated dose is received during the short transit period through the SAA,[6] which will cause a severe damage to the semiconductor devices in a satellite.

Due to the spacecraft electronics, the accumulated dose damage from electron and proton exposure will limit the system endurance. There are generally three important aspects: displacement effect, ionization effect and surface effect. Failure mainly results from the displacement effect caused by ionization radiation, which can make the degradation of bipolar transistor current gain.[1] The ionization radiation can disrupt system operation, perhaps irreversibly.[7]

At present, as a main method of space radiation simulation, γ-rays are widely used to simulate the total dose space radiation effect, which includes the electron belts ionization radiation, electrons, protons and the high-energy particle accumulation radiations.[8−10]

3. The γ-ray irradiation experiment on FOG control circuit

A FOG control circuit (FOGCC) radiation test was made to examine the radiation effect on electronic device performance. The γ-rays of 1.20MeV were generated by a Co^{60} source to simulate space radiation environment, the total γ-ray dose equals the dose inside the satellite cabin on the orbit for 2 years, which is 10krad, and dose rate is 1.5 rad/s.

There are four main parts in the experimental system: analogue amplifying block, digital signal processing (DSP) block, power supply block and signal sampling block. The analogue amplifying block and DSP block were irradiated by γ-rays. For the purpose of imitating the satellite cabin, an aluminium board was provided to protect the electron board from irradiation source. The power supply block, protected by a thick leaden carapace, was not irradiated by γ-rays to guarantee the good performance of the above two blocks. The signal sampling block was designed to sample the data from irradiated blocks through the anti-radiation cable, and located out of the radiation area. The experimental circuit structure is shown in Fig.1.

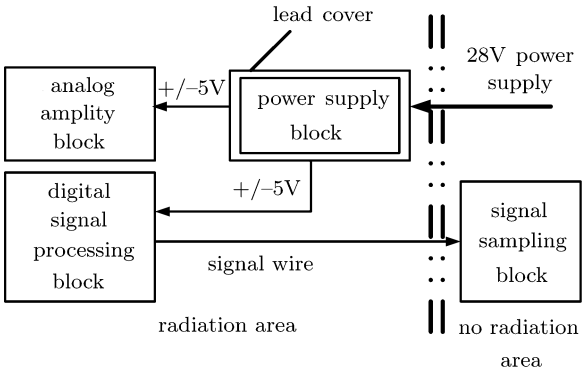


Fig.1. Experimental circuit structure.

A data frame of 80 minutes was sampled before the radiation experiment for comparing with the data during the radiation process. The waveform of the frame is shown in Fig.2. A data frame composed of two parts was sampled during irradiation process; the first part was obtained in first 5krad dose, and the second part was sampled between 5 and 10krad, and the waveforms of the two parts are shown in Fig.3. In the dose of 5krad, a power down and reset test was launched and then the system reworked normally. In the whole process, the increase of system noise could be accepted. There was no obvious degradation in FOGCC under an irradiation dose of 7.5krad, at a rate of 1.5rad/s, but the output distortion and drift were more prominent when the total dose was above 7.5krad. Another data frame of 60minutes after irradiation was sampled, as shown in Fig.4. No obvious distortion is found in step wave but there is a distinct drift compared with the waveform before irradiation.

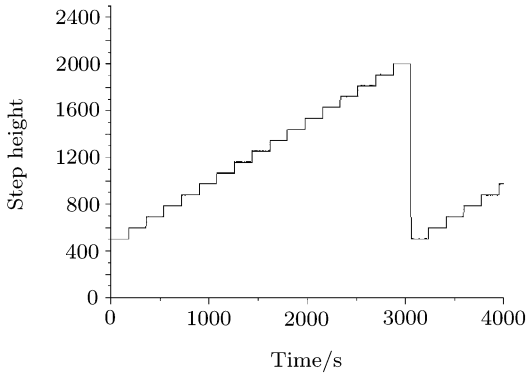


Fig.2. Data frame before irradiation.

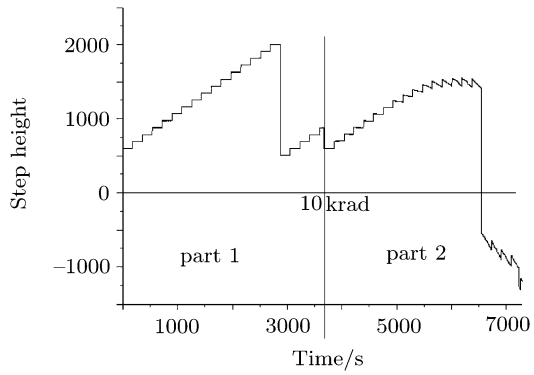


Fig.3. Data frame during irradiation.

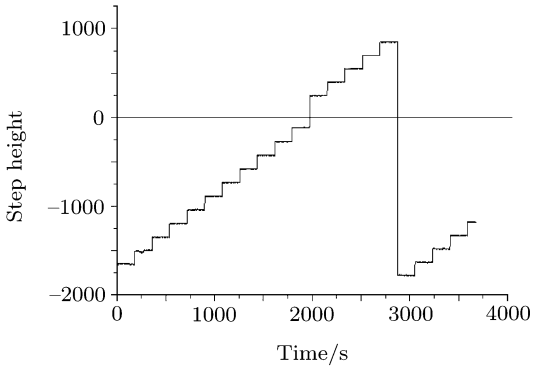


Fig.4. Data frame after irradiation.

The result obtained from decomposing test after experiment showed that the D/A converter had been affected seriously, which can lead to a large distortion and drift in FOG's waveform. Furthermore, performance of operational amplifying can be accepted through a simple analogue filter to guarantee that it does not affect the performance of FOG, although the noise of it is twice that of the data before irradiation and degradation occur. For other devices, such as DSP processor, A/D converter, voltage reference, linear regulator, programmable read-only memory and passive devices, γ-rays made little effect on them. This partly can be attributed to the shelter under the aluminium board. It is indicated that FOGCC can endure γ-rays radiation dose of 10krad, which is the whole radiation dose received in satellite during its lifetime of 2 years, under the protection of cabin material, except the D/A converter.

4. Elemental analysis for D/A converter distortion and drift (DADD)

The relative accuracy, differential nonlinearity and gain error of D/A converter have no obvious change with the increase of radiation dose, from the analysis of experimental data. However, the offset error, which can displace the output voltage drift curve, has a negative variation with the increase of total dose.

The offset error of D/A converter, independent of input digital data, arises from the zero-drift of junction field-effect transistor (JFET) input op-amplifier block. From the above study, we know that it is due to the drift of the emitter current of the input substrate PNP transistor under the total radiation dose when the D/A converter are irradiated by γ-rays. Although many new linear designs use a compensated input stage, it still has highly nonlinear response to total dose in the circuits. Owing to the limitation of research scope, there is not a reasonable model to describe the radiation dose effect on the integrated op-amplifier.

The radiation dose effect on the JFET input op-amplifier has been described in detail in Ref.[11], in which the displacement effect on the linear IC devices was also analysed.

There are two ways to reduce the distortion and drift of D/A converter in radiation environment. One is to increase shielding material, which would make an increase of weight and reduce heat elimination performance; the other way is to propose a model for DADD and then the compensation in D/A converter output can be achieved for further application.

5. DADD compensation network constructed based on ANFIS

With the inference capability of fuzzy logic (FL) and the learning capability of neural networks (NN), the neuro-fuzzy network (NFN) is more flexible and has a preferable capability in fitting a linear or nonlinear function.[12] These merits make it very suitable for DADD, which is a nonlinear data fitting application.

An ANFIS[12] based on the utilization of first-order Sugeno model[13] constitutes the main part of the DADD compensation network (DADDCN), and

the output signal of the D/A converter mixed with radiation distortion and drift can be expressed as

$$D(n) = D_{\mathrm{S}}(n) + D_{\mathrm{W}}(n), \tag{1}$$

where original input of D/A converter is $D_{\mathrm{S}}(n)$. $D_{\mathrm{W}}(n)$ is a distortion value due to the radiation dose $r_{\mathrm{k}}(n)$ through an unknown nonlinear dynamic transformation $f_{\mathrm{W}}(\bullet)$, the function of which is given by

$$D_{\mathrm{W}}(n) = f_{\mathrm{W}}(r_{\mathrm{k}}(n), r_{\mathrm{k}}(n-1), r_{\mathrm{k}}(n-2)\cdots). \tag{2}$$

The structure of DADDCN is shown in Fig.5, where $D_{\mathrm{W}}(n)$ is immeasurable, $D_{\mathrm{S}}(n)$ is measurable and $r_{\mathrm{k}}(n)$ can be measured by a radiometer; $\hat{D}_{\mathrm{W}}(n)$ is the ANFIS approximation of distortion value $D_{\mathrm{W}}(n)$, the function can be shown to be

$$\hat{D}_{\mathrm{W}}(n) = \hat{f}(r_{\mathrm{k}}(n), r_{\mathrm{k}}(n-1), r_{\mathrm{k}}(n-2)\cdots), \tag{3}$$

where $\hat{f}(\bullet)$ is the function which is implemented by ANFIS. $\hat{D}_{\mathrm{S}}(n)$ is the result of DADDCN, the equation is shown to be

$$\hat{D}_{\mathrm{S}}(n) = D(n) - \hat{D}_{\mathrm{W}}(n). \tag{4}$$

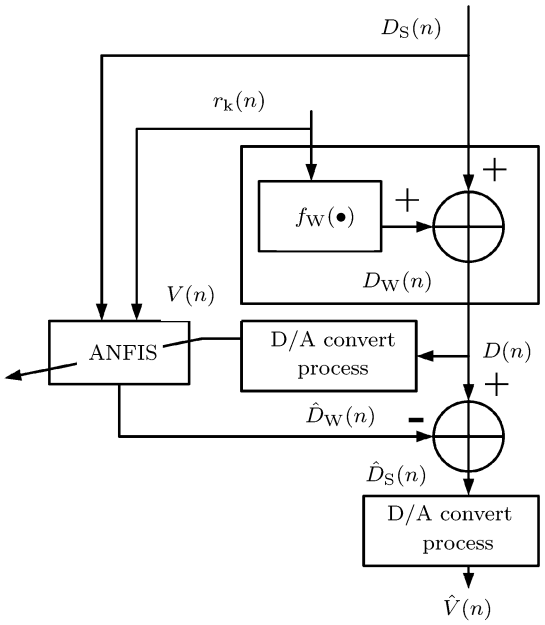


Fig.5. Structure of DADDCN.

Input signals in the ANFIS model are radiation dose $r_{\mathrm{k}}(n)$ and D/A converter original output $D_{\mathrm{S}}(n)$. The output signal is an ANFIS approximation of distortion value $\hat{D}_{\mathrm{W}}(n)$. Considering the approximation, we can divide the input dose $r_{\mathrm{k}}(n)$ and D/A converter original output $D_{\mathrm{S}}(n)$ into 4 parts on average and a bell-shaped function is used as the membership function of a network fuzzy set, which is defined as follows:

$$\mu(x) = \frac{1}{1 + \left|\dfrac{x - c_i}{a_i}\right|^{2b}}, \tag{5}$$

where x is the input variable, and a, b and c are premise parameters.

There are 5 layer nodes and 16 fuzzy if-then rules in the structure of ANFIS, in which 16 membership functions and 24 premise parameters are for layer 1, and 48 consequent parameters are for layer 4. There are totally 864 fitting parameters needed in the conventional ANFIS structure.

The compensation ANFIS should be trained by training data, so it is necessary to know the total radiation dose R_{total} and the dose rate P_{r} in practical application for ANFIS training. The distortion character of the D/A converter $V(n)$ can be obtained through a ground irradiation test based on R_{total} and P_{r}. The ANFIS was trained to minimize $E(\delta^2)$, and the function $\widehat{f}(\bullet)$ was changed to approach $f(\bullet)$ by least-square approximation and channel dynamic characters. For achieving this, the error mean-square estimation should be least,[14] and the equation used is as follows:

$$||\delta(n)||^2 = \min(||D_{\mathrm{S}}(n) - \hat{D}_{\mathrm{S}}(n)||^2). \tag{6}$$

A mixture algorithm has been used to train parameters of ANFIS for quickly identifying parameters. The training data is brought to the inputs, the premise parameters are assumed to be fixed and the optimal consequent parameters are estimated by an iterative least mean square procedure in the forward pass. In the reverse pass, the patterns are propagated again, but this time the consequent parameters are assumed to be fixed, and the back-propagation is used to modify the premise parameters.[13] The iteration training number of the ANFIS model is 1000; the minimum square estimation (MSE) between the practical system output and the model output is used as a network training index.

When using DADDCN in space radiation environment after the training process, the compensation value $\hat{D}_{\mathrm{W}}(n)$ will be calculated by ANFIS network. The output of D/A converter $\hat{D}_{\mathrm{S}}(n)$ is $\hat{D}_{\mathrm{S}}(n) = D(n) - \hat{D}_{\mathrm{W}}(n)$ after the compensation. Take $\hat{D}_{\mathrm{S}}(n)$ as the D/A converter output and convert it to the analogue voltage, which is approximate to the analogue voltage of $D_{\mathrm{S}}(n)$ in non-radiation environment.

As the DADDCN was tested in a radiation environment as above, we have the relationship between radiation dose $r_{\rm k}(n)$ and discrete time n as $r_{\rm k}(n) = n \times 1.5$, at a dose rate 1.5rad/s, with the D/A converter original input data $D_{\rm S}(n)$ being the height of step wave, as has been shown in Fig.3. The distortion curve of D/A converter output is shown in Fig.6. The distortion curve with compensation is shown by Line 1, compared with the distortion curve without compensation as shown by Line 2. The maximal residual of DADD compensation is 11.97mV in this test, while the total range is 4V. It is improved obviously as compared with the maximal residual of 3.72V at 10krad before compensation.

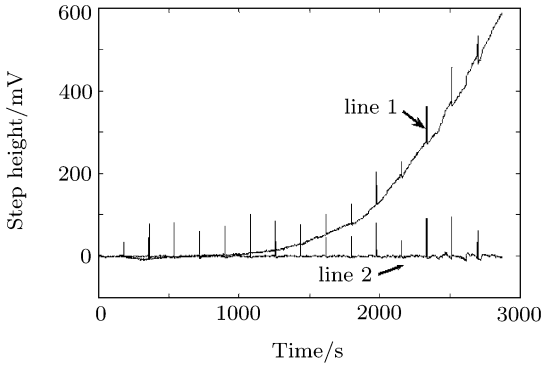


Fig.6. Distortion curve with compensation and curve without compensation.

6. Conclusion

The space radiation environment, which is a challenge for FOG space application, is full of various types of radiation sources. The performance degradation of FOGCC could be precisely confirmed only by sufficient experiments and tests,[15,16] which are the necessary passport to assure the reliability and lifetime of FOG.

The result of γ-ray radiation experiment was introduced, and it is demonstrated that the devices involved in FOGCC could endure the radiation of 10krad except for D/A converter and the degradation of D/A converter only made a negative variation of offset error due to the zero-drift of JFET input of op-amplifier block in D/A converter with the elemental analysis.

If there is ample time and outlay, the dose rate in γ-ray radiation experiment should be made with the radiation dose rate in the real space orbit, so that it will be more meaningful in studying the dose rate effect. The compensation network based on ANFIS proposed in this paper can only provide a simple compensation mode without the ability of self-adapting. A self-adapting block will be studied next, which can adapt the compensation parameters of ANFIS based on different dose rates to provide the best capability of compensation.

References

[1] Dollon M, Cros G, Sevellec A, Antoine P, Sa G M, Willemenot E, Urgell A, Hardy G, Loret T, Faussot N, Cottreau Y and Caiffe T 2003 *Proc. V. ESA Conf. On Spacecraft Guidance, Navigation and Control* SP**516** 41

[2] Kimoto Y, Nemoto N, Matsumoto H, Ueno K, Goka T and Omodaka T 2005 *IEEE Trans. Nucl. Sci.* **52** 1574

[3] Williams G M and Friebele E J 1998 *IEEE Trans. Nucl. Sci.* **45** 1531

[4] Mcllwain C E 1961 *J. Geophys. Res.* **66** 3681

[5] Pease R L, Johnston A H and Azarewicz J L 1988 *Proc. IEEE* **76** 1510

[6] Maurer R and Suter J 1987 *IEEE Trans. Nucl. Sci.* **NS34** 1757

[7] Stassinopoulos E G and Raymond J P 1998 *Proc. IEEE* **76** 1423

[8] Chen W, He B P and Wang G Z 2006 *Acta Phys. Sin.* **55** 3546 (in Chinese)

[9] Gao S J and Ouyang S W 2003 *Acta Phys. Sin.* **52** 1292 (in Chinese)

[10] Gong J C, He B P, Jiang J H, Luo Y H, Wang G Z and Zhou H 2003 *Acta Phys. Sin.* **52** 188 (in Chinese)

[11] Allan H J 2006 *IEEE Trans. Nucl. Sci.* **53** 1779

[12] Amaral T G B, Crisostomo M M and Pires V F 2002 *IEEE Int. Conf., Inrelligent Systems* **1** 67

[13] Sugeno M and Kang G T 1988 *Fuzzy Sets and Systems* **28** 15

[14] Jang J S R, Sun C T and Mizutani E 1997 Neuro-fuzzy and Soft Computing (Englewood Cliffs, NJ: Prentice-Hall) p75

[15] Liu H, Wei Q, He S Y and Zhao D 2006 *Chin. Phys.* **15** 1086

[16] Chen W, Yang Q W and Li W 2006 *Chin. Phys.* **15** 3000