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Adaptive Cancellation of Light Intensity Noise for Fiber Optic Gyroscope

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Abstract

In order to reduce the relative intensity noise (RIN) in the interferometric signal of the fiber optic gyroscope (FOG), an adaptive noise subtraction method is presented, which aims to overcome to the drawbacks that the fixed delay time and gain of the digital noise subtraction method. The drawbacks will make the performance of FOG to be degraded greatly in the changing environment. In the paper the adaptive noise subtraction system based on the recursive least squares algorithm (RLS) is formed in FPGA, in which the interferometric signal is regarded as the signal source, and RIN in the free end of the optical fiber coupler of FOG is looked as the noise reference signal. The two critical parameters that minimum delay time and its varying range result from measuring the minimum and maximum delay times of the interferometric signal in a certain temperature range. The off-line and on-line temperature experimental results verify the capability of adapting to the environmental temperature.

Keywords: *fiber optic gyroscope, relative intensity noise, recursive least squares*

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1. Introduction

The fiber optic gyroscope (FOG) based on optical Sagnac effect, by virtue of its many advantages contrasting to the mechanical gyro, has been widely used in these fields of inertial navigation and guidance, attitude control and so on [1]. The angle random walk coefficient is one of the most important performance parameters of FOG, and is employed to evaluate the noise level in FOG, which determines the signal-to-noise ratio (SNR) of the gyro. It is the simple method to enlarge the power of broadband light source in order to enhance signal noise ratio (SNR). However, with the increasing of light source power, the relative intensity noise (RIN) of the broadband light source becomes one of the significant factors of the SNR in FOG [2, 3].

There have been numerous methods to suppress RIN of the broadband light source, which include excessive modulation, external optical intensity modulation, gain-saturated optical amplifier, digital noise subtraction, etc. [4-7]. Owing to these advantages of the simple configuration and no insertion loss in the optical path of FOG, the digital noise subtraction method has been got more and more attentions. This method utilizes the correlation between RIN in the interferometric signal and RIN in the light signal at the free end of the optical fiber coupler in FOG [8, 9]. Through accurately adjusting the delay time and the added gain of RIN in the free end, and RIN can be subtracted from the interferometric signal in the digital circuit. However, there are some remarkable drawbacks that the delay time and the added gain are fixed in this method. So when the operating condition of FOG, especially the temperature is changed, the delay time and the gain of RIN in the interferometric signal will be changed, simultaneously. So the effect of this method will be degraded under the changing conditions, and under certain circumstance the performance of FOG could be degenerated seriously [4,10].

In order to solve the problems mentioned above, in the paper the adaptive noise subtraction method is presented, which is bases on the basic configuration of the digital noise subtraction method and adopts the recursive least squares algorithm (RLS). The rest of the paper is as follows: Section II analyses the impact of RIN on SNR of FOG. Section III introduces detailedly the configuration, the algorithm of the adaptive system and discusses the two critical parameters of the adaptive system. Section IV and Section V make the off-line and on-line

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temperature experiments to verify the effectiveness of the adaptive noise subtraction system. Finally, Section VI concludes the paper.

2. Impact of RIN on SNR

The angle random walk of FOG mainly consists of three contributors: thermal noise, shot noise and RIN. Thermal noise and shot noise can be expressed as $\left\langle i_T^2 \right\rangle = 4k_B T\Delta f / R_L$ and $\left\langle i_S^2 \right\rangle = 2e\left\langle I \right\rangle \Delta f$ respectively, where k_B is the Boltzmann constant, T is the temperature, Δf is the detection bandwidth, R_L is the feedback resistance of the transimpedance amplifier in the photoelectric detector, e is the electron charge, $\left\langle I \right\rangle$ is the average photocurrent. RIN is caused by the beating of various spectral components having random phases in the broadband light source, and represents the fluctuations of light intensity, which can be expressed as (1) [11]:

$$\left\langle i_R^2 \right\rangle = \frac{\left(1+\alpha^2\right)\left\langle I \right\rangle^2 \Delta f}{\Delta v} \tag{1}$$

Where α is the degree of polarization of the light source, and Δv is the linewidth of the broadband light source. So total noise in the interferometric signal of FOG is given by:

$$\begin{aligned}\left\langle i_N^2 \right\rangle &= \left\langle i_T^2 \right\rangle + \left\langle i_S^2 \right\rangle + \left\langle i_R^2 \right\rangle \\ &= \left[\frac{4k_B T}{R_L} + 2e\left\langle I \right\rangle + \frac{\left(1+\alpha^2\right)\left\langle I \right\rangle^2}{\Delta v}\right]\Delta f\end{aligned} \tag{2}$$

Where thermal noise is independent of the average photocurrent $\left\langle I \right\rangle$ and can be negligible compared with the other two terms. Shot noise is proportional to the average photocurrent $\left\langle I \right\rangle$, and RIN is proportional to the square of the average photocurrent $\left\langle I \right\rangle$. Therefore, with the light source power increasing, the RIN will replace shot noise and become a dominant noise. The sensitivity of FOG dependents on the level of SNR, and SNR of FOG is given by:

$$SNR = \frac{\left\langle I \right\rangle^2}{\left\langle i_N^2 \right\rangle} = \frac{\left\langle I \right\rangle}{\left[2e + \left(1+\alpha^2\right)\left\langle I \right\rangle / \Delta v\right]\Delta f} \tag{3}$$

Equation (3) shows that SNR can be improved by enlarging the light source power within a smaller range. But with the continually increasing light source power, the gyro's SNR will approach a saturation value gradually. Hence, RIN have to be suppressed in order to enhance the gyro's SNR [12].

3. Adaptive Noise Subtraction Method

The block diagram of the adaptive noise subtraction method is the same with the digital noise subtraction method, as shown in Figure 1. In the above figure, the emitting light of the light source moves to the 50%:50% ratio polarization maintaining 2×2 coupler (PM2×2) along the optic circuit, and then is split into the two same light beams. One of the two light beams is directed to the RIN detector (D2), the other travels through the integrated optic chip, fiber coil and PM2×2, and returns to the signal detector (D1) with Sagnac phase error finally. The signal reaching D2 will not contain Sagnac phase error, and its RMS variation will be overwhelmingly dominated by RIN. The light signal reaching D1, however, contains not only the Sagnac phase error but also the same RIN as D2. RIN to D1 is delayed the time by τ seconds compared with RIN to D2.

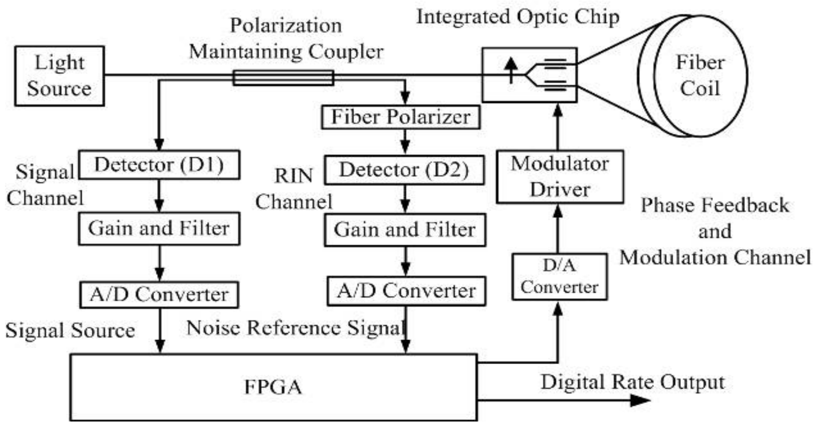


Figure 1. The block diagram of the adaptive noise subtraction method

At the same time, the attenuation of RIN to D1 is at least ten times larger than that of RIN to D2 due to their going through the different optic circuit. In Figure 1 the interferometric signal detected in D1 is given by:

$$s(t) = K_1 \left[I + i_R (t - \tau) \right] \cdot g(t) \tag{4}$$

Where K_1 is the optic circuit loss of the interferometric signal to D1. I is the average photocurrent. τ is the time it takes the light beams to travel through the fiber coil, and $\tau = 1/2 f_e$, f_e is the eigenfrequency of the fiber coil. $g(t)$ is the function of Sagnac effect, and is expressed by:

$$g(t) = 1 + \cos\left[\phi_b + \Delta\phi_s(t)\right] \tag{5}$$

Where ϕ_b is the phase bias, $\Delta\phi_s$ is Sagnac phase error. When Square wave phase modulation is used to provide $\pi/2$ phase bias, namely that $\phi_b = \pi/2$, (5) can be simplified as the following equation (6):

$$g(t) \approx \frac{1}{2}\left[1 + \Delta\phi_s(t)\right] \tag{6}$$

So equation (4) can be rewritten as follows:

$$\begin{aligned} s(t) &= \frac{1}{2} K_1 \left[I + i_R (t - \tau) \right] \cdot \left[1 + \Delta\phi_s(t)\right] \\ &= \frac{1}{2} K_1 \left[I + I \cdot \Delta\phi_s(t) + i_R(t-\tau) + i_R(t-\tau) \cdot \Delta\phi_s(t) \right] \\ &\approx \frac{1}{2} K_1 \left[I + I \cdot \Delta\phi_s(t) + i_R(t-\tau) \right] \end{aligned} \tag{7}$$

The RIN signal detected in D2 is given by:

$$x(t) = K_2 \left[I + i_R(t) \right] \tag{8}$$

Where K_2 is the optic circuit loss of the RIN signal to D2. After the two signals being processed by the same electric circuit such as the high-pass filter, the preamplifier and the synchronous sampling by A/D converter, the interferometric signal to D1 can be transformed into :

$$s(k)=\frac{1}{2}K_1A_1\left[I\cdot\Delta\phi_s(k)+i_R(k-N)\right] \tag{9}$$

And RIN signal to D2 can be transformed into:

$$x(k)=K_2A_2i_R(k) \tag{10}$$

Where A_1 is the gain of signal channel, A_2 is the gain of RIN channel, $N=\tau/T_s$ is the discrete time interval, T_s is the sampling period of A/D converter.

The digital noise subtraction method which is shown in Figure 2 is through adjusting properly the added gain K for the RIN signal, which makes $K=K_1A_1/2K_2A_2$, and then accurately delays L clock periods of FPGA, which makes $L\cdot T_c=N\cdot T_s=\tau$, T_c is the clock period of FPGA. Finally, the RIN signal can be subtracted directly from the interferometric signal. Copmare to the paper [13]. Here the rest of the interferometric signal doesn't contain the RIN signal, as shown in (11):

$$\begin{aligned}y(k)&=s(k)-K\cdot x(k)Z^{-L}\\&=\frac{1}{2}K_1A_1\left[I\Delta\phi_s(k)+i_R(k-N)\right]-K\cdot K_2A_2i_R(k-L)\\&=\frac{1}{2}K_1A_1I\Delta\phi_s(k)\end{aligned} \tag{11}$$

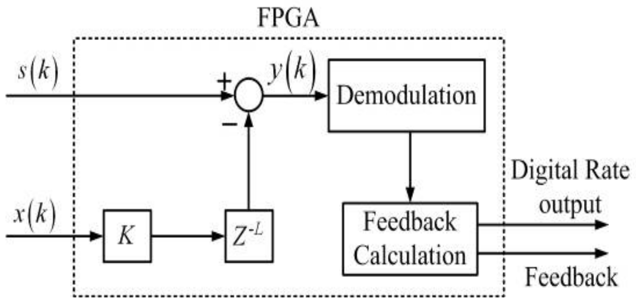


Figure 2. The diagram of the digital noise subtraction method

The effect of the digital noise subtraction method depends on the precision of the delay time and the added gain greatly. In the various working environment, the signal delay time is not always equal to τ but to $\tau+\Delta\tau$, $\Delta\tau$ is the changing amount of the delay time. So when this method directly is utilized, the effect of RIN suppression could not be satisfying. Especially, $\Delta\tau$ is equal to the half period of RIN signal, which causes the double RIN in the interferometric signal. Moreover the optic loss and the electric gain of FOG are also changed, which will further decrease the effect.

In order to enhance the reliability of the digital noise subtraction method, an adaptive noise subtraction system based on RLS is formed in FPGA, in which the interferometric signal $s(k)$ is regarded as the signal source, and the RIN signal $x(k)$ is regarded as the noise reference signal, as shown in Figure 3.

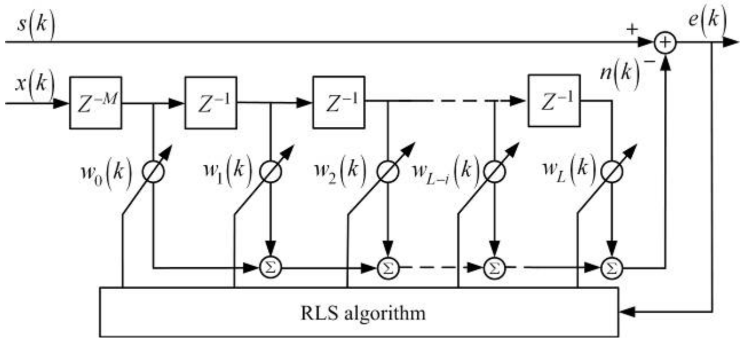


Figure 3. The diagram of the adaptive noise subtraction system

In the Figure 3,

$$n(k) = W(k) X^T(k),$$

$$X(k) = [x(k-M), x(k-M-1), \cdots, x(k-M-i), \cdots x(k-M-L)],$$

$$W(k) = [w_0(k), w_1(k), \cdots, w_{L-i}(k), \cdots, w_L(k)],$$

Where $X(k)$ is the delayed sequence of the noise reference signal, M is the delayed constant, L is the length of the delayed sequence of the RIN signal, $W(k)$ is the weighted coefficient vector, and $i = 0, 1, \cdots, L$. According to the content shown in Fig.3, the error signal $e(k)$ is given by:

$$\begin{aligned} e(k) &= s(k) - n(k) \\ &= \frac{1}{2} K_1 A_1 I \Delta\phi_s(k) + \frac{1}{2} K_1 A_1 i_R(k-N) - W(k) X^T(k) \end{aligned} \quad (12)$$

The principle of RLS is to adjust the weighted coefficient vector, and to make the sum of squares of the error signal to become a minimum value:

$$\begin{aligned} \varepsilon_{\min}(k) &= \sum_{i=0}^{L} e_i^2(k) = \sum_{i=0}^{L} [s(k) - w_i(k) x(k-M-i)]^2 \\ &= \sum_{i=0}^{L} \left[\frac{1}{2} K_1 A_1 I \Delta\phi_s(k) + \frac{1}{2} K_1 A_1 i_R(k-N) - w_i(k) x(k-M-i) \right]^2 \end{aligned} \quad (13)$$

Since RIN in the signal source is directly correlated to the noise reference signal, and the noise reference signal does not include the Sagnac phase error, so by adjusting automatically the weighted coefficient vector according to the RLS principle, when the delay time and the amplitude of RIN in the noise reference signal meets the following two conditions:

$$\begin{cases} N \cdot T_s = (M+i) \cdot T_c = \tau \\ K_1 A_1 i_R(k-N) = 2 w_i(k) x(k-M-i) \end{cases} \quad (14)$$

Equation (13) will reach the minimum value. Here RIN in the signal source is eliminated, and the error signal $\varepsilon(k)$ is:

$$e(k) \approx \frac{1}{2} K_1 A_1 I \Delta\phi_s(k) \tag{15}$$

In the configuration of the adaptive noise subtraction system, the two parameters of M and L are critical, which limit jointly the range of the delay time. The parameter M represents the minimum delay time within the range of the changing condition of FOG, while the parameter L represents the maximum variation of the delay time compared with the minimum delay time. For example, when the operating temperature environment of FOG has been changed in the temperature range. The delay time of the signal source $\tau \in [\tau_{\min}, \tau_{\max}]$, and the parameters of M and L can be calculated from the following equations.

$$\begin{cases} \tau_{\min} = 1/2 f_{\max} \\ \tau_{\max} = 1/2 f_{\min} \\ M = \tau_{\min} / T_c \\ L = (\tau_{\max} - \tau_{\min}) / T_c \end{cases} \tag{16}$$

Where T_c is the clock period of FPGA, $f_{\min}$ and $f_{\max}$ are the minimum eigenfrequency and the maximum eigenfrequency of FOG. After confirming M and L for the adaptive system, RLS algorithm begins to work on FPGA. Its steps include [13]:

Step1. initialization（$k = 0$）

$$\begin{cases} W(0) = 0 \\ R(0) = I \end{cases} \tag{17}$$

Step2. calculation ($k = 1, 2, \cdots end$)

$$\begin{cases} e(k) = s(k) - X^T(k) W(k-1) \\ R^{-1}(k) = R^{-1}(k-1) - \dfrac{R^{-1}(k-1) X(k) X^T(k) R^{-1}(k-1)}{1 + X^T(k) R^{-1}(k-1) X(k)} \\ W(k) = W(k-1) + R^{-1}(k) X^T(k) e(k) \end{cases} \tag{18}$$

4.The Off-Line Experiment

In the evaluating the effectiveness of the adaptive noise subtraction method, an off-line temperature experiment is constructed. In the experimental FOG the fiber pigtail from PM2×2 to D2 is aligned with a fiber polarizer (the extinction ratio of 30dB) so as to pass the same polarization mode of the light as D1, and D2 is with no integrated preamplifier. By setting properly the gain of the preamplifier attached to D2, to make sure the signal of D2 can not go beyond the sampling range of A/D converter in the RIN channel. Moreover, the clock frequency of FPGA is set at 200MHz, which can resolve precisely the delay time variation of 5ns.

The temperature range of the experiment is set from 0°C to 60°C. Moreover, the digital noise subtraction method is also employed so that the effect of the adaptive noise subtraction method is in contrast with the effect of the digital noise subtraction method. In the experiment firstly the eigenfrequency of the FOG is measured at 0°C and 60°C, and then calculate the delay times at the two temperatures, as shown in Table 1.

Table 1. Eigenfrequence and Delay Time

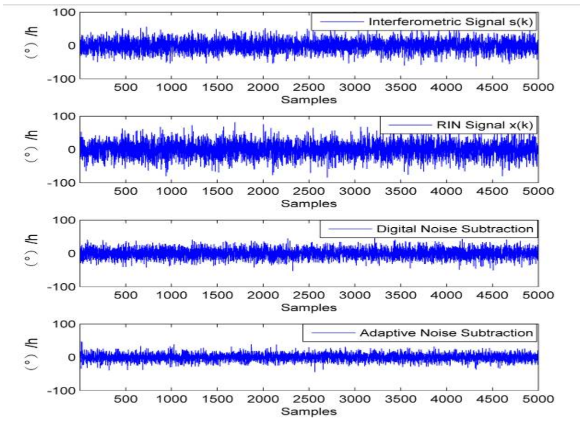
Temperature (℃)	Eigenfrequence (KHz)	***Delay Time (ns)***
0	252.40	1980.98
60	247.30	2021.84

Secondly according to Table 1 and (16) the two parameters of the adaptive noise subtraction system can be obtained, M is equal to 396 and L is equal to 8. Thirdly within the range from 0°C to 60°C, the experimental FOG is placed in the temperature box and to hold temperature at 10°C, 23°C and 50°C for an hour respectively, and to record the data of the interferometric signal and RIN signal. Finally the recorded data are off-line processed with the two methods. The effects of the two methods are shown in Figure 4, and the standard deviations of the interferometric signal disposed with the two methods are shown in table 2.

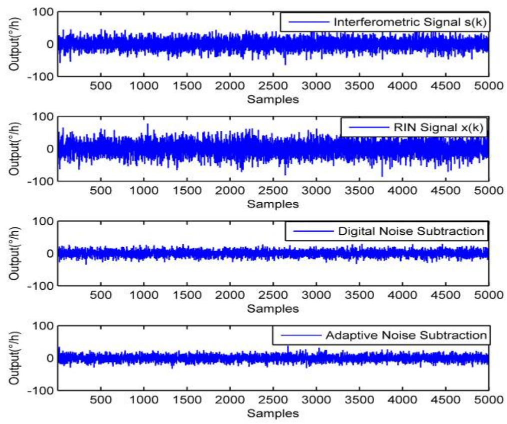
Table 2. Standard Deviation of the interferometric signal

Temperature (℃)	Interferometric Signal (°/h)	Digital Noise Subtraction (°/h)	***Adaptive Noise Subtraction (°/h)***
10	*17.39*	*14.04*	*10.52*
23	*15.26*	*8.98*	*8.78*
50	*18.59*	*20.95*	*11.61*

As shown in table 2, the two methods have the approximate same effects on suppress RIN at 23°C, but the effect of the digital noise subtraction method degrades remarkably at 10°C and 50℃. Especially, the noise level of the interferometric signal is not only to no reduce but to increase significantly at 50°C. While the adaptive noise subtraction method has always the better effect of suppressing RIN at three temperatures, and the standard deviation of the interferometric signal at each temperature, respectively, are decreased by 39.50%, 42.46% and 37.55%.

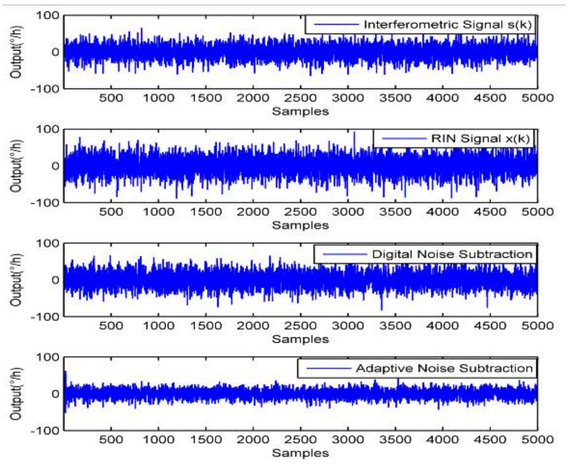


(a) Effects of two noise subtraction methods at 10°C



(b) Effects of two noise subtraction methods at 23°C

The reason of the results is that the delay time and the added gain is fixed in the digital noise subtraction method, which does not adapt to the changes of environment's temperature. In contrast, the adaptive noise subtraction method makes RIN signal to delay a series of time sequence and be weighted, the weighted coefficient of each delayed signal can be adjusted adaptively according to the RLS principle. So when the delay time of the interferometric signal changes during the time range determined by the parameter L, this method has the satisfied results. In the experiment the change of the each weighted coefficient is as shown in Figure 5. Figure 5 shows that: at 10°C, 23°C and 50°C, the RIN in the interferometric signal, in contrast with the minimum delay time parameter M at 0°C, delays respectively 1, 3 and 7 clock periods of FPGA. At three the delay times, the RIN in the interferometric signal has the largest correlation with the RIN noise reference signal, and at the others of the delay times the correlation is lower, so their weighted coefficients are almost the zero.



(c) Effects of two noise subtraction methods at 50°C

Figure 4. Comparison of two methods at the different temperature

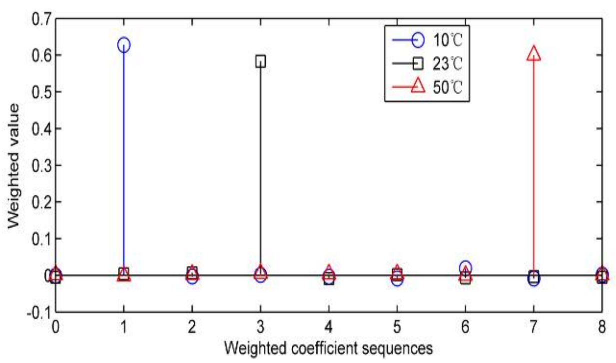


Figure 5. Weighted coefficient sequences

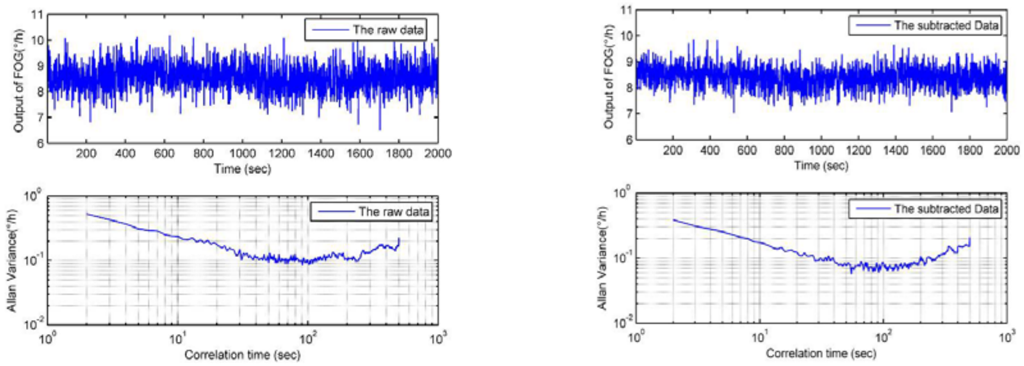
5.The On-Line Experiment

According to the data of the off-line experiment in the above section, to reduce the difficulty of implementation in FPGA, the parameter L of the adaptive system is set to 3, which can meet the delay time change from 0°C to 23°C of FOG. In the experiment the FOG is placed in the temperature box and to hold temperature at 10°C and 23°C for an hour, respectively, and to record the raw data and the subtracted data of FOG at the sampling frequency of 1Hz. At the each temperature, the output data of FOG and Its Allan variance curve is shown in Figure 6 and Figure 7.

Figure 6 and Figure 7 show that by employing the adaptive noise subtraction method at the two temperatures, the noise in the output data of FOG is reduced to a certain extent. The angle random walk coefficients of FOG derive from the results of Allan variance curve fitting with least squares algorithm, as shown in table 3. According to the data of table 3, the angle random walk coefficients of FOG are decreased by 31.57% at 10°C and by 24.68% at 23°C.

Table 3. Angle Random Walk Coefficients of FOG at 10°C and 23°C

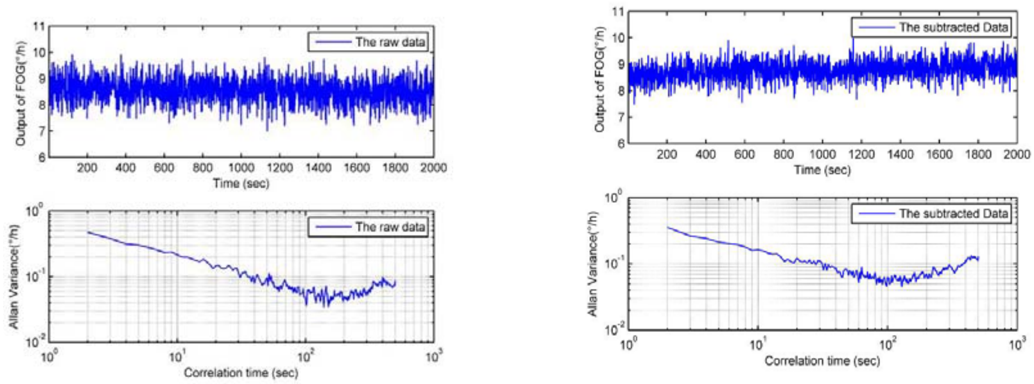
Temperature (℃)	The Raw Data (°/√h)	***The Subtracted Data (°/√h)***
10	0.00912	0.00624
23	0.00697	0.00525



(a) The raw data and its Allan variance at 10°C

(b) The subtracted data and its Allan variance at 10°C

Figure.6. Comparison of the raw and the subtracted data at 10°C



(a) The raw data and its Allan variance at 23°C

(b) The subtracted data and its Allan variance at 23°C

Figure 7. Comparison of the raw and the subtracted data at 23°C

Through the relad experiments, it can be found that the methods presented in the study can imrove the related performance according compare to the reference paper [7,9,11].

6. Conclusion and Future work

The adaptive noise subtraction method in the paper makes full use of the correlation of RIN in the interferometric signal and the signal in the free end of coupler of FOG. The advantages in contrast to the digital noise subtraction method are that its the delay time and gain are not fixed, moreover, in order to adjust automatically itself according to RLS principle. So this method is capable of adapting to the environmental change, at the same time the results of the off-line and on-line temperature experiment verify the effect. Because RLS algorithm refers to a great amount of the matrix operation, it will no doubt to add the difficulty of the implementation in FPGA. So the adaptive noise subtraction system has to employ much higher hardware configuration and computing speed to meet the calculation needs.

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