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Communication

Automatic Detection of Fiber Optic Gyroscope Intrinsic Frequency Based on Optimal Projection Approximation

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Abstract: To address the complexity and low detection accuracy issues in the intrinsic frequency detection process of fiber optic gyroscopes, a highly precise automatic measurement method based on optimal projection approximation is proposed. Building upon the digital closed-loop fiber optic gyroscope hardware circuit, this method generates a frequency-adjustable square wave with a 25% duty cycle through field-programmable gate array (FPGA) fractional division. Subsequently, it calculates the difference between the high and low levels of the sign bits of the modulated optical intensity signal sampled by the analog-to-digital converter (ADC). This yields an error signal related to the modulation frequency and intrinsic frequency. The modulation frequency is then approximated using the nearest projection of this error signal, thereby achieving automatic detection of the fiber optic gyroscope's intrinsic frequency. The experimental results indicate that this method, requiring no external auxiliary equipment, enables rapid and highly accurate measurement of the intrinsic frequency of the fiber optic gyroscope. The measurement of intrinsic frequency takes approximately 300 milliseconds, achieving a measurement accuracy of up to 0.001 Hz.

Keywords: fiber optics; fiber optic gyroscope; intrinsic frequency; optimal projection approximation; automatic detection

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1. Introduction

Fiber optic gyroscopes (FOGs), based on the Sagnac effect, are angular rate sensors known for their advantages such as compact size, solid-state structure, and high reliability [1–3]. High-precision fiber optic gyroscopes typically employ digital closed-loop control, which often requires modulation with a square wave signal at the same frequency as the intrinsic frequency. Deviations in the frequency of the square wave modulation signal from the intrinsic frequency can degrade the gyroscope's accuracy [4–6]. Particularly in applications like long-term navigation, rapid response, and precise tracking and high-precision inertial navigation, high accuracy in maintaining the modulation square wave at the intrinsic frequency is crucial [7,8]. Furthermore, the current method for measuring the intrinsic frequency typically involves equipment such as signal generators and oscilloscopes. Manual adjustment of the signal generator's output frequency is performed to set the output optical intensity signal's duty cycle to 50%, which is then taken as the fiber optic gyroscope's intrinsic frequency. This testing process is cumbersome and prone to errors. Yuefeng Qi et al. employed a new phase modulator that can simultaneously modulate the light waves transmitted in two different directions, which overcomes the modulation of traditional Y-waveguide phase modulator disadvantages of intrinsic frequency limitation. The research on the new phase modulator has made incremental progress but is still in the conceptual and laboratory stages [9]. Hence, there is a need to investigate high-precision methods for measuring the intrinsic frequency of fiber optic gyroscopes [10].

Currently, intrinsic frequency measurement methods can be broadly categorized into three types: those based on square wave modulation, sawtooth wave modulation, and sine wave modulation. Among these, square wave modulation-based intrinsic frequency algorithms measure the intrinsic frequency by examining the relationship between differently modulated square waves and the output optical intensity. They offer advantages such as speed and ease of implementation. A symmetric square wave modulation algorithm was proposed by Youwei Zhou et al., which employs equidistant continuous sampling over multiple cycles to determine the square wave duty cycle, reducing measurement costs and achieving an accuracy of 0.01 kHz [11]. In this scenario, the square wave modulation of the phase modulator is substituted with sine wave modulation to establish a connection between the second harmonic and the intrinsic frequency. Chen Yuzhong et al. determined the intrinsic frequency by measuring the second harmonic of the output optical intensity, achieving an accuracy of up to 2 Hz, an order of magnitude improvement over square wave modulation [12]. Wang Xiang et al. designed a method based on sawtooth wave modulation for measuring the intrinsic frequency. They changed the phase modulation waveform to a sawtooth wave, where the modulation error reflects the degree of deviation of the sawtooth wave modulation frequency from an even multiple of the intrinsic frequency. By adjusting the sawtooth wave frequency based on the modulation error and achieving zero modulation error, the frequency of the sawtooth wave signal becomes an even multiple of the intrinsic frequency, achieving a measurement accuracy of 1 Hz [9]. However, these intrinsic frequency measurement methods have relatively low efficiency and are susceptible to various interference sources in the optical and electrical paths, making it challenging to provide high measurement accuracy.

To address these challenges, this paper presents a low-cost, high-precision method for measuring the intrinsic frequency of fiber optic gyroscopes. In the FPGA, we generate a frequency-adjustable square wave signal with a 25% duty cycle through fractional division. By utilizing the relationship between the output optical intensity error, intrinsic frequency, and square wave modulation frequency, we employ the nearest projection approximation algorithm to eliminate measurement errors caused by various interferences in the optical and electrical paths during the fiber optic gyroscope's intrinsic frequency measurement. This approach enables accurate and cost-effective intrinsic frequency measurements.

2. Principles of Intrinsic Frequency Measurement

2.1. Intrinsic Frequency Measurement with Square Wave Modulation

The time τ_e taken for one round-trip propagation in the optical fiber loop of a fiber optic gyroscope is defined as the transit time. The intrinsic frequency of the fiber optic gyroscope is defined as:

$$f_e = 1/2\tau_e = c/2nL, \tag{1}$$

In Equation (1), n is the refractive index of the optical fiber, and L is the length of the fiber. The phase modulation signal $\varphi_m(t)$ is given by:

$$\varphi_m(t) = \begin{cases} \varphi_m & kT \le t \le kT + \tau/2 \\ 0 & kT + \tau/2 \le t \le kT + 2\tau \end{cases}, \tag{2}$$

In Equation (2), k is an integer, $T = 2\tau$ is the modulation period, φ_m is the modulation depth, and $f = 1/2\tau$ is the modulation frequency. When the modulation frequency is less than the intrinsic frequency, the modulation phase difference $\Delta\varphi_m(t)$ is:

$$\Delta\varphi_m(t) = \begin{cases} \varphi_m & kT \le t \le kT + \tau/2 \\ 0 & kT + \tau/2 < t \le kT + \tau_e \\ -\varphi_m & kT + \tau_e < t \le kT + \tau_e + \tau/2 \\ 0 & kT + \tau_e + \tau/2 < t < kT + 2\tau \end{cases}, \tag{3}$$

The light intensity I received by the photodetector after the optical wave has coherently propagated is:

$$I = I_0\{1 + \cos(\varphi_s + \Delta\varphi_m)\}, \tag{4}$$

In Equation (4), I_0 is the incident light intensity, and φ_s is the Sagnac phase shift. When the gyroscope is at rest, $\varphi_s = 0$, and the output light intensity I is:

$$I = \begin{cases} I_0\cos(\varphi_m) & kT \le t \le kT + \tau/2 \\ I_0 & kT + \tau/2 < t \le kT + \tau_e \\ I_0\cos(\varphi_m) & kT + \tau_e < t \le kT + \tau_e + \tau/2' \\ I_0 & kT + \tau_e + \tau/2 < t < kT + 2\tau \end{cases} \tag{5}$$

The output light intensity I with applied phase difference is illustrated in Figure 1.

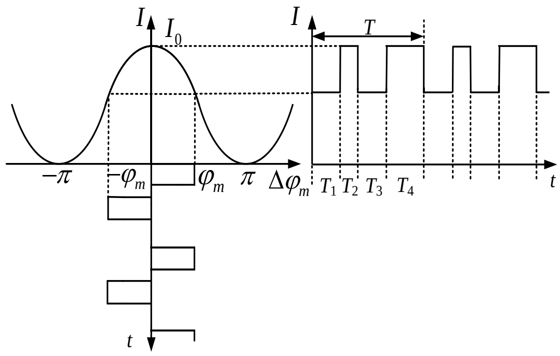

Figure 1. Diagram of light intensity with applied phase difference.

In Figure 1, within the modulation period T, the light intensity is divided into four segments, denoted as T_1, T_2, T_3, and T_4. The modulation frequency is generated using the phase accumulator principle, following these steps: a 20-bit frequency register is defined, and this register accumulates with the frequency control register x. When the frequency register overflows, it generates the modulation frequency signal. T_2 and T_4 are counted using the FPGA system clock with a frequency of f_{sys}, and the count difference is given by:

$$\Delta N = \frac{2^{22}}{x} - \frac{f_{sys}}{f_e}, \tag{6}$$

The analysis above indicates that when the count difference ΔN is zero, the intrinsic frequency of the fiber optic gyroscope is:

$$f_e = \frac{x f_{sys}}{2^{22}}, \tag{7}$$

However, due to factors such as fractional division error, circuit noise, and quantization error, the count difference often contains noise components, affecting the measurement of the fiber optic gyroscope's intrinsic frequency. The optimal projection approximation technique allows for the mapping of experimental data onto a specific functional space, thus eliminating noise interference and thereby enhancing the precision of measuring the intrinsic frequency of the fiber optic gyroscope.

2.2. Optimal Projection Approximation Algorithm

In accordance with Equation (1), we constructed the function space Span{1, $1/x$}. Applying the principle of nearest projection approximation, we set $\varphi_0 = 1$ and $\varphi_1 = 1/x$, thereby formulating the system of equations:

$$\begin{pmatrix} (\varphi_0, \varphi_0) & (\varphi_0, \varphi_1) \\ (\varphi_1, \varphi_0) & (\varphi_1, \varphi_1) \end{pmatrix} \begin{pmatrix} c_0 \\ c_1 \end{pmatrix} = \begin{pmatrix} (\Delta N, \varphi_0) \\ (\Delta N, \varphi_1) \end{pmatrix}, \tag{8}$$

If we define the range of x to be $[a, b]$, then:

$$\begin{cases} (\varphi_0, \varphi_0) = \int_a^b dx = b - a \\ (\varphi_1, \varphi_0) = (\varphi_0, \varphi_1) = \int_a^b \frac{1}{x} dx = \ln b - \ln a \\ (\varphi_1, \varphi_1) = \int_a^b \frac{1}{x^2} dx = \frac{1}{a} - \frac{1}{b} \\ (\Delta N, \varphi_0) = \int_a^b \Delta N dx \\ (\Delta N, \varphi_1) = \int_a^b \Delta N \frac{1}{x} dx \end{cases}, \tag{9}$$

Solving Equation (9) yields:

$$c_0 = \frac{f_{sys}}{f_e} \tag{10}$$

Hence, we obtain the intrinsic frequency of the fiber optic gyroscope with the nearest projection approximation.

3. Experimental and Results Analysis

3.1. FPGA Program Design

In the experiment, the fiber optic gyroscope used was the FOG-98 model, with a superluminescent light-emitting diode as the light source emitting at a wavelength (λ) of 1310 nm. The length of the optical fiber was 1275 m, resulting in an approximate intrinsic frequency of the fiber optic gyroscope of 83 kHz. To achieve automatic detection of the fiber optic gyroscope's intrinsic frequency using the optimal projection approximation, it was necessary to design functions within the FPGA based on the phase accumulator principle. These functions included fractional division, a 25% duty cycle square wave modulation, and counting the modulation intensity for each modulation state. In the fractional division section, the fractional division was set to be four times the intrinsic frequency. The bit width of the frequency register "Eige4Acc" was set to 21 bits, and the frequency control register "Eige4Inc" was configured. Assuming a system clock frequency of 39.9 MHz and an initial intrinsic frequency of 82 kHz, according to Equation (6), the initial value of "Eige4Inc" was set to 8409. The 25% duty cycle square wave modulation was designed to transition between four states (S1, S2, S3, S4) based on the overflow of "Eige4Acc." In the S1 state, the modulation depth was set to a certain value, while in states S2, S3, and S4, the modulation depth was set to 0. Counting the modulation intensity was accomplished by monitoring the high and low levels of the bits in the light intensity signal collected by AD9235. The counts for light intensity in the four modulation states (S1, S2, S3, S4) were denoted as count1, count2, count3, and count4, respectively. The count difference was obtained by subtracting count2 from count4. The FPGA program for automatic detection of the fiber optic gyroscope's intrinsic frequency using the optimal projection approximation was simulated, and the waveform is illustrated in Figure 2.

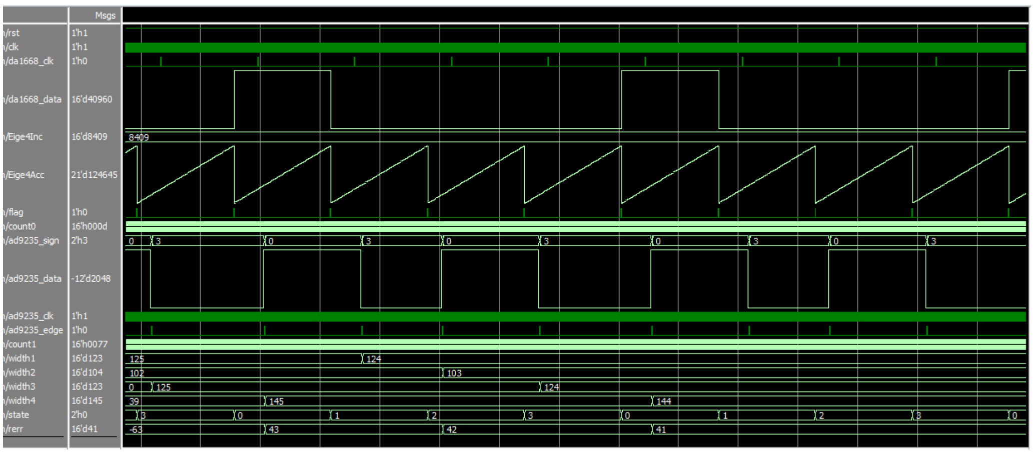

Figure 2. FPGA program simulation waveform for intrinsic frequency auto-detection.

Simulation results indicate that in states S1 and S3, the light intensity counts are equal. However, in states S2 and S4, due to a deviation between the modulation frequency and the intrinsic frequency of the fiber optic gyroscope, the light intensity counts are not equal. The difference in counts reflects the magnitude of the deviation between the modulation frequency and the intrinsic frequency.

3.2. Experimental Results and Analysis

Other hardware equipment used during the experimental process included the APS3005S-3D power supply, the FOG-98 fiber optic gyroscope, and a computer. The initial value of the modulation signal frequency was set to 82 kHz, and the modulation frequency was linearly varied through program control. Both the modulation frequency and count difference were transmitted to the computer via a serial port. In MATLAB, the intrinsic frequency of the fiber optic gyroscope was obtained using the optimal projection approximation. During the experiment, the frequency control register "Eige4Inc" increased by 1 every 1 millisecond, with an intrinsic frequency scanning range of 82 to 85 kHz. The experimental results are illustrated in Figure 3.

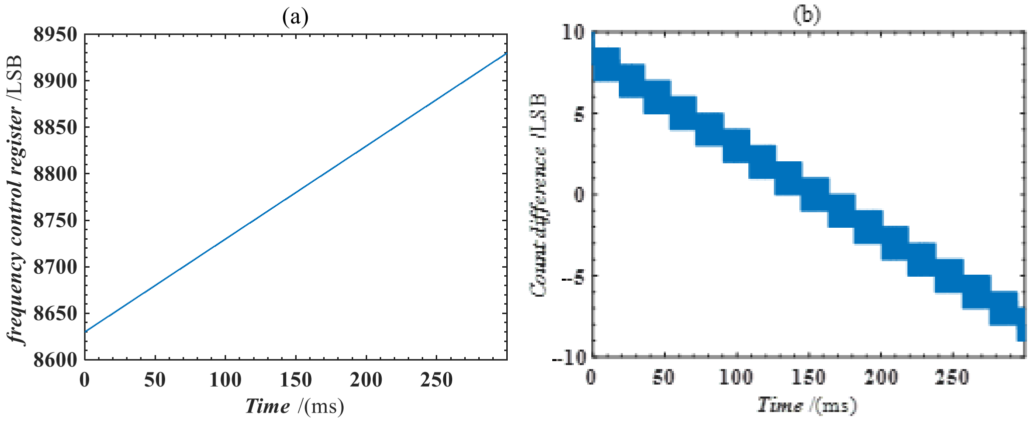

Figure 3. Intrinsic frequency scanning experiment results. (**a**) Frequency control register scanning results; (**b**) count difference scanning results.

Figure 3a illustrates the outcomes of the frequency control register scanning, while Figure 3b depicts the results of the count difference scanning. Notably, Figure 3b exhibits discernible noise, attributed to factors like fractional division errors, circuit noise, and quantization errors. Based on the experimental data, it is discerned that a = 8630 and b = 8929. Utilizing Equations (9) and (10), the intrinsic frequency of the fiber optic gyroscope is computed as 83,567.2534 Hz. Multiple measurements of the gyroscope's intrinsic frequency were undertaken, and the experimental results are tabulated in Table 1. The average of six measurements is 83,567.2532 Hz, with a standard deviation of 0.000675 Hz. This underscores that the automatic intrinsic frequency detection method, grounded in the optimal projection approximation, achieves an accuracy of 0.001 Hz with a testing time of less than 300 ms. The findings underscore that the precision of the measurement method proposed in this paper is indeed 0.001 Hz. Furthermore, the square wave modulation presented in this paper is relatively straightforward to implement in the FPGA and demands fewer FPGA resources in comparison to alternative methods.

Table 1. Multiple measurements of intrinsic frequency.

Test Result	1	2	3	4	5	6
Hz	83,567.2534	83,567.2540	83,567.2537	83,567.2526	83,567.2532	83,567.2522
Avg/Hz	83,567.2532					
Var/Hz	0.000675					

Experimental results demonstrate that the proposed method of measuring intrinsic frequency, utilizing a 25% duty cycle square wave modulation, achieves an accuracy of 0.001 Hz. Compared to other methods for measuring the intrinsic frequency of fiber optic gyroscopes, the automatic intrinsic frequency detection method based on the optimal projection approximation, as presented in this paper, is straightforward to implement, simple, effective, and offers high measurement precision.

4. Conclusions

This paper addresses the challenges of complexity and low detection precision in the intrinsic frequency detection process of fiber optic gyroscopes. To overcome these challenges, we employed the phase accumulator principle to generate a frequency-adjustable square wave with a 25% duty cycle. We then utilized the high and low levels of the sign bit in the intensity signal sampled by the ADC after modulation to calculate the count difference in modulation states S2 and S4. By employing the nearest projection approximation between the modulation frequency and the count difference, we successfully achieved automatic detection of the fiber optic gyroscope's intrinsic frequency. In the case of the FOG-98 gyroscope model, the intrinsic frequency measurement time was approximately 300 milliseconds, and the measurement accuracy reached 0.001 Hz. This advancement significantly enhances the efficiency and precision of intrinsic frequency measurement in fiber optic gyroscopes.

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