An improved measurement system for FOG pure lag time with no changing of FOG work status

X Chen, J H Yang*, Y L Zhou and X W Shu

College of Optical Science and Engineering, Zhejiang University, Hangzhou 310027, China
State Key Laboratory of Modern Optical Instrumentation (Zhejiang University), Hangzhou, Zhejiang, 310027, China

*Email: xxianhua@zju.edu.cn

Abstract. The minimum pure lag time is an important factor for characterizing the dynamic performance of fiber optical gyroscope. It is defined as the time duration from the reception of velocity-shock signal to the output of corresponding fiber-optic gyroscope data. Many engineering projects have required for this index specifically, so the measurement of the minimum pure lag time is highly demanded. In typically measurement system, the work status of tested FOG has to be changed. In this work, a FOG pure lag time measurement system without changing the work status of the FOG has been demonstrated. During the operation of this test system, the impact structure generated a shock towards the FOG, and the pure lag time was measured through data processing analysis. The design scheme and test principle have been researched and analyzed in detail. And a prototype has been developed and used for experiment successfully. This measurement system can realize a measurement accuracy of better than $\pm 3 \mu s$ and a system resolution of $10.86 \text{ns}$.

1. Introduction

Fiber-optic gyroscope (FOG) is an angular velocity sensor based on the Sagnac effect. It has shown great advantages such as small volume, light weight, wide range of accuracy, and no need for moving parts[1], and has been extensively applied in defense applications such as aviation, spaceflight, navigation, and weapons[2,3].

For the development of high speed FOG inertial navigation system[4], the pure lag time is a key index. The FOG pure lag time is defined as: the time duration from the reception of velocity-shock signal to the output of corresponding FOG data.

The minimum pure lag time directly reflects the instantaneity of FOG as well as its feedback ability.
for large dynamic angular velocity signal. As more and more attentions has been paid to rapid response weapons research projects[5-7], the index of FOG pure lag time has been required specially in such projects. Since pure lag time is related with FOG’s work status (such as temperature, communication frame rate, electromagnetic environment etc.), keeping the FOG at the normal work status is very important to get an accurate pure lag time[8,9].

In this paper, a convincing measurement system has been realized for FOG’s pure lag time measurement. This measurement system realized higher measuring accuracy in a convincing method with sampling rate equal to normal frame rate of FOG. The minimum pure lag time of a typical FOG product has been measured and error of the system has been analyzed.

2. Design of the measurement system

Before demonstrating pure lag time measurement system, it is necessary to introduce FOG data test system. FOG data test system is a proven system for quality test of FOG products, which collects data from tested FOG working normally[10].

Since in our system, FOG’s work status should remain as usual during the measurement, it becomes a solving idea that convincing pure lag measurement system can be developed based on the FOG data test system.

2.1. The scheme of pure lag time measurement system

As shown in figure 1(a), in a FOG data test system, the data from FOG is firstly preprocessed by data collection module, and then sent to upper computer for calculation. Figure 1(b) shows the data transmission scheme of pure lag time measurement system. Each time a frame of FOG data has been received, a time information would been measured, which reflects the time duration from the generation of velocity-shock signal. Then the frame of FOD data and the measured time information will be packaged together and sent to upper computer (as will discussed in Section 2.4).

![Diagram of measurement system](image)

**Figure 1.** Comparison of pure lag measurement system and data test system. (a) FOG data test system. (b) FOG pure lag time measurement system.

2.2. Principle of pure lag time measurement system

2.2.1 Establishing the time model of pure lag time measurement. Usually in the application of FOG, the FOG outputs data in fixed frame rate in their application, and the time interval for each frame of data is \( \Delta t \).

Then the time model of pure lag time test for FOG can be established as shown in figure 2. The corresponding moments that data collection module receives FOG data \( D_0, D_1, D_2 \ldots D_n \) are \( t_0, t_1, \ldots t_n \).
respectively. The angular velocity impact happens at $t_p$, which is located between $t_0$ and $t_1$. Then we can get

$$\Delta t_f = t_1 - t_0$$  \hspace{1cm} (1)$$

$$\Delta t_d = t_p - t_0$$  \hspace{1cm} (2)$$

$$\Delta t_b = t_1 - t_p$$  \hspace{1cm} (3)$$

where $\Delta t_f$ denotes the time interval between $t_p$ and the previous data reception moment $t_0$. And $\Delta t_b$ denotes the time interval between $t_p$ and the later data reception moment $t_1$.

Because of the existence of the time duration from the reception of velocity-shock signal to the output of corresponding FOG data (pure lag time), after the angular velocity impact happens, the previous FOG data ($D_{i-1}$ to $D_{i-1}$) remains unchanged until $D_i$ is received, which appears more than twice as large as $D_{i-1}$. Then it can be judged that the angular velocity impact has been firstly reflected by the received data $D_i$. And The pure lag time, $\Delta t_d$, can be described as:

$$\Delta t_d = t_i - t_p = \Delta t_b + (i - 1)\Delta t_f$$  \hspace{1cm} (4)$$

![Figure 2. Principle model of FOG pure lag measurement.](image)

2.2.2 Pure lag time measurement principle. For this system, during a pure lag time measurement, the position of $t_p$ is random. The value range of $\Delta t_b$ can be described as:

$$0 < \Delta t_b < \Delta t_f$$  \hspace{1cm} (5)$$

There is a minimum pure lag time $\Delta t_{d_{\text{min}}}$ for a certain work status of FOG. It is the minimum time duration from the reception of velocity-shock signal to the output of corresponding FOG data. $\Delta t_{d_{\text{min}}}$ is the true value of minimum pure lag time and here $\Delta t_{d_{\text{min-result}}}$ is defined as the measurement result of $\Delta t_{d_{\text{min}}}$.

If the work status of tested FOG is determined, its minimum pure lag time $\Delta t_{d_{\text{min}}}$ is also fixed. Here we determine a non-negative integer $m$ as

$$\left\lfloor \frac{\Delta t_{d_{\text{min}}}}{\Delta t_f} \right\rfloor = m$$  \hspace{1cm} (6)$$

$\left\lfloor \cdot \right\rfloor$ denotes the largest integer less than or equal to its argument.
There will be two different situations with different location of $t_p$ between $t_0$ and $t_1$.

(1) In the case that

$$\Delta t_f > \Delta t_b > \Delta t_{d\text{min}} - m\Delta t_f$$  \hfill (7)

Supposing that at the $t_i$ moment, the responding FOG data reflects the angular velocity impact, then the $i$ can be determined as:

$$i = m + 1$$  \hfill (8)

The pure lag time, $\Delta t_d$, can be described as:

$$\Delta t_d = \Delta t_b + m\Delta t_f$$  \hfill (9)

(2) While in another case that

$$\Delta t_{d\text{min}} - m\Delta t_f > \Delta t_b > 0$$  \hfill (10)

Supposing that at the $t_i$ moment, the responding FOG data reflects the angular velocity impact, then the $i$ can be determined as:

$$i = m + 2$$  \hfill (11)

The measurement result of pure lag time, $\Delta t_d$, can be described as:

$$\Delta t_d = \Delta t_b + (m + 1)\Delta t_f$$  \hfill (12)

2.2.3 Analysis of measurement result of pure lag time. Each time of measurement a pure lag time, $\Delta t_d$, can be gotten and the number of FOG data, $i$, which reflects the angular velocity impact. After enough times of measurement, a measured value of minimum pure lag time, $\Delta t_{d\text{min}}$, can finally be gotten as described later in this article.

As mentioned in the previous section, a tested FOG with determined work status has a certain value of minimum pure lag time $\Delta t_{d\text{min}}$. For the number $i$, there are two cases which correspond to $i_1$ and $i_2$ respectively (as determined by equation (8) and (11)). $i_1$ and $i_2$ meets the relationship below

$$i_2 - i_1 = 1$$  \hfill (13)

And parameter $m$ in equation (6) can be determined by equation (8) and equation (11) as follow:

$$m = i_1 - 1$$  \hfill (14)

Or

$$m = i_2 - 2$$  \hfill (15)

In the $i_1$ case, the value range of $\Delta t_{d\text{min}}$ can be determined by the measurement result $\Delta t_d$ through equation (7) and equation (9):

$$\Delta t_{d\text{min}} < \Delta t_d$$  \hfill (16)

In the $i_2$ case, the value range of $\Delta t_{d\text{min}}$ can be determined by the measurement result $\Delta t_d$ through equation (10) and equation (12):

$$\Delta t_{d\text{min}} > \Delta t_d - \Delta t_f$$  \hfill (17)

According to equation (16) and equation (17), repeating the measurement for some times, the
minimum value of measurement results of $\Delta t_d$ in the case of $i = i_1$ can be described as

$$\Delta t_{ds} = \left\{ \left[ \Delta t_d \right]_{i=i_1} \right\}_{\min}$$

(18)

And the maximum value of measurement results of $(\Delta t_d - \Delta t_f)$ in the case of $i = i_2$ can be described as

$$\Delta t_{dy} = \left\{ \left[ (\Delta t_d - \Delta t_f) \right]_{i=i_2} \right\}_{\max}$$

(19)

Then $\Delta t_{d_{\min}}$ can be limited in a certain range as

$$\Delta t_{ds} > \Delta t_{d_{\min}} > \Delta t_{dy}$$

(20)

Then $\Delta t_{d_{\min}\_result}$ can be determined as

$$\Delta t_{d_{\min}\_result} = \frac{\Delta t_{ds} + \Delta t_{dy}}{2}$$

(21)

The uncertainty of the measurement result of minimum pure lag time $\Delta t_{d_{\min}}$ can be described as below

$$\delta_{\text{result}} = \frac{\Delta t_{ds} - \Delta t_{dy}}{2}$$

(22)

The measurement result of $\Delta t_{d_{\min}}$ can be denoted by the form of $\Delta t_{d_{\min}\_result} \pm \delta_{\text{result}}$.

2.3. The design of trigger module

Trigger module is constituted of two parts: impact structure and trigger circuit. The impact structure consists of sliding block and impacted body. The impacted body is fastened to a rotary table. Once the sliding block is released and shocks the impacted body, the impacted body will drive the rotary table[11]. In this way, the angular velocity impact can be delivered to the tested FOG. There is an electrode at the contact segment of sliding block and impacted body, so electric pulse can be generated as soon as the angular velocity impact is delivered to the tested FOG. The trigger module can guarantee that the angular velocity impact and the electric pulse occur at the same time, in order to realize the precise record of angular impact moment.

2.4. Design of data collection and procession module

F28M35 of TI has been chosen as processing core of data collection and procession module. Figure 3 shows the working process of data collection and procession module.
Figure 3. Working schematic diagram of data collection and processing module.

The packaged data received by upper computer consists of three parts: frame header, FOG data, and time information. The time information is determined by a 16-bits data, \( c \). The most significant bit of time information is used as flag bit. For this measurement system, as long as \( c \) equals to 0xffff, the recorded time duration is determined. And the resolution of system is equivalent to timer resolution, which described as

\[
\mu = \frac{\Delta t_{FS}}{2^{15} - 1}
\]  

3. Realization of the measurement system

Pure lag time of FOG has been tested in the completed prototype of measurement system. The tested FOG works in broadcasting mode with a communication frame rate of 2KHz. The FOG has been tested for 10 times and the measurement result and analysis are explained below.

For this tested FOG, the time interval \( \Delta t \) between adjacent FOG data is 500 \( \mu s \). The measurement results are shown in Table.1, which are arranged and numbered from small to large for convenience.

| \( \Delta t_i \) (\( \mu s \)) | i | \( \Delta t_j \) (\( \mu s \)) | \( \Delta t_i - \Delta t_j \) (\( \mu s \)) |
|----------------|---|----------------|----------------|
| 244.83         | i1 | 244.83         | -              |
| 286.65         | i1 | 286.65         | -              |
| 354.81         | i1 | 354.81         | -              |
| 446.42         | i1 | 446.42         | -              |
| 486.91         | i1 | 486.91         | -              |
| 534.73         | i2 | -              | 34.73          |
| 581.28         | i2 | -              | 81.28          |
| 659.36         | i2 | -              | 159.36         |
| 702.59         | i2 | -              | 202.59         |
| 739.47         | i2 | -              | 239.47         |

As shown in the table, measurement results from group 1 to group 5 fit the case described by equation(7) and equation(8). According to equation (16), the upper limit of \( \Delta t_{\text{min}} \) can be get from corresponding \( \Delta t \), and the result of these upper limits are arranged in the 1st column of Table.1.
Measurement results from group 6 to group 10 fit the case described by equation (10) and equation (11). According to equation (17), the lower limit of \( \Delta t_{\text{min}} \) can be get from their \( \Delta t \), and the result of these lower limits are arranged in the 10th column of Table 1.

### 3.1. Measurement results and measurement accuracy

From equation (18), \( \Delta t_{dx} \) can be gotten as

\[
\Delta t_{dx} = \left[ \left[ \Delta t_{d} \right]_{n=n_1} \right]_{\text{max}} = 244.83 \mu s
\]

From equation (19), \( \Delta t_{dy} \) can be gotten as

\[
\Delta t_{dy} = \left[ \left[ \Delta t_{d} \right]_{n=n_2} \right]_{\text{max}} = 239.47 \mu s
\]

According to equation (21), (24) and (25), the measurement result of \( \Delta t_{\text{min}} \) can be gotten as

\[
\Delta t_{\text{min-result}} = \frac{\Delta t_{dx} + \Delta t_{dy}}{2} = 242.15 \mu s
\]

And the measurement uncertainty can be gotten from equation (22)(24)(25) as

\[
\delta_{\text{result}} = \frac{\Delta t_{dx} - \Delta t_{dy}}{2} = 2.83 \mu s
\]

Therefore, the measurement result of minimum pure lag time can be described as

\[
\Delta t_{\text{min-result}} \pm \delta_{\text{result}} = (242.15 \pm 2.83) \mu s
\]

### 3.2. System resolution

The system resolution of a completed measurement system is certain. The recorded time duration \( \Delta T_{FS} \) is 3.560 \( \mu s \) once the c is set to 0xffff (as mentioned in Section 1.3). So the system resolution can be gotten as

\[
\mu = \frac{\Delta T_{FS}}{2^{15}-1} = \frac{3.560 \mu s}{2^{15}-1} = 108.6 ns
\]

### 4. Conclusion

Keeping the FOG at the normal work status is very important to get an accurate test result of pure lag time. Based on the FOG data test system, a measurement system of FOG pure lag time has been designed and realized. This measurement system can realize accurate pure lag time measurement without changing the FOG’s work status. In the construction of test system, trigger module was designed to generate angular-velocity impact, and test data was collected and analyzed by data collection and procession module. The prototype has been developed and the pure lag time of FOG product has been measured successfully. A measurement uncertainty of \( \pm 2.83 \mu s \) and system resolution of 108.6ns have been achieved. In the follow-up research, the system can be further improved by controlling the moment of angular velocity impact precisely by program, so that the high accuracy can be gotten easily and the testing efficiency can also be improved.
References

[1] Zhang G C 2008 The Principle and Technologies of Fiber-Optic Gyroscope (Beijing: National Defense Industry Press)

[2] Sanders G A, et al. 2016 Fiber optic gyroscope development at Honeywell Spie Comm. + Sci. Sens. Imaging 9852 985207.

[3] Minakuchi S, Sanada T, Takeda N, Mitani S, Mizutani T, Sasaki Y and Shinozaki K 2015 Thermal strain in lightweight composite fiber-Optic gyroscope for space application. J. Lightwave Technol. 33 2658-62.

[4] Jin J, Song N F and Zhang C X 2002 Design of high speed detection circuit for fiber-optic gyroscope J. Chinese Inertial Tech. 10 49-53.

[5] Zhou Y L 2015 Application of over modulation technique in fiber optic gyroscope north-seeking. J. Zhejiang Univ. (Engineering Science) 49 1817-1820.

[6] Wang Y Z, Ma L, Yu H, Gao H Y and Yuan Y J 2016 Int. Symp. Optoelectronic Tech. Appl. 10158 101580S

[7] Yoon Y G, Lee S M and Kim J H 2015 J. Inst. Control 21 168-172.

[8] Xue N, Liu R, Zhang C, Zhou H, Wang L, Shu X W and Chen X F 2011 A FOG output delay time measurement device and its measuring method. CN 201110090599.9

[9] Chen X, Zhou Y L, Yang J H and Shu X W 2015 A pure lag time measurement device and its measuring method. CN 201510612439.4

[10] Liu S, Chen M and Zhao L 2007 Design of fiber optical gyroscope test data collecting system Computer Measurement & Control 15 972-974.

[11] Wang Y Y, Zhou Y L, Yang J H, Chen X F and Liu C 2015 A programmable impact device for pure lag time test. CN201320612757.7