Uncertainty evaluation for single-axis interferometric fibre optic gyroscope

Z Fan\textsuperscript{1}, Q Sun\textsuperscript{1}, L Du\textsuperscript{1}, J Bai\textsuperscript{1}, J Liu\textsuperscript{1,2}
\textsuperscript{1} Division of Mechanics and Acoustics, National Institute of Metrology, North 3\textsuperscript{rd} Ring Road 18, Beijing, China
\textsuperscript{2} School of Instrument Science and Opto Electronics Engineering, Beijing Information Science & Technology University, North 5\textsuperscript{th} Ring Road 12, Beijing, China

E-mail: fanzhe@nim.ac.cn

Abstract. Due to the lack of verification regulation and calibration specification for single-axis interferometric fibre optic gyroscope in China, its uncertainty evaluation is studied for the first time. The test system based on rate table is built, and the calibration experiment has been conducted. The dominant uncertainties contributed by rate table, data acquisition system, repeatability, scale factor and bias are analyzed. The combined uncertainty of the fibre optic gyroscope is $7.7 \times 10^{-5}$ and the expanded uncertainty is $U=1.5 \times 10^{-4}$, $k=2$.

1. Introduction
Fibre optic gyroscope (FOG) is one of the most precise instruments for angular velocity measurement based on fibre Sagnac effect\textsuperscript{[1]}. Comparing with the traditional mechanical gyroscope, FOGs have no moving parts, so they are reliable and insensitive to vibration and shock. Due to the advantages of FOGs like digital output, wide dynamic range, short start-up time, very high sensitivity, it has been widely used in the modern defense industry and civil production areas such as weapons systems, mineral exploration, earthquake prediction, ocean survey, geodetic mapping and so on\textsuperscript{[2,3]}. Fibre optic gyroscope is thought to be one alternative to the mechanical gyroscope, and even it can replace laser gyroscope in some high-precision areas. With the development of FOG technology and the wide application of productions, it becomes important to test the performance of FOGs and evaluate the uncertainty of FOGs for further improvement.

Most of the recent research on the test of FOGs focuses on the test method. IEEE Std 952-1997\textsuperscript{[4]} gives the specification and test requirements for a single-axis interferometric fibre optic gyro and provides a compilation of recommended procedures for testing a fibre optic gyro. GJB 2426-2004\textsuperscript{[5]} lists the main parameters under test and introduces the standard test procedure of FOGs. However, there is lack of verification regulation and calibration specification in China until now, and uncertainty for single-axis interferometric FOGs is one of the key.

This paper firstly introduces the Sagnac effect and basic configuration of FOG. Secondly, the test system is built and the calibration experiment is conducted. Finally, the uncertainty of the measurement by fibre optic gyroscope is evaluated.

2. Basic principles and test system

\textsuperscript{1} fanzhe@nim.ac.cn
2.1. Fibre optic gyroscope
The basic scheme of a fibre optic gyroscope is shown in Figure 1.

Interferometric fibre optic gyroscope uses ASE broadband light source to serve the input signal light. Then a coupler is applied to split the input signal light into two counterpropagating waves, clockwise wave (CW) and counterclockwise wave (CCW). When the two waves pass through the long distance fibre ring, they will recombine on the photodetector (PD). Due to the Sagnac effect, a phase difference of the two waves would be produced when the FOG spins.

\[
\Delta \phi = \frac{2\pi LD}{\lambda c} \cdot \Omega \tag{1}
\]

where \( \lambda \) is the wavelength in vacuum, \( D \) and \( L \) is the diameter and length of the fibre ring respectively, and \( \Omega \) is the angular velocity of the FOG.

In general, we gain the measured voltage that is linear with the phase difference by open loop detection or closed-loop detection. The output model of the FOG is obtained by least squares linear fitting

\[
Y = K \Omega + F_0 \tag{2}
\]

\[
K = \frac{\sum_{j=1}^{M} \Omega_j \cdot Y_j - \frac{1}{M} \sum_{j=1}^{M} \Omega_j \cdot \sum_{j=1}^{M} Y_j}{\sum_{j=1}^{M} \Omega_j^2 - \frac{1}{M} \left( \sum_{j=1}^{M} \Omega_j \right)^2} \tag{3}
\]

\[
F_0 = \frac{1}{M} \sum_{j=1}^{M} Y_j - \frac{K}{M} \sum_{j=1}^{M} \Omega_j \tag{4}
\]

where \( K \) is the scale factor, and \( F_0 \) is the bias of linear fitting, which is caused by the rotation of the earth, the additional phase produced by Shupe effect and Kerr effect. \( Y_j \) is the average measured voltage at the j-th measurement, and it can be calculated by the following equation.

\[
Y_j = \frac{1}{N} \sum_{i=1}^{N} Y_{ji} - \frac{1}{2N} \left( \sum_{i=1}^{N} Y_{si} + \sum_{i=1}^{N} Y_{ei} \right) \tag{5}
\]

where \( Y_{si} \) and \( Y_{ei} \) is the measurement voltage while the rate table is stationary in the beginning and at the end respectively.

2.2. Test system and results
Rate table test system is built to evaluate the uncertainty of the FOG as shown in Figure 2. The rate table include a direct drive brushless motor, and is designed to provide superior angular velocity. Angular velocity range of the rate table is \((0.002 \sim 1500) \degree/s\). Its rate stability is 0.0001% over 360°. We can conveniently control the real-time speed of the rate table on the computer. The FOG (model: F70S) is fixed firmly to the tabletop by the use of special clamp apparatus. The output results are displayed on the other computer.

After warming up, continuously set the input angular velocity to static, \( \pm 5\degree/s, \pm 10\degree/s, \pm 15\degree/s, \pm 30\degree/s, \pm 60\degree/s, \pm 90\degree/s, \pm 150\degree/s, \pm 180\degree/s, \pm 200\degree/s, \pm 250\degree/s, \pm 300\degree/s \) and static. The measured results
are shown in Figure 3. In each test, no less than 50 data is acquired. The measured voltage can be expressed as \( Y = 8.89106 \times \Omega + 0.02553 \), and the unit is mV.

\[
Y = 8.89106 \times \Omega + 0.02553
\]

The measured voltage can be expressed as \( Y = 8.89106 \times \Omega + 0.02553 \), and the unit is mV.

\[
Y = 8.89106 \times \Omega + 0.02553
\]

3. Uncertainty evaluation

Below, we provide a detailed uncertainty analysis on fibre optic gyroscope. According to the equation (2) and ISO 98-3[6], the model of uncertainty of angular velocity is given as

\[
u^2(\Omega) = \frac{u^2(Y)}{K^2} + \frac{u^2(F_0)}{K^2} + \left( \frac{Y - F_0}{K^2} \right) u^2(K)
\]

(6)

3.1. Rate table

The rate table contains a high precision photoelectric encoder with 377600000 cnts per rev, and servo loop control technology is applied. The uncertainty of rate table is given by a rotation speed measurement system, and it is \( U_{rel} = 1.0 \times 10^{-5}, k = 2 \).

3.2. Data acquisition system

High precision 6-1/2 digits or 7-1/2 digits voltmeter or multimeter is always used to test the output voltage. Here a digital acquisition part is integrated in the fibre optic gyroscope. It will give 3.0\times10^{-5} uncertainty in angular velocity measurement.

3.3. Repeatability

As is shown above, 50 data is acquired continuously in the same condition. 3\sigma law is applied to eliminate all the outliers in each test. Table 1 shows the contribution to the uncertainty.

\[
\begin{array}{cccc}
\text{Angular velocity (°/s)} & \text{Standard uncertainty (mV)} & \text{Angular velocity (°/s)} & \text{Standard uncertainty (mV)} \\
\text{Static} & 4.3\times10^{-4} & +30 & 5.9\times10^{-3} & +180 & 1.7\times10^{-2}
\end{array}
\]
The relative standard uncertainty is below 5.0×10^{-3}.

3.4. Scale factor

According to the equation (3), the uncertainty of the scale factor can be obtained that

\[ u^2(k) = \frac{\sum_{i=1}^{M} (\Omega_i^2 + \bar{\Omega}^2) - u^2(Y_i)}{\left( \sum_{i=1}^{M} \Omega_i^2 - M \cdot \bar{\Omega}^2 \right)^2} \]

where \[ u^2(Y_i) = \frac{1}{50} u^2(Y_x) + \frac{1}{200} (u^2(Y_u) + u^2(Y_t)) \]

and \[ \bar{\Omega} = \frac{1}{M} \sum_{i=1}^{M} \Omega_i = 0 \]. Submit all the parameters into the equation. Then the standard uncertainty of scale factor is 2.1×10^{-6}.

3.5. Bias

According to the equation (4), the uncertainty of the bias can be obtained that \[ u^2(F_0) = \frac{1}{M^2} \sum_{i=1}^{M} u^2(Y_i) \].

The standard uncertainty of bias is 2.7×10^{-4}.

3.6. Combined uncertainty

The combined uncertainty of the fibre optic gyroscope is 7.7×10^{-5} according to the discussion above. The expanded uncertainty is calculated to be U=1.5×10^{-4} for the coverage factor of 2 (k=2).

4. Conclusions

The uncertainty of single-axis interferometric fibre optic gyro is evaluated for the first time in China. The dominant uncertainties contains rate table, data acquisition system, repeatability, scale factor and bias are given. The analysis shows the combined uncertainty of the fibre optic gyroscope is 7.7×10^{-5} and the expanded uncertainty is U=1.5×10^{-4}, k=2.

Acknowledgments

This work is supported by National Key R&D Program of China for National Quality Infrastructure under Contract No. 2017YFF0204905, General Administration of Quality Supervision, Inspection and Quarantine of the People’s Republic of China under Contract No. ANL1613 and National Institute of Metrology under Contract No. AKYC17110.

5. References

[1] Narasimhappa M, Sabat S L, Nayak J 2014 IET Science, Measurement & Technology 9 241
[2] Perez R J, Alvarez I, Enguita J M 2016 Sensors 16 604
[3] Minakuchi S, Sanada T, Takeda N Journal of Lightwave Technology 2015 33 2658
[4] IEEE STD 952-1997(R2003) Guide and test procedure for single-axis interferometric fiber optic gyros 2003
[5] GJB 2426A-2004 Test methods for fiber optic gyroscope 2004
[6] ISO/IEC GUIDE 98-3 Guide to the expression of uncertainty in measurement 2008