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A DYNAMIC ANGLE METROLOGY SYSTEM BASED ON FIBRE-OPTIC GYROSCOPE AND ROTARY TABLE

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Abstract

Dynamic angle measurement (DAM) plays an important role in precision machining, aerospace, military and artificial intelligence. Because of its advantages including high sensitivity, solid state and miniaturization, fibre-optic gyroscope (FOG) has great application prospects in the field of DAM. In this paper, we propose a dynamic angle metrology method based on FOG and a rotary table to evaluate the DAM accuracy with FOG. The system synchronously collects data from the FOG and rotary table, and analyses the DAM accuracy of the FOG for different sway conditions compared with that of the angle obtained from the rotary table. An angle encoder in the rotary table provides absolute or incremental angular displacement output with angular displacement measurement accuracy of 10″ (0.0028°) and angular displacement repeat positioning accuracy of 3″ (0.00083°), and can be used as an angle reference. The experimental results show that the DAM accuracy of the FOG is better than 0.0028° obtained with the angular encoder, and the absolute DAM accuracy of the FOG is better than 0.0048° for given conditions. At the same time, for the multi-path signal synchronization problem in the metrology field, this paper proposes a signal delay measurement method combining test and algorithm procedures, which can control a delay within 25 µs.

Keywords: circular grating angle encoder, fibre-optic gyroscope, dynamic angle metrology.

1. Introduction

Dynamic angle measurement (DAM) is an important part of geometric measurement [1–4]. The real-time online measurement technology with dynamic angular quantity has been paid more and more attention, and plays an important role in the fields of precision machining, aerospace, military and artificial intelligence [3, 5–7]. With the development of technologies, various DAM methods have been proposed, and the measurement resolution and accuracy have been greatly improved.

Among the existing methods, circular grating, laser interference, *position sensitive device* (PSD) and self-collimation technology, CCD image processing [8] and computer vision technology [6] can be considered as DAM methods. In the field of metrology, circular grating is an important basic component of modern photoelectric precision angle measuring instruments and technology [9–11]. It is a high-precision and high-resolution method. At present, manufacturing precision and resolution of the circular grating photoelectric shaft encoder can be achieved perfectly. A 27-bit incremental circular shaft encoder designed and manufactured by Heidenhain GmbH for the Italian Galileo telescope control system has an angular accuracy of 0.036″ and a resolution of about 0.01″. It is the most accurate circular photoelectric encoding device. Circular gratings are often used as an etalon for high-precision angle measurement by metrology institutes. The angle measurement method based on laser interference technology converts the change of the measured angle into an optical path difference or a phase change of the fringe in the interference optical path, and provides the angle information by measuring the interference signal [12–15]. When the rotational angle is small, the error of the optical path changes with the angle is approximately linear, and high precision can be obtained. As the rotational angle increases, nonlinearity between the optical path and the angle comes into being, resulting in a sharp increase in various errors, and the measurement range is limited to several degrees. The PSD-based DAM method maps the angular change of the measured object on the PSD through the designed optical system [16, 17]. By recording the photoelectric position in real time with the PSD, the angle error of the measured object can be measured in real time. This method has some advantages including fast response speed, good dynamic characteristics and simple structure. The disadvantages are its insufficient precision and strict alignment requirements of the measurement system components, so the actual use of the process is greatly limited. The angle detection method based on image processing mostly extracts the edge features of the image of the measured object, and performs a straight line fitting to obtain the measured angle [18–20]. The system structure is simple, the measurement environment is easy to implement, but its accuracy depends on the algorithm of feature extraction and the accuracy of the image sensor. But with these methods, we cannot achieve a wide measurement range, high speed, wide bandwidth, high precision and portability simultaneously.

Using a *fibre-optic gyroscope* (FOG) to measure the rotational angle is another kind of angle measurement [21]. FOGs have the advantages of high theoretical precision, all-solid state, high reliability and low cost, and play an important role in high-precision angular velocity measurement [22, 23]. At present, the common applications of FOGs are inertial navigation and attitude control [24, 25]. However, in spite of the above mentioned advantages of FOG, it has not been used in the field of high-precision DAM and metrology of the dynamic angle. Therefore, our group explored the feasibility of applying FOG to DAM, and set up an experimental system for synchronous acquiring the angular velocity of FOG and the angle of a high-precision rotary table. We analysed the measurement error caused by the non-synchronization of the two signals and designed a signal synchronization algorithm. Finally, we analysed the DAM range and accuracy of the FOG compared with the output angle of the circular grating.

The second part of the paper introduces the composition and experimental conditions of the measurement system. In the third part the influence of the unsynchronized error in the real-time dynamic synchronous acquisition is analysed, and an algorithm of reducing the unsynchronized error is proposed. The experimental results are presented in the fourth part. The fifth part contains the conclusions.

2. System design

The angular displacement reference selected in this paper is a single-axis rotary table calibrated by China Metrology Institute. Its built-in angular encoder provides an absolute or incremental angular displacement output with angular displacement measurement accuracy of 10″ (0.0028°)

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and angular displacement repeat positioning accuracy of 3″ (0.00083°). The FOG used in this system has bias stability of 0.01°/h.

The designed angular displacement metrology system is presented in Fig. 1. The FOG is fixed on the surface of a rotary table, and its sensitive axis is parallel to the rotational shaft of the rotary table. The data acquisition synchronization system synchronously receives data from the FOG and the rotary table angle encoder. The synchronization signal of the system is sent by the internal control box of the rotary table. The synchronization signal frequency is 2000 Hz. After the data synchronization system collects two series of data from the FOG and the rotary table, it packages the data and sends them to the host computer for processing. The rotary table is controlled by the host computer through a serial communication interface.

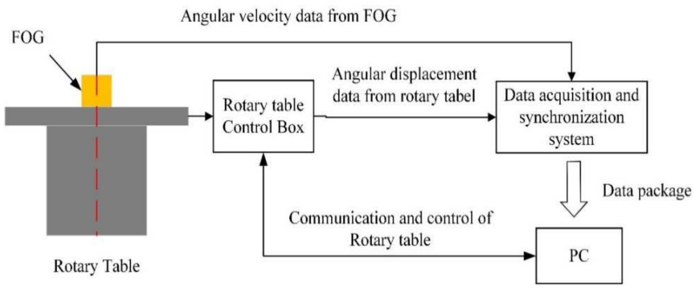

Fig. 1. Schematic of dynamic angle metrology system.

During the experiment, the host computer controls the rotary table to sway according to the combinations of amplitude and frequency shown in Table 1. The host computer processes and compares the data from FOG and rotary table and analyses the DAM accuracy of FOG compared with that of the rotary table.

Table 1. Combinations of amplitude and frequency of the rotary table sway.

Amplitude (°)	10	5	1	0.5	0.1
Frequency (Hz)	1	1	3	4	5

3. Synchronization error analysis and algorithm design

In the field of metrology, there is a strict requirement for the synchronization between the signal to be measured and the reference signal. If there is an obvious signal non-synchronization during the data acquisition process, the error caused by the non-synchronism can cause a significant interference to the metrology results. In this section, we firstly analyse the non-synchronization error caused by the delay between the two signals, and secondly use the error analysis to design a generalizable signal synchronization algorithm.

Assume that the reference signal s1 is a sinusoidal signal:

$$s1 = A \cdot \sin(2\pi \cdot f \cdot t), \tag{1}$$

where A represents amplitude of the sinusoidal signal, f is frequency, and t is time.

The signal to be calibrated is $s2$, whose frequency and amplitude are exactly the same as those of the reference signal, and a delay Δt is superimposed on the reference signal:

$$s2 = A \cdot \sin\left[2\pi \cdot f \cdot (t + \Delta t)\right] . \tag{2}$$

The subtraction of the reference signal $s1$ and the signal to be calibrated $s2$ gives an error due to the signal delay. Assuming a signal amplitude of 10°, frequency of 1 Hz, delay of 500 µs, and sampling frequency of 2000 Hz, the simulated non-synchronization error can be obtained as shown in Fig. 2. It can be seen from the figure that the non-synchronization error increases with the amplitude of sway, and at the same time the delay and the error are also positively correlated. When sway amplitude is 10°, the system's non-synchronization error is about 0.063° as delay is 1 ms, which is not negligible for a precise measurement of a dynamic angle.

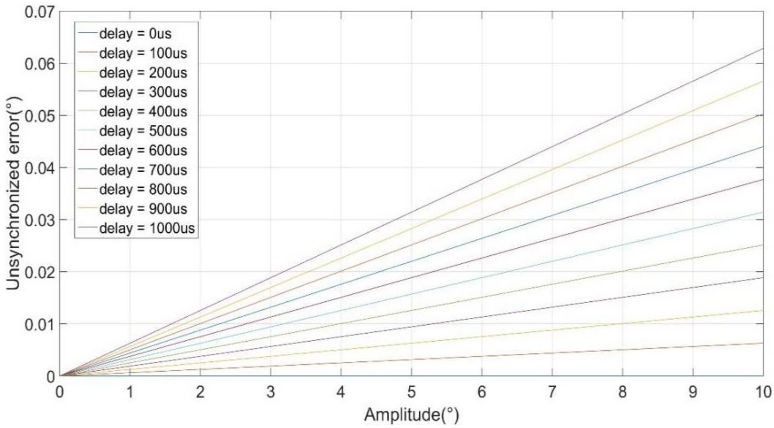

Fig. 2. Effect of amplitude and delay on non-synchronization error.

Choosing a right synchronization algorithm to eliminate the effect of delay is critical to the measurement results. The general synchronization algorithm uses the cross-correlation function of the two signals to calculate delay. However, a drawback of this algorithm is that for two signals at a given sampling frequency, the minimum delay of the two signals calculated by the cross-correlation function corresponds to the sampling period of the system [26–28]. For example, if a sampling frequency of the system is 1000 Hz, then the minimum delay calculated by the cross-correlation function is 1 ms. If the two signals have a smaller delay, it cannot be measured. The above analysis indicates that a 1 ms delay can result in an angular error of the order of 0.01°, so this method is not effective. A combination of interpolation and cross-correlation functions makes possible to calculate smaller delays, but different interpolation algorithms affect computational accuracy [29].

After a period of experimentation and analysis, we found that the magnitude of the difference between the two signals is related to sampling frequency, amplitude, frequency and delay of the original signal. Then, we considered using this characteristic of the signal for delay determination. The difference between the two signals shown in (1) and (2) can be used to obtain the non-synchronization error:

$$\Delta s = s2 - s1 = 2 \cdot A \cdot \sin\left(\frac{2\pi f \Delta t}{2}\right) \cdot \cos\frac{2\pi f (t + \Delta t)}{2} . \tag{3}$$

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Observing (3), we can find that the magnitude of the non-synchronization error is a function of amplitude, frequency, and signal delay of the original signal. At the same time, the non-synchronization error has a phase difference of 90° compared with the original signal, and positive or negative values of the phase difference depend on whether the signal to be measured is delayed or advanced relative to the reference signal. As shown in Fig. 3, the two signals have a small delay, and the resulting non-synchronization error is magnified 500 times to visually show their relationship. In the left figure, when signal 1 is ahead of signal 2, the non-synchronization error is lagged by 90° with respect to the original signal; in the right figure, signal 1 is shifted behind signal 2, and the non-synchronization error is advanced by 90° with respect to the original signal. We can use the above relationship to first obtain the non-synchronization error through experimental tests, and then calculate the delay value and the relative relationship of the two signals. In the experiment, with this synchronization method, the delay of less than 25 μs can be obtained, which corresponds to non-synchronization error of 0.0016.

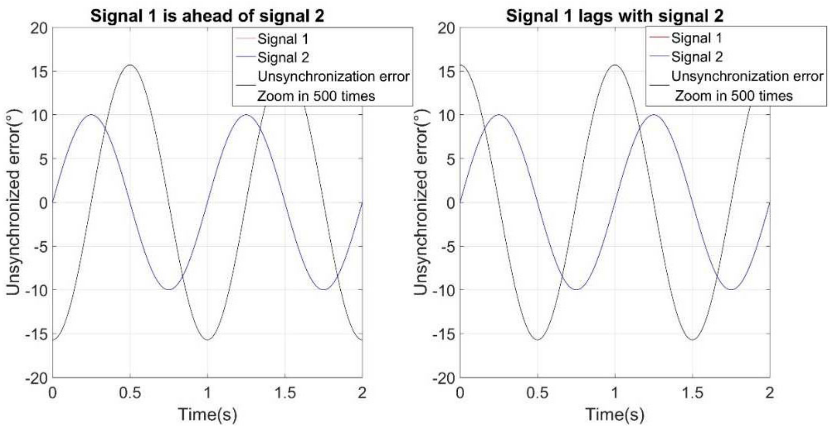

Fig. 3. The relationship between lead and lag of two signals and unsynchronization error.

4. Experimental result

Based on the above mentioned system and algorithm, the FOG angular velocity data and the rotary table angle encoder data are acquired synchronously. When the rotary table is operating in a sway state, it sways in accordance with the combinations of amplitude and frequency shown in Table 1. Fig. 4 shows the comparison of the angle obtained by the rotary table angle encoder and the FOG when sway amplitude is 10° and frequency is 1 Hz. It can be observed that the angular accuracy of the FOG is very high compared with that of the angular encoder, and the two signals almost coincide. Fig. 5 shows the difference between the two signals, which can be considered as the angle measurement error of the FOG, and its maximum value is less than 0.002°.

Figure 4 shows the angle measurement errors of the FOG when the rotary table sways at amplitudes of 10°, 5°, 1°, 0.5°, and 0.1°, respectively. In fact, the angle encoder, which is used as an angle reference in this paper, has a maximum angle measurement error of 10″ (0.0028°). Therefore, in the worst case, we can conclude that the fibre-optic gyro angle measurement error is better than 0.0048° for different motion conditions, which is the sum of the measurement error of the angular encoder (0.0028°) and the measurement error between the fibre-optic gyroscope

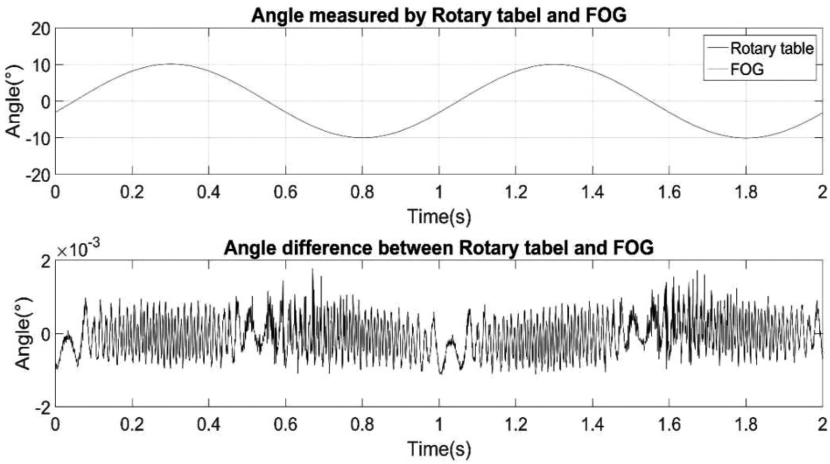

Fig. 4. Angle measured by two sensors under amplitude = 10°, frequency = 1 Hz sway movement.

and the angular encoder (0.002°). Therefore, the FOG can be used as a dynamic angle measuring etalon with an accuracy better than 0.0048° after being compared with the rotary table angle encoder.

5. Conclusion

As a new solid-state instrument widely used in the field of inertial navigation, FOGs have the advantages of high theoretical precision, all-solid state, high reliability and low cost. Combining these advantages of FOGs with DAMs in the metrology field has great prospects. Using FOGs as a DAM etalon is a task that no one has yet carried out. This is also the core innovation of this paper.

In this paper, a rotary table angle encoder calibrated by China Metrology Institute is used as the etalon for DAM. A DAM system is built to synchronously collect and process data from the rotary table angle encoder and FOG, and analyse the DAM error of FOG for different sway conditions. The experimental results show that the DAM accuracy of FOG is better than 0.0048° for given motion conditions. At the same time, a synchronization algorithm proposed in the paper has an important significance for the future metrology research. Moreover, the FOG can measure angular velocity of 10^4°/s and angle of 0–360°. In this system, the maximum sway amplitude of the rotary table can only reach 10°, and the corresponding frequency is 1 Hz, which limits the capability of testing the DAM accuracy of FOG to a smaller range and lower frequency of the sway motion.

It is worth noting that the FOG directly outputs the angular velocity information. If the dynamic angle is to be obtained, the angular velocity needs to be integrated. Due to the existence of FOG's bias, a dynamic angle drift occurs during the integration process. For repetitive sway motion mentioned in this paper, the low-frequency drift can be filtered by adding a high-pass filter during data processing, but this method is limited to a random rotational motion. Therefore, if the FOG is to be used as a dynamic angle etalon for various motion conditions, it is necessary to consider a filtering algorithm of the low-frequency angle drift. And at the same time we need to cooperate with the metrology institute to develop a DAM standard suitable for the FOG.

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References

[1] Chen, T., Zhang, L., Zhang, G., Chen, B. (2006). Design of a displacement/angle measurement system based on laser triangulation principle. *2006 International Technology and Innovation Conference*, 319–322.

[2] Plosker, E., Arnon, S.J. (2014). Statistics of remote roll angle measurement. *Applied Optics*, 53, 2437.

[3] Te, C., Long, C., Yingfeng, C., Xing, X. (2018). Estimation of vehicle sideslip angle via pseudo-multisensor information fusion method. *Metrol. Meas. Syst.*, 25(4), 499–516.

[4] Łuczak, S. (2014). Dual-axis test rig for MEMS tilt sensors. *Metrol. Meas. Syst.*, 21(3), 351–362.

[5] Chen, L., Zhang, D., Zhou, Y., Liu, C., Che, S.J. (2018). Design of a high-precision and non-contact dynamic angular displacement measurement with dual-Laser Doppler Vibrometers. *Scientific Reports*, 8, 9094.

[6] Skalski, A., Machura, B. (2015). Metrological analysis of microsoft kinect in the context of object localization. *Metrol. Meas. Syst.*, 22(4), 469–478.

[7] Mayagoitia, R.E., Nene, A.V., Veltink, P.H. (2002). Accelerometer and rate gyroscope measurement of kinematics: an inexpensive alternative to optical motion analysis systems. *Journal of Biomechanics*, 35, 537–542.

[8] Yang, X.B., Xiao-Jun, H.E., Zhang, L., Kai, X.U., Jin, G.J. (2008). Effect and Simulation of the Deviant Angle Error on TDI CCD Cameras Image. *Opto-Electronic Engineering*, 35, 45–50.

[9] Masuda, T., Kajitani, M.J. (1989). An automatic calibration system for angular encoders. *Precision Engineering*, 11, 95–100.

[10] Kinnane, M.N., Hudson, L.T., Henins, A., Mendenhall, M.H.J. (2015). A simple method for high-precision calibration of long-range errors in an angle encoder using an electronic nulling autocollimator. *Metrologia*, 52, 244–250.

[11] Kisała, P., Skorupski, K., Cięszczyk, S., Panas, P., Klimek, J. (2018). Rotation and twist measurement using tilted fibre bragg gratings. *Metrol. Meas. Syst.*, 25(4), 429–440.

[12] Rui, M., Deng, X., Shen, H.J. (2001). *Study on the laser interference angle measurement*. Forest Engineering.

[13] Sollogub, V.S.J. (1982). Laser interference method of measuring small taper angles in plates in the IR range. *Measurement Techniques*, 25, 725–728.

[14] Pavan, Y.K., Chatterjee, S., Negi, S.S.J. (2016). Small roll angle measurement using lateral shearing cyclic path polarization interferometry. *Applied Optics*, 55, 979–983.

[15] Filatov, Y.V., Loukianov, D., Probst, R. (1997). Dynamic angle measurement by means of a ring laser. *Metrologia*, 34, 343.

[16] Tian, W.J. (2004). Study on PSD-based Angle Detecting Principle for ESG. *Chinese Journal of Scientific Instrument*, 25, 406–408, 412.

[17] Zhu, G.L., Xue-Bing, W.U., Zou, W.J.J. (2006). PSD-Based Angle Measurement System. textitElectrical Measurement & Instrumentation, 353–370.

[18] Pan, T., Xu, W.J. (2015). Detection of Rope and Rope's Swaying Angle of Overhead Crane Based on Computer Vision. *Computer Measurement & Control*, 23, 2263–2265, 2269.

[19] Dong-Liang, X.V., Liu, H.J. (2008). Research of winding angle detection system based on computer vision. *Mechanical & Electrical Engineering Magazine*.

[20] Wang, J., Ni, X.H.J. (2013). Angle Measurement Based on Computer Vision. *Applied Mechanics & Materials*, 456, 115–119.

[21] Lefèvre, H.C.J. (1997). Fundamentals of the Interferometric Fiber-optic Gyroscope. *Optical Review*, 4, A20–A27.

[22] Prayogo, R.C., Triwiyatno, A. (2018). Quadruped Robot with Stabilization Algorithm on Uneven Floor using 6 DOF IMU based Inverse Kinematic. *2018 5th International Conference on Information Technology, Computer, and Electrical Engineering (ICITACEE)*, 39–44.

[23] Cheng, P., Oelmann, B. (2010). Joint-angle measurement using accelerometers and gyroscopes – A survey. *IEEE Transactions on instrumentation and measurement*, 59, 404–414.

[24] Zheng, X., Wei, W. (2009). Reliability Study of Redundant Configuration of IMU Fiber Optic Gyroscope Inertial Measurement Unit. *International Conference on Reliability, Maintainability and Safety*, 87–90.

[25] Ravaille, A. *et al.* (2018). *Rotation measurements using aa resonant fiber optic gyroscope based on Kagome fiber*. arXiv preprint arXiv:1812.04694.

[26] Wolf, M., Cheema, S.A. Haardt, M. (2016). Synchronization and channel estimation for optical block-transmission systems with IM/DD. *International Conference on Transparent Optical Networks*.

[27] Mencel, A.J. (1986). The fast synchronization in a direct sequence of spread spectrum systems. *Cells Tissues Organs*, 194, 205–210.

[28] Zhao, Y., Cao, J., Li, Y. (2018). An Improved Timing Synchronization Method for Eliminating Large Doppler Shift in LEO Satellite System. 2018 *IEEE 18th International Conference on Communication Technology (ICCT)*, 762–766.

[29] Tonello, A.M., Rinaldo, R.J. (2005). A time-frequency domain approach to synchronization, channel estimation, and detection for DS-CDMA impulse-radio systems. *IEEE Transactions on Wireless Communications*, 4, 3018–3030.