An Optical Gyroscope Based Technique for Calibrating Angular-Measuring Instrument

Chenpeng Cui, Yuanwei Jiu, Chun Wang, and Fengshou Gu

Abstract This paper analyzes the error model of inductosyn install in an angular-measuring instrument, and then build up a test error system using the ultra-high precision Ring Laser Gyroscope to get the error of inductosyn. Compare the traditional Fourier Function calibrations and the linear interpolation calibrations methods; this paper presents a bit memory based method to calibrate the error of inductosyn in electrical resolution. As a result, after compensation, the inductosyn error is ±0.8 arcsecond, RMS of the error is less than 0.3 arcsecond.

Keywords Inductosyn · Error model · Ring laser gyroscope · Calibration

1 Introduction

The accuracy requirement of angular measurement is stringent in variety application occasions, like space image detection, high-precision turntable, scanning measurement. Not only the static angle accuracy is necessary, but also the dynamic angle measurement ability is needed. The traditional angle sensors are angle encoder, optical gyroscope, resolver, inductosyn, etc. Encoder (photoelectric rotary encoder) assemble demand is strict, eccentricity and the tilt in the installation process must under 3–5um at shaft and plane, optical gyroscope due to shift with time, could not be used in the motion control in space environment. Resolver accuracy can't fulfill the arcsecond requirement due to volume and weight. Inductosyn can get high precision at same time the installation requirement is not accurate, below 30–50um at shaft and plane. In order to achieve sub-arcsecond accuracy, there are two way to reduce errors of inductosyn instrument. One is to improve inductosyn manufacturing craft

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and raising angle solver circuit designs ability. The other one is to calibrate the error of the exiting angular-measuring instrument with compensation function or method [1]. In order to improve inductosyn accuracy, the error of inductosyn should be measured. Due to the dynamic angle standard device and traceability technology [2], which based on Ring Laser Gyroscope, the error table can be obtained. The RLG is measured by the national small angle standard and the high precision turntable. The index and interpolation measuring deviation were distributed within ±0. 4 arcsecond. The angular measuring repeatability was less than 0. 2 arcsecond [3, 4].

RLG accuracy is much higher than the inductosyn based angular sensor, but it is shifting with time, 12 arcsecond per minute, as its principle shows, we must standardize the zero before using it to eliminating the Earth rotation effect. Beside the shorts above, the space environment like vacuum, radiation, terminal deflection restricted the applications of RLG in orbit. In contrast, the inductosyn is not sensitive to space environments with high stability and reliability. On the other hand, we can still using RLG on ground to testing the inductosyn error table in a short time (~5 s) according to the requirements of use.

Using the RLG equipment to get the error of inductosyn, the paper developed a bit based look up table software algorithm to improve the inductosyn precision. Compare to the function compensation algorithm, this method can make the inductosyn angle instrument to sub-arcsecond, error RMS is less than 0.3 arcsecond.

2 Common Mathematical Error Model of the Single-Axis Induction Synchronizer

The induction synchronizer also known as inductosyn, can be used as an angular measuring instrument. It is a magic-electrical angle measurement, can achieve high accuracy with 180 pair poles or more compare to resolver. It can be used in ultra-high precise position servo systems, especially in space crafts. This paper using inductosyn sensor as an angular instrument in a scanning mirror mechanism, and the mechanism is a part of a remote satellite. In order to satisfy the stringent angular measurement accuracy requirement, the error of inductosyn should be calibrated on ground.

From [1, 5–7], the error of inductosyn mainly consists of two parts, one is zero position errors and subdivision errors. The manufacturing and the eccentricity and tilt in the installation process cause zero position errors. The amplitude of induced voltage and harmonic voltage, along with electrical reasons cause subdivision errors.

Components and derivation of inductosyn error can be show in Table 1.

From [5–10], the commonly zero error mathematical model of inductosyn could show as "Eq. (1)".

$$y(x) = a_0 + a_1 \cdot \sin(x) + a_2 \cdot \cos(x) \tag{1}$$

From [1], the subdivision errors and zero error can be modeled based on FFT.

Table 1 Error components of inductosyn

Cause of error	Manifestations	Harmonic order
Non-Ideal voltage (Captive voltage drop, edge voltage, interference)	Zero position error	p, 3p, 5p …
3th, 4th harmonic voltage	Subdivision Errors performs as fourth sine function	4p
The errors of the amplitude of the induced voltage in sine phase and cosine phase of stator	Subdivision Errors performs as secondary sine function	2p,2p ± 1
The eccentricity and the tilt in the installation process	Zero Position Errors perform as primary cosine function in 360 degree (mechanical angle)	p
The errors of the amplitude of the induced potential of the sine phase and cosine phase of stator or the rotor conductor	Zero Position Errors perform as frequency K random form	K and a series harmonic voltage

p is the number of pairs of poles

FFT technique can transform the error datas. Measure a limited length set of discrete data y(n) in a fixed sampling period is the basic idea of FFT. We use FFT to get their expression spectrum coefficients as the N data points are measured on sampling interval.

$$Y(k) = \sum_{n=0}^{N-1} y(n) \cdot e^{-j \cdot k \cdot \frac{2 \cdot \pi}{N} \cdot n}, 0 \ll k \ll N - 1 \tag{2}$$

Then calculate Fourier inverse transformation of the spectrum coefficients, the linear combination mathematical expressions could be gotten.

$$y(n) = \frac{1}{N} \sum_{n=0}^{N-1} x(n) \cdot e^{j \cdot k \cdot \frac{2 \cdot \pi}{N} \cdot n} = \sum_{n=0}^{N-1} x(n) \cdot e^{j \cdot k \cdot \frac{2 \cdot \pi}{N} \cdot n}, 0 \ll k \ll N - 1 \tag{3}$$

According to the Eqs. (2) and (3), we can get

$$a_k = \sum_{n=0}^{N-1} x(n) \cdot e^{j \cdot k \cdot \frac{2 \cdot \pi}{N} \cdot n}, 0 \ll k \ll N - 1 \tag{4}$$

Then analyze amplitude frequency characteristic by taking the measured datas into the Eq. (4). As a result we get the inductosyn error model according to the actual datas and the amplitude frequency characteristic.

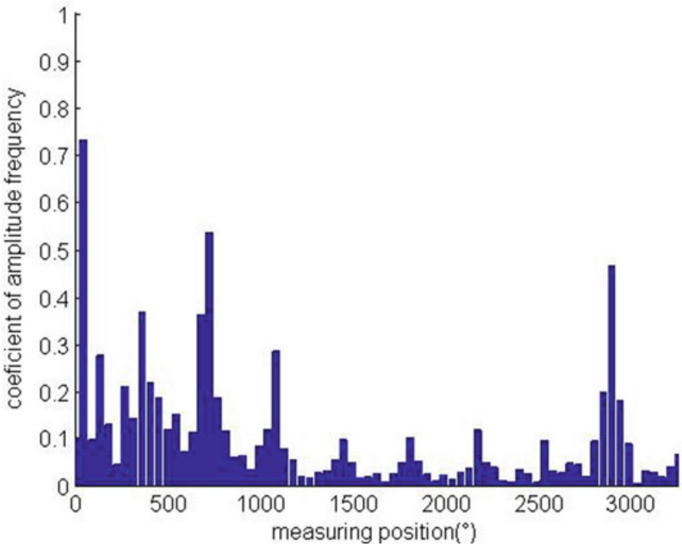

Fig. 1 Amplitude-frequency characteristic

$$y(x) = a_0 + a_1 \cdot \sin(p_1 \cdot x) + a_2 \cdot \cos(p_2 \cdot x) + a_3 \cdot \sin(p_3 \cdot x) + a_4 \cdot \cos(p_4 \cdot x) + \ldots + a_{n-1} \cdot \sin(p_{n-1} \cdot x) + a_n \cdot \cos(p_n \cdot x) \quad (5)$$

Therein,

p_n—amplitude frequency characteristic parameters
a_n—system model parameters

$$x = \frac{2\pi i}{n}, i = 0, 1, 2 \ldots N - 1$$

Form part 4, we get the error with position of the inductosyn instrument, the FFT result see Fig. 1. The main errors are 45°, 360°, 720°, 2880°.

The axis is shifting with position as the instrument is holding by two pivots, the error curve of each 2° present no repeatability. The error curve shift as the eccentricity and the tilt changed with position, see Fig. 2.

3 Comparision of Different Caliberation Methods

From part 4, the error of inductosyn before compensation can be achieved, then we use the "cftool" of Matlab to compare the different methods of compensation angular error. The residual RMS error is 1.033 arcsecond in 1th Fourier equation fit, 0.7484 arcsecond in 4th Fourier equation, 0.5985 arcsecond in 8th Fourier equation.

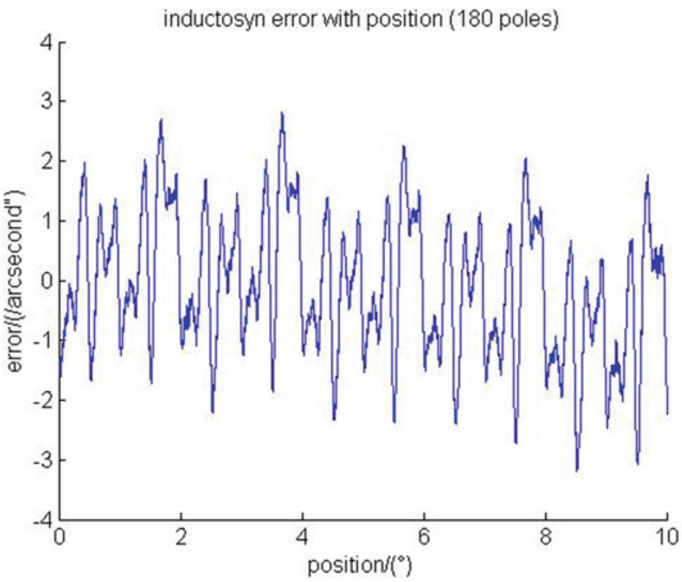

Fig. 2 Inductosyn error with position (180 poles)

The inductosyn be used is JGX/360-WND, which has 180 poles, mechanical angle 2°represent electrical angle 360°. See Figs. 3, 4 and 5.

The residual error is 0 uses the linear method, see (Fig. 6). The linear interpolation method is simple, intuitive and easy to implement in embedded control system.

In the test, the inductosyn was used to measure the single-axis scan mirror motion relative to the pivot base, the RLG mounted on the pivot were used to measure the

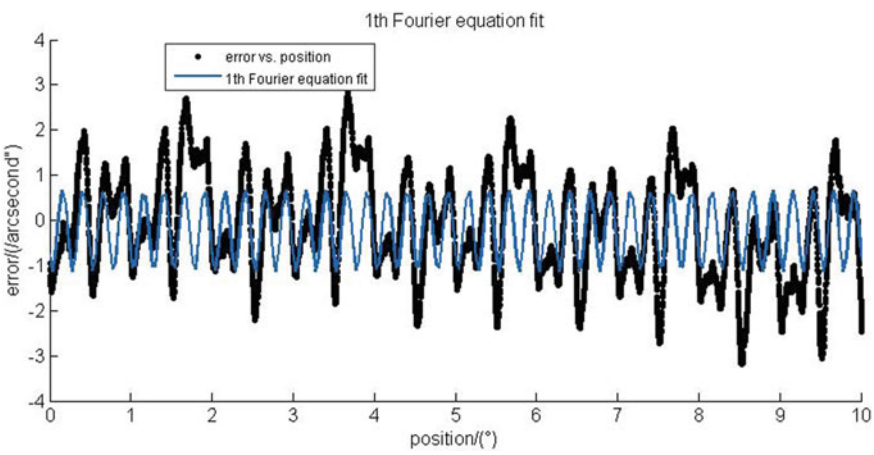

Fig. 3 1th Fourier equation fit

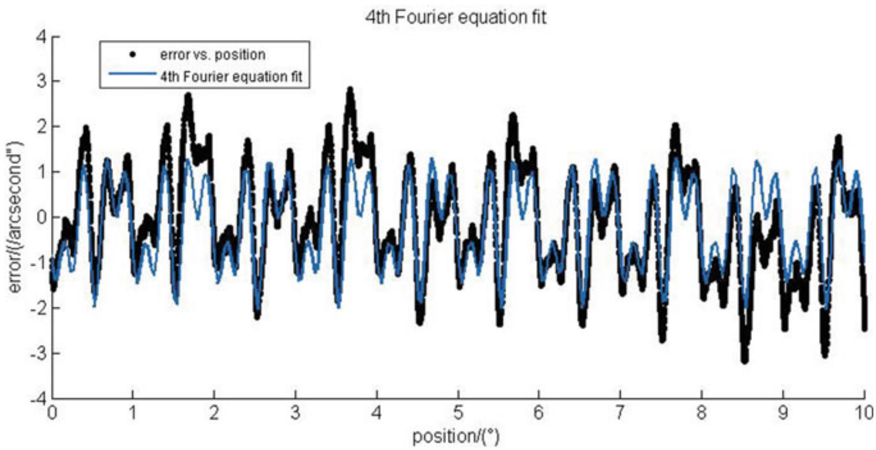

Fig. 4 4th Fourier equation fit

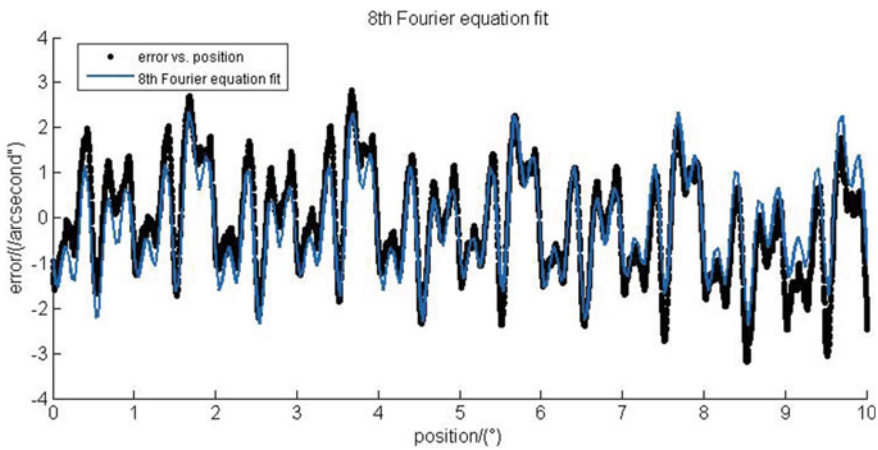

Fig. 5 8th Fourier equation fit

absolute motion of the scan mirror. After compensating for the pivot base motion (the motion due to Earth rotation), the difference between the gyro readouts and the inductosyn readouts representing the inductosyn error are computed and stored. As the datas are equal interval collection and storage, the calibration data of sequence i is (x_i, y_i). So the calibration datas between i and $i + 1$ can be obtained by linear interpolation method. Consider the inductosyn out data of one angle is x, the model of interpolation is

$$x_c = x - \left(y_i + \frac{x - x_i}{\Delta x} \right) * (y_{i+1} - y_i)), x_i < x < x_{i+1} \quad (6)$$

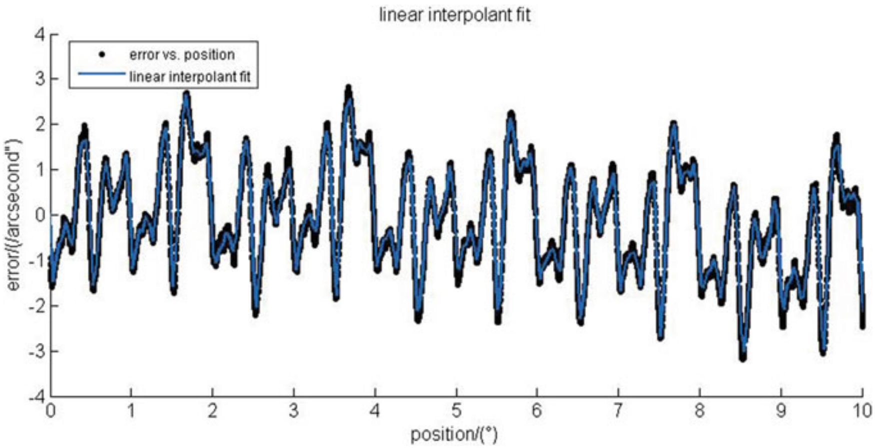

Fig. 6 Linear interpolation fit results

x_c is calibration value, Δx is the spacing of test datas, it determined by the resolution of the readout circuit and the calibration storage memory chip. In this operation, the resolution of indutosyn readout circuit is 2° divide by 2ˆ16, 0.1098 arcsecond. As a result, we define this kind of calibrate method as bit memory based method, which means the spacing of datas is a bit of memory chip and equal the resolution of the inductosyn readout circuit.

Then we put the interpolation data in the memory, use look-up table method in the practice angle compensation.

4 Testing of Inductosyn Angle Measuring Errors

From the principle of optical gyroscope angle measuring instrument, using the angular measuring deviation mechanism and effectiveness of the scale factor, bias, and frequency stability etc. to testing the gyrosope. As a result, the Ring Laser Gyroscope (RLG) index error, segmentation errors (interpolation measuring deviation) were distributed within ±0.24 arcsecond. The angular measuring repeatability was less than 0.1 arcsecond [3, 5, 11]. Then use RLG (MG033 of AVIC Xi'an Flight Automatic Control Research Institute) as a angular measuring instrument to measure the dynamical error of inductosyn is useful, the installation requirements are not strict. Compare to the move-less measurement instrument, such as Photo-electric autocollimator (±1000 arcsecond), can measure much more large scale.

The basic idea of testing the inductosyn errors was using an ultra-high precision Ring Laser Gyroscope (RLG) to build an inductosyn errors test system. The rotor and stator of inductosyn were installed in parallel on the rotor and stator of the pivot bearing instrument, as shown in Figs. 7 and 8.

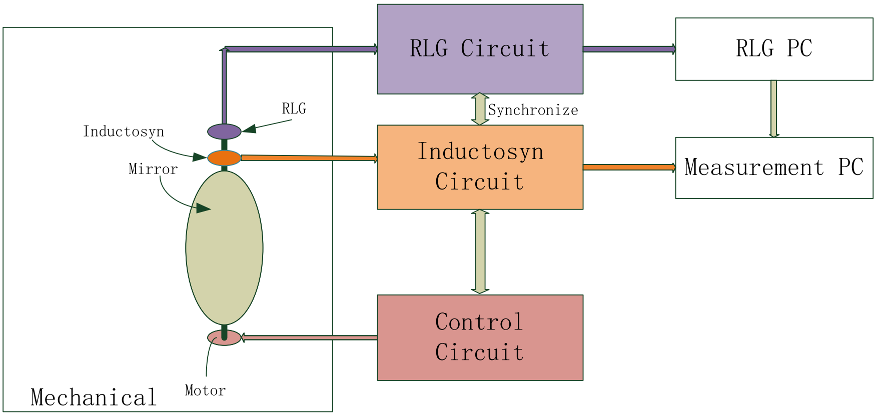

Fig. 7 Inductosyn errors test system

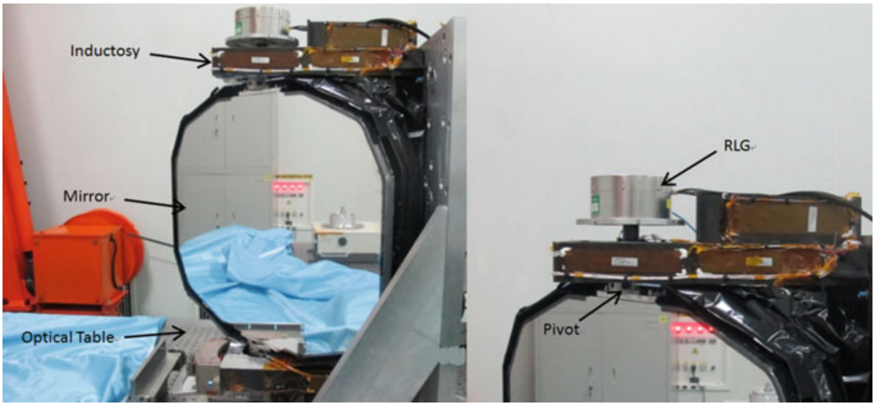

Fig. 8 Inductosyn instrument and ultra-high precision RLG

Figure 9 shows the lab of inductosyn error test. The inductosyn circuit consist amplifier and resolver to digit converter. The 360 electrical degree of the inductosyn is 2 mechanical degrees; the circuit converts the 2 mechanical degrees to a 16 bit digital signal, 1 bit represent 0.1099 arcsecond. The inductosyn circuit send synchronize signals to RLG circuit to get the angle of the mechanism at the same time. After storage the angle of inductosyn measurement PC and RLG PC, subtract the two can get error. Then using linear interpolation method, store the error table in resolution of 0.1099 arcsecond per bit in the memory of inductosyn circuit. After calibration, the error of inductosyn Re (Fig. 10), ±0.8 arcsecond. RMS of the error is less than 0.3 arcsecond.

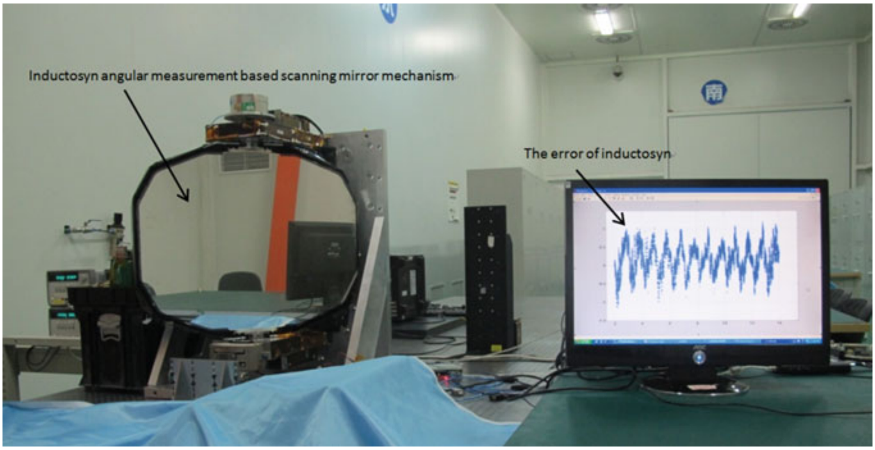

Fig. 9 Inductosyn error test lab

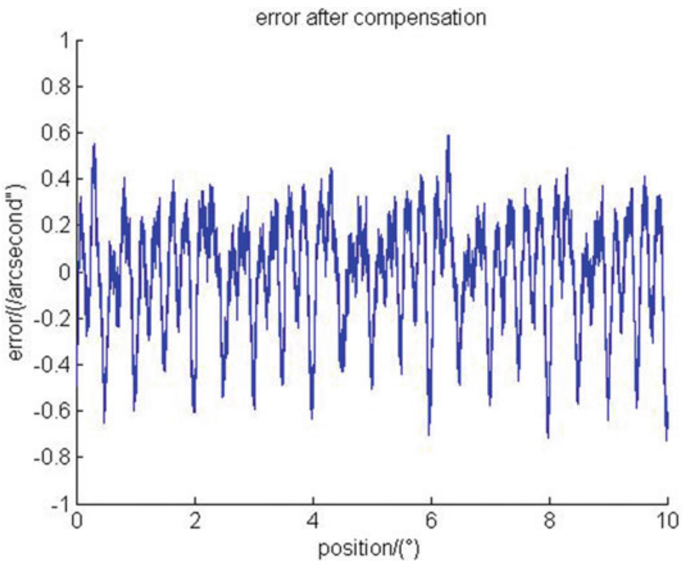

Fig. 10 Inductosyn error after compensation

5 Conclusion

Because of limitation in installation and electronics shortage, the accuracy of inductosyn is corrupted with errors. Using ultra-high precision RLG to measure the error of inductosyn, then we can get a high angular instrument after calibrate the error of inductosyn. Especially the mounting limitation of pivot axis, the repeatability of each electrical pole is not similar. Using precision RLG gyroscope as calibration references can get the full scale dynamic position error.

The error table generated by RLG on ground may not satisfied usage on space operations as the error characteristics of inductosyn may vary due to terminal environments, mounting transmutation and component aging. In the future, the difference error calibration scheme of ground and space environments should be studied to fulfill the using range of angular compensation.

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