Design and Realization of Calibration Device for Angular Positioning Error of Universal Turntable

Huahui Yang[1, 2, a], Fu Liu[2], Jun Zhou[3, b], Weili Feng[3, c]

[1]Machinery Engineering College, Shijiazhuang 050003, China;

[2] Machinery Technological Research Institute, Shijiazhuang 050003, China;

[3]Beijing Aerospace Institute for Metrology and Measurement Technology, Beijing 100076, China.

[a]yanghuahui1992@163.com, [b]f13501036004@sina.com, [c]zhoujunrose@126.com

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Abstract. In order to realize the calibration measurement of universal turntable in high precision, a calibration device is designed and realized. The device was mainly composed of horizontal capacitance sensor, mental circular grating, ultrasonic motor, and double-row angular contact bearings was selected as its slewing mechanism, so rotation precision of calibration instrument can be improved. Finally, this paper put the error testing results of calibration instrument each system, which satisfy the demand for calibration measurement and provide references for carrying out uncertainty analysis.

1. Introduction

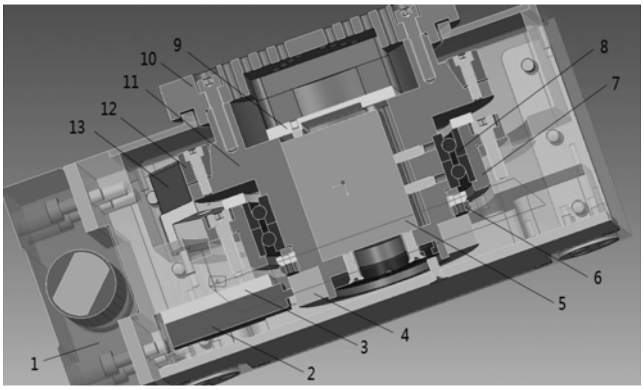
Turntable is used as measuring instrument for the calibration of inertial devices axis attitude angular position, angular velocity and dynamic characteristics, and also is an important basis for inertial devices performance, accuracy and quality, which essentially played the role of measurement standards[1-2].

Three-axis turntable, swaying platform, and tilt table are the main calibration instrument of inertial devices, of which the parameter index mainly contains the datum plane performance indicators, shafting performance indicators, angular position performance indicators, angular velocity, angular acceleration performance and swaying characteristics, etc. in which the angular positioning error is an important indicator of turntable calibration parameters[2]. So the turntable calibration is an important requirement in order to achieve the turntable angular position error detecting by the measuring or testing equipment, and it can ensure reliable and accurate the angular positioning values of the turntable.

The calibration techniques of angular positioning error can be divided into mechanical methods, electromagnetic methods and optical methods[3]. In this paper, the horizontal capacitance sensor[4] and a metal circular grating[5-6] are combined to design and implement a calibration device for measuring the angular positioning error of universal turntable.

2. System structure

Calibration device consists of capacitive sensors for measuring the horizontality, metal grating for measuring the circle dividing, ultrasonic motor for driving rotary composition and mechanical structure with high-precision double-row angular contact bearing. The fixing cover of the capacitive sensors is loaded with integrated circuit board for data acquisition and processing. The system structure is shown in Fig.1.



1. Magnetic base 2. USM 3. Motor base 4.ceramic disc 5. Horizontal capacitance sensor 6. Lock master 7. External pressure ring 8. Bearings 9. Fixing cover 10. Working disk 11. Spindle 12. Circular grating 13. Reading head

Fig. 1 Structure of calibration device

Calibration device means the whole structure made of aluminum alloy shell, equipped with hardened stainless steel datum plane in 5 working surface (external end face), which is parallel or perpendicular to each other or to the calibration device shaft and sensitive direction of horizontal capacitance sensor after grinding. One side is designed to magnetic suction surface, which extend the range of applications and environments and ensure the structural strength, making the device operation simple and convenient.

3. Measuring principle

Calibration device uses differential horizontal capacitance sensor as the measurement zero position, which has the function of measuring an absolute angle between sensitive direction of sensor and geoid, so the relative measurement zero can remain at near horizontal plane position. Metal circular grating with high-resolution reading head can achieve the full range of 360 ° entire circumference angle measuring function as a wide range goniometer device. As is shown in Fig.2, when using the calibration device to calibrate the turntable, the calibration device can be placed on the turntable mounting surface (inclined plane). If the tilt angle of the turntable mounting surface exceeds readings range of capacitive sensor, the servo motor will drive shaft back to go near the horizontal plane position until the capacitive sensor output an angular value. The shaft rotation angle can be acquired by the metal circular grating. If the tilt angle does not exceed, the value can be read directly. Based on the above ideas, the calibration device can effectively test the tilt angle between each frame, each rotary axis of common turntable and geoid, so the relative positional relationship between the frame and rotary axis of DUT (Device Under Test) can be measured by this method.

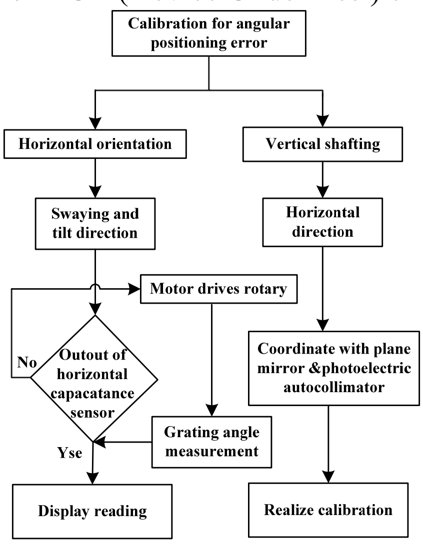


Fig. 2 Principle of calibration device

Based on the analysis of the measuring principle above, the angular positioning error in swaying and tilt direction can be acquired. If the angular positioning accuracy in horizontal orientation of T-type, O-type or other structure type turntable's vertical shaft need to be measured, the metal circular grating and high-precision shaft of calibration device can compose the 360 ° entire circumference angle measuring system. The system can replace the multi-teeth table or polygons to achieve the indexing accuracy calibration in horizontal orientation with plane mirror.

4. Detailed design

4.1 Shaft Design

Calibration device always remains horizontal position as measurement zero position. The calibration device shafting and sensitive direction of horizontal capacitance sensor demands good verticality. The parallelism of 5 datum plane and calibration device shafting also demands high precision. So the requirements of calibration device shaft design includes as follows:

1) high rotary precision, small runout, provide installation and location reference for angle measuring system, especially ensure the circular grating disc has good concentricity with device shaft;

2) earing radial load and axial load, has good stiffness;

3) small rotating friction and low rotary inertial;

4) tightness, heat insulation and can prevent electromagnetic interference.

Based on the above requirements, the calibration device uses double row angular contact bearings as the main rotary elements. As is depicted in Fig.3. The Double row angular contact bearing is connected to spindle of calibration device or bearing chock by pinch fit. The lock master can effectively increase preloaded in axial direction, thus to improve rotary accuracy of rotating shaft by this method. The bearing chock is connected to external pressure ring by screws fixation. External pressure ring can not only increase preload force further, but also can effectively limit axial shaking. The spindle of calibration device rotates at low speed, and angular positioning measurement belongs to the static method, therefore the axial displacement and radial displacement of the spindle during movement are very small, and the vibration amplitude and vibration frequency is very low. The bearing features smooth operation and long structure service life.

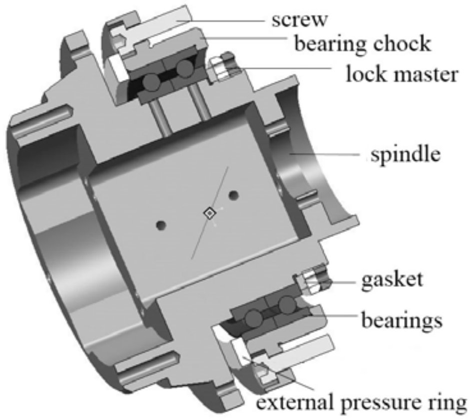


Fig. 3 Structure of precision shafting

4.2 Grating angle measuring system design

The circular indexing measuring system of calibration device uses Renishaw incremental reflective mental circular grating as goniometer device. Its large internal diameter, volume light, can effectively resist vibration and shock. The grating also has low rotary inertial to ensure that the rotary shaft has much smaller driving load, having 18000 engraved lines with two adjacent engraved lines spacing 20μm, using cone installation to ensure higher positioning accuracy. The structure of grating is schematically shown in Fig.4.

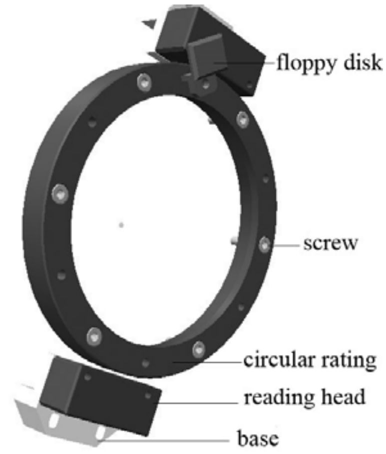


Fig. 4 Structure of circular grating

To reduce angle measuring errors of grating encoder due to mechanical installation (such as decentration, inclination and sway motion), the device uses two high-precision RGH20 reading head for mounting diameter[7]. The head has multiple segments 200, resolution 0.0001° (0.1μm), with the optical filter system providing excellent anti-stain and anti-minor injuries capabilities to acquire stable and reliable angle measuring signal value.

A floppy disk function as the zero position reticule is fixed by the fastening screws. It can effectively eliminating the cumulative errors due to zero drift of the angle measuring system of encoding grating. Zero floppy disk and the reading head is designed to provide a non-contact, no friction loss measurement, which has a lot advantages such as small size, light weight and easy to install, etc.

4.3 Angle measuring system of capacitive sensor design

The angle measuring system uses grooving elastic horizontal capacitance sensor as the measuring component which features high accuracy, good linearity, simple structure and output stable signal. The size of sensor is only Ø24×6*mm*. And it was compressed tightly by multi-block bowl-shaped coil, with the -150″~ 150″ angular measurement range, 1$\mu m/m$ (0.206″) resolution. The capacitive can measure small slope angle in high precision within the pitch error less than ± 0.5″.

The basic assembly structure of horizontal capacitance sensor is shown in Fig.5. The capacitive sensor is fastened in spindle cavity by several jbckscrews. The fixing cover of sensor is fixed on shaft end to ensure firm and stable, with the data acquisition and signal processing circuit of sensor installed on end-surface.

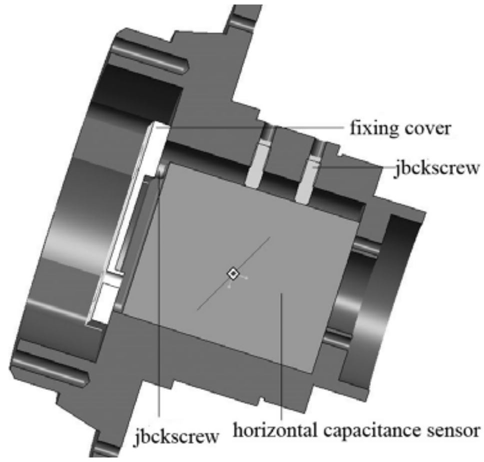


Fig. 5 Assembly diagram of capacitive sensor

4.4 Servo motor control system

The traveling wave type ultrasonic motor based on piezoelectric material adverse pressure effect characteristics is used in Servo control system. The stator and rotor features smooth continuous contact with advantages of low speed and high torque, fast response speed, no electromagnetic interference, steady state output and wide range of dynamic speed from 1$\mu m/s$ to 250*mm/s*. Every step resolution of servo motor can reach up to 100*nm*, so it will be easy to achieve precise positioning control.

As is shown in Fig. 6. The piezoelectric ceramic ring is adhered with spindle by adhesive bonding force. The motor base is designed with a U-shaped hole in order to adjust the relative position of the stator and rotor. In addition to avoid a big positioning precision error due to large impact vibration of servo motor, the motor base is designed in large shape with four-corner strapped stably. The signal of motor control will be obtained by the speeding feedback information of grating disk and original setting information via the PC operation.

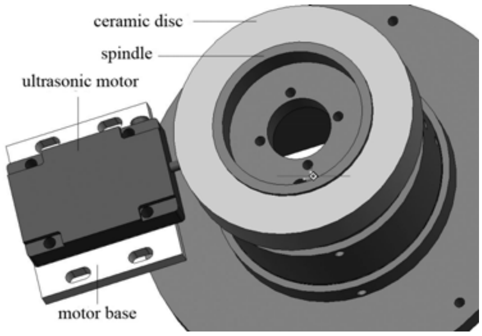


Fig. 6 Schematic diagram of servo motor

5. Experimental verification and error analysis

Angle measurement error of calibration device mainly comes from angle measuring system of horizontal capacitance sensor and metal circular grating. So the error analysis can be taken on separately for two angle measurement system in the calibration experiment, which can provide reference for measurement uncertainty evaluation of calibration device.

5.1 Experiment and Error analysis of grating angle measuring system

The experiment selects ELCOMAT3000 photoelectric autocollimator, 391 multi-tooth indexing table and plane mirror as measuring instrument. As is shown in Fig.7. The mirror is fixed on shaft end of calibration device through the transition-disc. The concentricity between calibration device shaft and transition-disc spindle will be adjusted within 0.01mm in micrometer scales. Rotating the multi-tooth indexing table to zero scale. Adjusting the photoelectric autocollimator and plane mirror aligned. Setting the photoelectric autocollimator to zero and rotate the multi-tooth indexing table clockwise at 15°39′7.8″ interval. The calibration device shaft will be driven rotating in the opposite direction by the servo motor, which can maintain the photoelectric autocollimator and plane mirror collimating. The read-out value of photoelectric autocollimator and calibration device will be acquired to calculate 6 group angle errors.

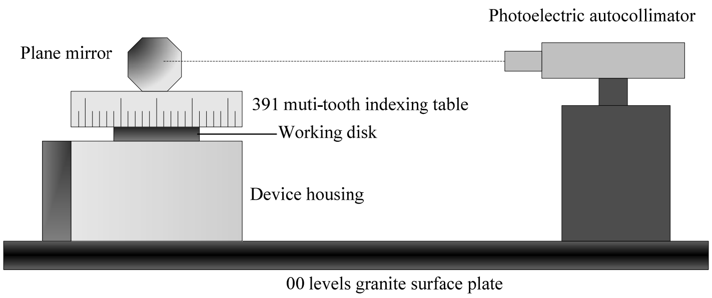


Fig. 7 Schematic diagram of error calibration

The error compensation mathematical model need to be established to improve the precision of grating angle measuring system [8-9]. With six groups of data of original error processed based on harmonic analysis algorithm [10-12], the harmonic amplitude and phase values can be worked out which can establishes the error compensation mathematical model shown in Eq. (1).

$$\varepsilon(\theta) = C_1 \sin(\theta + \varphi_1) + C_3 \sin(\theta + \varphi_3) + C_6 \sin(\theta + \varphi_6) \quad (1)$$

Where the coefficient is component of six groups of harmonic amplitude and phase errors with small changes. The values are then computed as C_1=2.37, φ_1=43.28°; C_2=1.51, φ_1=234.35°; C_3=0.35, φ_1=240.85° and the error compensation model curves is drawn as shown in Fig.8. After using the mathematical model for error compensation in grating angle measuring system, the calibration test was conducted again with the same method before compensation. The angle measurement error values after comparison was gained for error calibration of grating. And the correlation curve of angular deviation measured is shown in Fig.9.

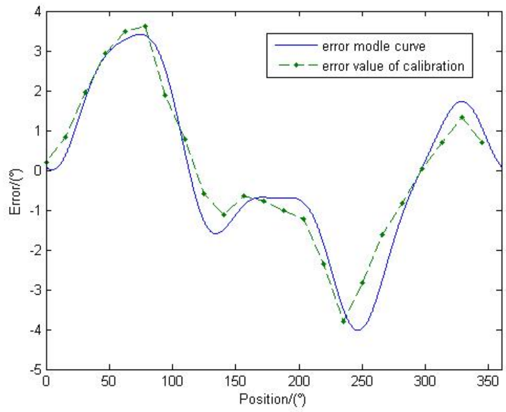


Fig. 8 Error compensation model curves

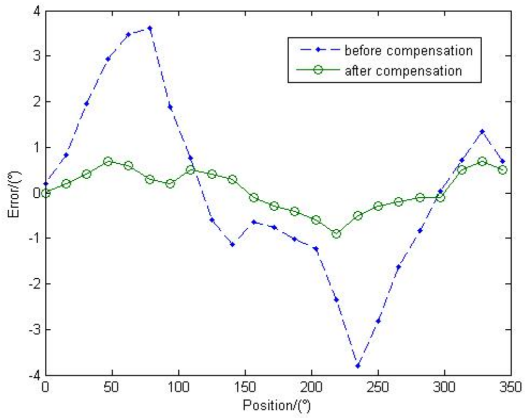


Fig. 9 Correlation curve of angular deviation

Using the Bessel function as Eq. (2) to calculate the standard deviation after compensation, we can obtain the angle measurement standard deviation σ_1 = 0.45″, and three angle measurement standard deviation $3\sigma_2$ <1.4″, therefore the angle measurement accuracy can meet design requirements.

$$\sigma = \sqrt{\frac{\sum_{i}^{24}(\delta_i - \overline{\delta})}{(n-1)}} \tag{2}$$

Where:

Standard deviation σ-metal circular grating angle measurement, second;

n-number of measurements;

Deviation δi-- individual measurements obtained, seconds;

Mean $\overline{\delta}$ - individual measurements of deviation, second.

5.2 error analysis of horizontal capacitance sensor

The device is fixed on high precision standard small angle generator working plane when carrying out the accuracy calibration experiments for capacitive sensor. Adjusting the capacitive sensor to zero position. Firstly a positive testing experiments is carried out with working plane rotation clockwise. Then testing the sensor in opposite direction. The calibration testing experiment is carried out at 30″ interval and 150″ range. The result is shown in Fig.10 and the fitting average line is shown in Fig.11.

Fig. 10 Indication error of horizontal capacitance sensor ″

Standard angle	Clockwise rotation	Anticlockwise rotation	average	Indication error
150	150.6	150.4	150.5	0.5
120	119.8	119.8	119.8	-0.2
90	90.6	90.4	90.5	0.5
60	59.8	60.4	60.1	0.1
30	30.2	30.2	30.2	0.2
0	0.1	-0.1	0.0	0.0
-30	-30.2	-30.0	-30.1	0.1
-60	-60.2	-59.4	-59.8	0.2
-90	-89.6	-89.4	-89.5	0.5
-120	-119.6	-119.4	-119.5	0.5
-150	-149.8	-150.0	-149.9	0.1

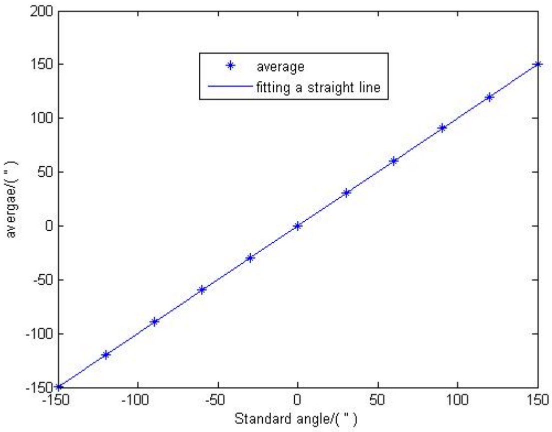


Fig. 11 Fitting a straight line

Figure 11 shows the output signal of sensor has good linearity. Figure 10 shows the maximum indication error value of horizontal capacitance sensor is less than 0.5″ to meet the calibration requirement: $\delta_{max} \leq (1+A\times2\%)$. *A* request the absolute value of nominal value on testing position.

6. Conclusion

The calibration device is designed and realized in this paper. The calibration device consists of capacitive sensor for measuring the horizontality and metal grating for measuring the circle dividing, which can realize the angular positioning error of turntable in swaying and tilt direction, or horizontal orientation of vertical shafting. The device can be used for calibration of three-axis turntable, swaying platform, and tilt table with advantages of wide application range and convenient installation.

In the end, the angle measurement accuracy analysis experiment of horizontal capacitance sensor and metal circular grating is carried out to establish error compensation model. The testing results meet the needs of requirement of design.

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