Design of Torque Standard Device for Extreme Environment

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Abstract. A torque standard device suitable for extreme environment is designed. The standard device transmits the torque value of calibrated torque sensor in extreme environment to normal temperature environment through torque transmission shaft to realize the calibration function. The mechanical design of the shaft of the device is carried out, and the error sources of the calibration device are analyzed, and the error distribution is carried out according to the technical indicators of the standard device. The calculation results show that the maximum allowable error of the standard device is 0.7Nm, which meets the calibration accuracy requirements of the extreme torque standard device.

1. Introduction

Since the 21st century, China’s aerospace field has made rapid progress. In the development and implementation of major space probes such as “Tiangong”, “Chang’e” and “Yutu”, there are a large number of ultra-precision and ultra-complex mechanical structures that need to be assembled in the test workshop under the extreme environment of simulating the real space in space and violent alternating temperature torque and electrical performance parameters and other performance tests and reliability tests [1-3]. In order to ensure the accuracy of torque measurement results, it is necessary to calibrate the torque sensor used in the measuring equipment regularly in the process of testing the mechanical structure bearing torque and measuring the performance of the torque sensor in the high and low temperature alternating environment in the test workshop.

At present, the static weight torque calibration device is mainly used to calibrate the torque sensor at home and abroad [4-6]. In China, China Shipbuilding Industry 704 Research Institute and China Institute of Metrology [7-11] have done a lot of research work in the development of torque standard machine. Chen Y.P. and others of CSIC 704 Research Institute have developed 1kNm high-precision torque standard machine device. By using air bearing and standard arm material with low coefficient of thermal expansion, the influence of friction torque and temperature on measurement uncertainty is reduced, and the expanded uncertainty is 0.0058% (k = 2). A lot of research work has also been done by foreign research institutes [12-13] represented by PTB. The expanded uncertainty of 20kNm torque standard machine developed by PTB is 2 × 10-5 (k = 2).

However, the calibration methods of the torque sensor mentioned above are all carried out under laboratory conditions, which are quite different from the working temperature conditions of the device. In view of this, referring to the calibration method of torque sensor in normal temperature environment, this paper studies the calibration technology of torque sensor in extreme environment, and designs a standard device of torque sensor in extreme environment with measurement range of 0Nm ~ 500Nm and expanded uncertainty of 0.8Nm (k = 2). The device can realize the calibration of torque sensor in
extreme environment (-100 °C ~ 100 °C), using torque transmission. By connecting the torque sensor in the extreme environment test chamber with the high-precision torque sensor outside the test chamber, the on-line calibration of the torque sensor in the extreme environment is realized.

2. Working principle of torque standard device in extreme environment

The mechanical structure of standard device of torque sensor in extreme environment is shown in figure 1. Its working principle is: the structure of horizontal reference torque standard device is adopted for extreme environment torque standard device. The servo motor and precision reducer on the left side of the extreme environment test chamber output torque, and the torque in the shafting is loaded by the torque brake on the right side outside the extreme environment test chamber. The ceramic bearing plays a supporting role on the shaft system, but the friction torque introduced by it will affect the accuracy of the torque standard device. Therefore, a high-precision torque sensor is installed on both sides of the extreme environment test chamber to realize the measurement of the friction torque of the ceramic bearing. The calibrated torque sensor is installed in the extreme environment test chamber. By comparing the measurement results of high-precision torque sensor 1 with that of calibrated torque sensor, the calibration of torque sensor in extreme environment is realized. The high-precision torque sensor used in the standard device needs to be sent to the national or provincial measurement institutions for calibration. The measurement results of the calibrated torque sensor can be traced to the national torque measurement standard. The complete traceability chain of the torque sensor used in the simulation space test is established to ensure the accuracy of the measurement results.
transmitted to the high-end precision torque by the torque transmission shaft 2 supported by the ceramic bearing. The sensor 2 is finally connected with the torque brake through the flange coupling 2. The influence of bending moment caused by shaft self-weight on the measurement accuracy of torque standard device is greatly reduced by using ceramic bearing support.

Under the drive of servo motor, the torque brake is set to no-load state, and the friction torque of ceramic bearing is measured by two high-precision torque sensors, and then the final measurement result is compensated. The synchronous loading of torque is realized by the torque transmission shaft between the high-precision torque sensor and the torque sensor to be calibrated. The torque output of the standard device of torque sensor in extreme environment is compared and the output torque value of the calibrated torque sensor to realize the calibration of the calibrated torque sensor.

3. Design of torque standard device for extreme environment

3.1. Mechanical design of torque transmission shaft

In the design of torque transmission shaft, the strength and stiffness of torque transmission shaft are comprehensively designed, and the material is alloy steel 42CrMo with ultra-high strength. Considering that the working environment of torque transmission shaft of standard device of torque sensor in extreme environment is (-100 ~ 100) °C and redundant design of the device, the torsional stiffness and torsional strength of torque transmission shaft are checked with 3 times of torque range of standard device.

For the shaft with circular cross-section transmitting torque, the strength conditions are as follows:

\[ d \geq \frac{16T}{\pi WP \tau} \]  

(1)

Where \( T \) is the torque value loaded in the shafting; \( WP \) is the torsional section coefficient; \( \tau \) is the torsional shear stress; \( \left[ \tau \right] \) is the allowable torsional shear stress.

According to the material manual, \( \left[ \tau \right] \) is 186mMpa, and the calculation result is greater than or equal to 34.3mm.

Starting from the torque stiffness of the torque transmission shaft, the stiffness conditions are as follows:

\[ d \geq \frac{32TL^2}{\pi G \phi} \]  

(2)

Where \( T \) is the torque value loaded in the shafting; \( L \) is the shafting length; \( G \) is the shear modulus of the material; and \( \left[ \phi \right] \) is the allowable torsion angle.

The torsional angle of the shafting on the whole length is no more than 1 ° and the calculated result is greater than or equal to 68.3 mm.

Therefore, considering the stiffness and strength of the torque transmission shaft, the design torque transmission shaft diameter is 70mm.

3.2. Software design

The software is programmed by LabVIEW. The main functions of the measurement and control software are as follows:

Verification process control: there are start verification, parameter setting, system reset, system stop function buttons on the measurement interface to control the whole verification process, and the operation is simple and clear.

Data management function: the relevant information and measurement data of each verification of the device will be recorded and saved by the measurement software, and a database will be generated, which has the functions of data management and query. In addition, the report printing function can input the calibration information of the instrument to generate an instrument calibration data record form.
Friendly man machine interface: the verification process of the device is clearly displayed on the measurement interface, including the status of motion control card, servo driver and servo motor, calibration point of torque sensor, table display of verification results, etc.

The functional structure of the measurement software of the standard device is shown in figure 2.

4. Precision design of torque standard device in extreme environment

The maximum measurement accuracy of the calibrated torque sensor in the extreme environment test box is 2.5Nm. According to the metrological theory, the maximum allowable error of the torque standard device in extreme environment is designed to be 0.8Nm. Therefore, the error sources in the calibration test process of the standard device are analyzed and calculated comprehensively.

The mathematical model of torque calibration for extreme environment torque standard device is as follows:

\[ T' = T + \Delta T_1 + \Delta T_2 + \Delta T_3 \]  

Where \( T \) is the output torque value (Nm) of the standard device; \( \Delta T_1 \) is the torque value (Nm) obtained by friction torque compensation of supporting shafting bearing; \( \Delta T_2 \) is the converted torque value (Nm) introduced by shafting assembly; \( \Delta T_3 \) is the converted torque value (Nm) introduced by torque loading system.

According to formula (3), the main error sources of the standard device are as follows: the measurement error introduced by the standard high-precision torque sensor, the measurement error caused by the friction torque measurement of the shaft support ceramic bearing, the measurement error caused by the coaxiality error during shafting assembly, the measurement error introduced by the torque loading system and other errors.

4.1. Precision design of equal action principle

According to the analysis of the mechanical structure, error sources and technical indicators of the standard device for extreme environmental torque in the previous section, the accuracy of the standard device is designed [15]. According to the principle of equal action and the requirement of the maximum allowable error of 0.8Nm, the error components can be obtained by the formula of square sum root:

\[ \delta(x) = \delta_1(x) + \delta_2(x) + \delta_3(x) = \delta(x) \]

\[ = \frac{0.8Nm}{\sqrt{5}} = 0.36Nm \]  

Therefore, the relative limit error of each error is as follows:

\[ \alpha = \frac{0.36}{500} \times 100\% = 0.072\% \]  

According to the principle of equal action, the standard device has the same requirements for each error component. However, due to the limitation of processing technology and cost, the measurement error should be adjusted and redistributed according to the actual situation.

Figure 2. function diagram of measurement and control software for torque standard device in extreme environment
4.2. Standard sensor error design
The error source of standard sensor is the indication error of high precision standard torque sensor. The limit error of the standard torque sensor is 0.36nm, and the limit accuracy grade of the sensor is 0.072. Considering the device accuracy and project budget, the standard torque sensor adopts the high-precision torque sensor with accuracy level of 0.03. According to the measurement accuracy of the selected high-precision standard torque sensor, the indication error of the high-precision torque sensor \( \delta \) is taken as 0.15Nm. Before use, it should be sent to the national defense science and technology industry large torque first-class metering station or provincial measurement and testing institutions for calibration and test.

4.3. Design of friction torque error
Due to the long span of shaft system of extreme environment torque standard device, the torque transmission shaft must be supported. In this device, the ceramic bearing with small friction torque is used to support the torque transmission shaft. When ceramic bearings are used to support shafting, friction torque will be introduced in the process of torque loading, so it is necessary to measure and compensate the friction torque. The single limit error of friction torque of ceramic bearing is 0.36nm, and the limit accuracy grade of sensor is 0.072. Therefore, the high-precision torque sensor adopts the torque sensor with the accuracy level of 0.05, and the error introduced \( \delta \) is 0.25Nm. Before use, it should be sent to the national defense science and technology industry large torque primary metering station or provincial measurement and testing institutions for calibration and test.

4.4. Assembly error design
In the process of assembly and adjustment of extreme environment torque standard device, the coaxiality of reducer output shaft, high-precision torque sensor, calibrated torque sensor and electric brake must be ensured. The mean error of shaft coaxiality should be within the allowable range. Otherwise, the calibration device will fail to meet the design index, and the service life of the device will be reduced if it is operated for a long time. The shaft diameter of shafting is designed to be 70mm. According to the single limit error of assembly error of calibration device, the relative error of single limit is 0.072%. Therefore, the limit coaxiality error of shafting assembly is as follows:

\[
\Delta r = 35 \times 10^{-5} \times 0.072\% \approx 25.04\mu m
\]

According to the limit alignment error, the alignment error of shafting is designed to be 0.02mm. The error \( \delta \) is 0.14Nm.

4.5. Torque loading system error
In the calibration process of extreme environment torque standard device, the precision torque loading system composed of servo motor, precision reducer, high-precision torque sensor and PID closed-loop control program is used to realize the output of calibration torque sensor. The loading accuracy of the torque loading system will directly affect the final measurement results. Theoretically, the loading accuracy should reach 0.072%, which can be appropriately adjusted according to the accuracy of the actual PID closed-loop control program. According to the investigation, the accuracy of the PID torque control system can reach more than 0.1%. Therefore, the error of the torque loading system \( \delta \) is 0.5Nm.

4.6. Other error design
Other measurement errors mainly include hardware equipment error, software programming error, bending moment caused by shaft self weight, air pressure, humidity and human factors. The software and hardware errors can be reduced by selecting high-precision data acquisition card and writing perfect measurement program as far as possible. These errors can not be measured by the existing measurement methods and means, so they can not be corrected. Therefore, the error assigned to this item should be larger, and the limit error of this item \( \delta \) is 0.36Nm.
4.7. Synthesis of measurement error

According to the principle of error independent action and the formula of square sum root, the maximum allowable error of torque standard device in extreme environment is obtained as follows:

$$\delta(x) = \sqrt{\sum \delta_i^2}$$

$$= \sqrt{\delta_1^2 + \delta_2^2 + \delta_3^2 + \delta_4^2 + \delta_5^2}$$

$$= \sqrt{0.15^2 + 0.25^2 + 0.14^2 + 0.50^2 + 0.36^2}$$

$$= 0.70 \text{Nm}$$

Therefore, the maximum allowable error of the standard device of torque sensor in extreme environment is 0.7Nm, which meets the design requirements of the standard device.

5. Conclusion

In this paper, the device design and simulation analysis of an extreme environment torque standard device for space docking precision mechanism assembly ground simulation test equipment torque parameter calibration are carried out, and the error analysis and precision analysis design are carried out. Through mechanical theory, the shaft diameter of torque transmission shaft is designed to be 70mm. The distribution of temperature in the shafting and the influence on torque transmission are simulated and analyzed. The main error sources of the calibration device are analyzed in detail from the aspects of friction torque compensation, torque loading system error and assembly error, and the corresponding accuracy design is carried out. The calculation results show that the maximum allowable error of the torque sensor calibration device in extreme environment is 0.7nm, which meets the technical requirements of the maximum allowable error of 0.8nm proposed in this paper. This provides the design basis and theoretical basis for the later development of the extreme environmental torque standard device for ground test mechanism.

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