Precision design of differential combination torque measuring device for butt lock with in situ calibration

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Abstract. In order to solve the problem that the current docking mechanism of the docking lock differential combination test cannot be met, an in-situ calibrated docking lock differential combination torque measurement device is designed. The calibration device uses the torque transmission shaft to differentially lock the docking lock in high and low temperature environments. The combined torque value is transmitted to the normal temperature environment for measurement, and the in-situ calibration of the measured torque sensor is achieved through a clever design. Analyze the error sources of the device, and distribute the errors according to the device technical indicators. The calculation results show that the designed in-situ calibrated butt lock differential combination torque measuring device has a measuring system of 2.25%, and the maximum allowable error of the calibration system is 0.62%, which meets the technical specifications of the device.

1. Introduction

The space docking mechanism is the key mechanism for the rendezvous and docking of Shenzhou spacecraft, space station cabin and Tiangong spacecraft, and the torque characteristics of its key components (such as non drive combination, main drive combination, etc.) play an important role in the realization of docking function of the whole mechanism [1,2]. Due to the influence of high and low temperature environment in space, the torque characteristics of key components will change significantly, which increases the functional risk of docking locking and unlocking separation, resulting in poor docking sealing performance and vacuum leakage. Therefore, it is necessary to test the torque characteristics of key components of space docking mechanism under high and low temperature environment on the ground. However, the current torque test and calibration methods in normal temperature environment can not meet the requirements of torque characteristic test and calibration of key components of space docking mechanism in high and low temperature environment.

Due to the blockade of key technologies, it is necessary for China to tackle key problems independently. In China, some related research and testing work has been carried out in the early stage of space system. Aiming at several key components, such as main drive combination, differential combination, lead screw connection combination, spring mechanism and butt lock drive combination, a torque test system based on the principle of series standard sensor is built. Through simple modification of ordinary high and low temperature box, the high and low temperature test environment is obtained, which can simulate the high and low temperature environment in the range of ± 60 °C. The basic test function is initially realized, which can partially meet the test requirements.
Although some work has been carried out on the torque ground test of the key components of the space docking mechanism in China, it is still far from meeting the requirements of the ground torque test of the key components of the space docking mechanism. The main problems are: (1) the accuracy of the torque measurement system itself is not high and cannot be calibrated in situ; (2) the torque measurement system is affected by high and low temperature environment (3) the high and low temperature range simulated by the torque measurement system is insufficient. In this paper, the precision of the device is designed based on the test object of differential combination of docking lock, which is the key component of space docking mechanism.

2. Working principle of differential combination torque measuring device for butt lock with in-situ calibration

The technical specifications of the in-situ calibrated differential combination torque measuring device for butt lock are as follows:

1) Temperature range: (-70 ~ 100) °C;
2) range and uncertainty: (2 ~ 20) Nm, \( U_r = 4\% (k = 2) \);
3) calibration uncertainty: \( U_r = 1\% (k = 2) \).

The mechanical structure of the in-situ calibrated butt lock differential combination torque measuring device [3-5] is shown in figure. 1. Its working principle is: the in-situ calibration butt lock differential combination torque measuring device adopts horizontal structure. The differential combination of butt lock is placed in the high and low temperature test box. One input end and three output ends extend out of the high and low temperature test box through the input shaft and output shaft respectively. The input shaft from left to right is servo motor, reducer, coupling, torque sensor, coupling and electric brake. The structure of the three output shafts is basically the same, which is composed of coupling and torque sensor and electric brake. In the installation of differential combination mechanism, the input shaft and output shaft 1, the output shaft 2 and the output shaft 3 of the system are installed in a staggered way to avoid mechanical interference and effectively solve the problem that the driven shaft must be used due to the lack of space.

There are four torque sensors that need to be calibrated in the original position calibration of differential combination measurement system. However, in order to reduce the cost and consider the efficiency of calibration, two standard torque sensors are used for calibration. Firstly, two torque sensors in the measurement system are calibrated, and then the other two torque sensors are calibrated. The standard torque sensor is connected with the torque sensor to be calibrated and the electric brake through the coupling. The torque is applied by the torque precision loading system, and the torque value measured by the standard torque sensor and the torque sensor to be calibrated is calibrated. The standard torque sensors 1 and 2 used in the calibration system need to be sent to the national or provincial measurement institutions for calibration. After calibration, the measurement results of torque sensors can be traced back to the national torque measurement benchmark. The complete traceability chain of torque sensors used in the simulation space test process can be established, thus ensuring the reliability and accuracy of torque measurement results.
3. Error analysis of differential combination torque measuring device for butt lock with in situ calibration

The measurement uncertainty of the in-situ calibrated differential combination torque measuring device of butt lock is: $U_r = 4\%$ ($k = 2$). Therefore, it is necessary to analyze and calculate the measurement error sources of the differential combination torque measuring device with in-situ calibration. The mathematical model of torque measurement is as follows:

$$ T' = T + \Delta T_1 + \Delta T_2 \tag{1} $$

Where $T'$ is the output torque value (Nm) of the measuring device; $T$ is the torque value (Nm) of the measured torque sensor data; $\Delta T_1$ is the converted torque value introduced by the assembly error (Nm); $\Delta T_2$ is the converted torque value (Nm) introduced by the torque loading system.

It can be seen from formula (1) that the main error sources of the measurement system are as follows: measurement error introduced by torque sensor, measurement error caused by coaxiality error during shaft assembly, measurement error introduced by torque loading system and other errors.

The calibration uncertainty of the in-situ calibrated differential combination torque measuring device of butt lock is: $U_c = 1\%$ ($k = 2$). Therefore, it is necessary to analyze and calculate the calibration error sources of the in-situ calibrated differential combination torque measuring device of butt lock. The mathematical model of torque calibration is as follows:

$$ T'_c = T_c + \Delta T_{1c} + \Delta T_{2c} \tag{2} $$

Where, $T'_c$ is the output torque value (Nm) of the calibration system; $T_c$ is the torque value (Nm) of the standard torque sensor data; $\Delta T_{1c}$ is the converted torque value introduced by the assembly error (Nm); $\Delta T_{2c}$ is the converted torque value (Nm) introduced by the torque loading system.
It can be seen from formula (2) that the main error sources of calibration system are as follows: measurement error introduced by standard torque sensor, measurement error caused by coaxiality error during shafting assembly, measurement error introduced by torque loading system and other errors.

3.1. Error design of torque sensor
In situ calibrated differential combination torque measuring device of butt lock transfers torque borne by differential combination of butt lock in high and low temperature environment to experimental environment through torque transmission shaft, and then uses torque sensor to measure. Therefore, indication error of torque sensor 1(δ) is an important error source of the measurement system. In the process of calibration, the in-situ calibrated differential combination torque measuring device of butt lock transmits the torque borne by differential combination in high and low temperature environment to the test environment through the torque transmission shaft, and then calibrates the measuring torque sensor by comparing the indication values of the measured torque sensor and the standard torque sensor. Therefore, the indication error 1c(δ) of the standard torque sensor is an important error source of the calibration system.

3.2. Mechanical assembly error
In the assembly process of the in-situ calibrated differential combination torque measuring device of butt lock, the center lines of the reducer output shaft, the measuring torque sensor axle shaft, the differential combination input and output shaft and the electric brake shaft center should be in the same straight line, so as to ensure that the coaxiality of the device shaft system is within the allowable range of assembly error, otherwise the calibration device can not reach the design index and long time operation will reduce the service life of the device. The error caused by mechanical assembly in the measurement process is recorded as: 2(δ) and the error caused by mechanical assembly in the calibration process is recorded as: 2c(δ).

3.3. Output error of torque loading system
In the measurement process, the electric brake and the measuring torque sensor constitute the torque loading system of the measurement system through the software closed-loop control, so as to realize the loading of the differential combination torque of the butt lock. As the output of the torque load of the measurement system, the loading accuracy of the loading system directly affects the final measurement accuracy of the measuring device. The torque output error of the torque loading system in the measurement system is recorded as: 3(δ). In the calibration system, the electric brake and the standard torque sensor are controlled by software closed-loop to constitute the torque loading system of the calibration system, so as to realize the torque loading of the calibration system. As the output of the standard system torque load, the loading accuracy of the loading system directly affects the final measurement accuracy of the calibration system. The torque output error of the torque loading system in the calibration system is recorded as 3c(δ).

3.4. Other errors
Other errors include bending moment, air pressure, humidity, data acquisition software and human factors. In the measurement system and calibration system, these errors are recorded as 4(δ), 4c(δ), respectively.

4. Precision design of differential combination torque measuring device for butt lock with in situ calibration
4.1. Precision design of equal action principle
According to the analysis of the mechanical structure, error sources and technical indicators of the first two sections of the differential combination torque measurement device of the butt lock, the accuracy
of the measurement system and calibration system of the differential combination torque measurement device of the in-situ calibration butt lock is designed. According to the principle of equal action [6-9], the uncertainty of measurement system is 4% and that of calibration system is 1%. The error components of measurement system and calibration system can be obtained by square root formula as (3) and (4) respectively.

\[
\delta_i(x) = \delta_2(x) = \delta_3(x) = \delta_4(x) = \frac{4\%}{\sqrt{4}} = 2\%
\]

(3)

\[
\delta_{i_c}(x) = \delta_{2_c}(x) = \delta_{3_c}(x) = \delta_{4_c}(x) = \frac{1\%}{\sqrt{4}} = 0.5\%
\]

(4)

According to the principle of equal action, each error component is the same, but considering the constraints of existing technology and cost, we should make appropriate modification and reasonable distribution of each error according to the actual situation.

4.2. Error design of torque sensor

In the measurement system, the error source of torque sensor is mainly the indication error of torque sensor. The limit error of torque sensor is 2%. Considering the accuracy of the device and the project budget, the torque sensor with accuracy level 1 is adopted. According to the accuracy grade of the selected torque sensor, the indication error of the torque sensor is 1%. The error source of torque sensor in calibration system is the indication error of standard torque sensor. The limit error of standard torque sensor is 0.5%. Considering the device accuracy and project budget, the standard torque sensor adopts the torque sensor with accuracy level of 0.25. According to the accuracy grade of the selected torque sensor, the indication error of the torque sensor is 0.25%. Before use, it should be sent to national or provincial measurement and testing institutions for calibration test.

4.3. Assembly error design

In the process of assembly and adjustment, the center lines of reducer output shaft, measuring torque sensor shaft center, differential combination input and output shaft and electric brake shaft center must be in the same straight line, so as to ensure that the coaxiality of the device shaft system is within the allowable range of assembly error, otherwise, the calibration device can not meet the design requirements. Long time operation will reduce the service life of the device. The shaft diameter of the shafting is designed to be 30mm. In the process of assembly, the coaxiality of shaft system and torque sensor is adjusted to 50 μm through assembly. Therefore, the error introduced by assembly is 0.17%.

4.4. Torque loading system error

In the process of measurement and calibration, the differential combination torque measurement device of butt lock is loaded by the torque loading system composed of electric brake, torque sensor and PID closed-loop control program. The loading accuracy of the torque loading system will directly affect the final measurement results. In theory, the loading accuracy should reach at least 2% in the measurement process and at least 0.5% in the calibration process. According to the accuracy of actual PID closed-loop control program, the precision of PID torque control system designed in this device can reach 0.2%, so the error of torque loading system is 0.2%.

4.5. Other error design

Other measurement errors mainly include software and hardware errors, bending moment due to shaft self weight, air pressure, human factors and other unpredictable errors. Software and hardware errors can be reduced by using high-performance data acquisition equipment and writing reasonable measurement programs. These errors can not be measured and compensated by the existing measurement methods and means. Therefore, the limit errors of this item are 2% and 0.5%.
4.6. Synthesis of measurement error

According to the principle of error independent action and the formula of square sum root, the maximum allowable error of the measuring system of in-situ calibrated butt lock differential combination torque measuring device can be calculated as follows:

$$\delta(x) = \sqrt{\sum \delta_i^2} = \sqrt{\delta_1^2 + \delta_2^2 + \delta_3^2 + \delta_4^2} = \sqrt{1^2 + 0.17^2 + 0.2^2 + 2^2} = 2.25\%$$

$$\delta_c(x) = \sqrt{\sum \delta_c^2} = \sqrt{\delta_1^2 + \delta_2^2 + \delta_3^2 + \delta_4^2} = \sqrt{0.25^2 + 0.17^2 + 0.2^2 + 0.5^2} = 0.62\%$$

(5) (6)

Therefore, the maximum allowable error of the measurement system is 2.25% and that of the calibration system is 0.62%. It can meet the design requirements of the technical index of the differential combination torque measuring device of the in-situ calibration butt lock.

5. Conclusion

In this paper, the accuracy analysis and design of the in-situ calibration differential combination torque measurement device for docking lock of space docking mechanism is carried out. The main error sources of the device are analyzed in detail from the torque sensor error, torque loading system error, assembly error and other aspects, and the corresponding accuracy design is carried out. The calculation results show that the maximum allowable error of the measuring system is 2.25%, and that of the calibration system is 0.62%. The maximum allowable error of the measurement system is 4% and that of the calibration system is 1%. This provides the design basis and theoretical basis for the later development of the in-situ calibrated differential combination torque measuring device of butt lock.

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References

[1] Guo X.C., (2016) Research on some key technologies of high and low temperature performance test system for space station transposition mechanism [D]. Harbin: Harbin Institute of technology.
[2] Zhang C.f., Bai H.M., (2014) Spacecraft space docking mechanism technology [J]. Chinese Science (Series E), 1: 20-26.
[3] Lin J., Dai M., Lin J.J., et al. (2016) Development of 0.5mn • m ~ 10N • m high precision torque standard device [J]. Shipbuilding Engineering, 38:75-78.
[4] Chen Y.P., Lin J.J., Ni J.Q., et al. (2016) Development of 1kn • m high precision torque standard machine [J]. Mechatronics, 22: 63-67.
[5] Wang Q. (2012) Development of reference torque standard machine [D]. Tianjin: Tianjin University.
[6] Zhang B.Y., Yang T.H., Zhu Y. et al. (2019) Accuracy design of circular grating angle encoder calibration device in high and low temperature environment [J]. China test. 10: 100-104.
[7] Liu Y.Y., Guo L.J., Yang Y., et al. (2014) Research on Calibration Technology of aircraft liquid level sensor [J]. Machine tool and hydraulic, 42: 72-74.
[8] Zhu L.K., Hu J.C., Li D.S., et al. (2016) Precision design of exhaust gas collection device for gas calorific value measurement standard [J]. Computer measurement and control, 24: 199-201.
[9] Zheng K., Zhu Q., Bao X.F. (2016) Calibration technology of linear displacement sensor based on precision length meter [J]. Measurement technology, S1: 65-68