Research on calibration test technology of Multi-component force sensor

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Abstract—Multi-component force sensor is a common force measurement instrument that can perceive all six force values and torque values in space. It is mainly used in aerospace, equipment manufacturing and other fields. At present, the calibration of multi-component force sensor is mainly carried out in professional measurement laboratory with special measuring equipment. In the field of measurement and control, the stress condition of multi-component force sensor is very complex, and the sensitivity obtained by calibration test often has certain deviation from the sensitivity of multi-component force sensor under actual load condition. This paper analyzes and tests the common problems of the multi-component force sensor in the actual measurement, control and calibration test. The test proves that the combined loading and loading order and loading position of the multi-component force sensor will affect its sensitivity output. It is necessary to pay attention to the related influence in the use of multi-component force sensor and design the calibration scheme according to the specific loading situation.

1. Introduction
This template, modified in MS Word 2003 and saved as A sensor is a device or device capable of sensing a specified measured signal and converting it into a usable output signal according to a certain rule [1]. Multi-component force sensor is a force sensor that can simultaneously perceive three sets of force value components and three sets of moment components in space. It can decompose the force value or moment value in space along cartesian coordinate system and output it.

Multi-component force sensors are widely used in aerospace, equipment manufacturing, vehicle industry and other fields, such as multi-component force measurement platform used for vector thrust engine measurement, wrist force sensor used for industrial robots, multi-component force sensor used for dummy test, wind tunnel strain day equality used for wind tunnel test. In the above application scenarios, multi-component force sensors are an indispensable part of the measurement and control system under corresponding application conditions, and are accurate and reliable data sources for the measurement and control system. At present, multi-component force sensing technology is mainly developing towards high precision, large range and high resolution. In order to pursue high precision index, methods such as reasonable design of elastomer of multi-component force sensor and research on decoupling algorithm of output of multi-component force sensor are often adopted [2].
In fact, in the process of measurement test, it is found that the accuracy of multi-component force sensor is affected by factors such as the mechanical structure and the applicability of decoupling algorithm. The factors such as loading mode and tooling design also have great influence on the calibration result of multi-component force sensor during the measurement calibration test. Therefore, it is one of the necessary means to improve the precision of Multi-component force sensor to study the loading calibration test technology of Multi-component force sensor.

2. Laboratory calibration of Multi-component force sensors

In order to scientifically evaluate the universal metrological performance of Multi-component force sensors and unify the evaluation standards, it is necessary to calibrate and grade them according to certain rules and methods. The current JJF 1560-2016 Multi-component Force Sensor Calibration Specification in China stipulates the environmental requirements of multi-component force sensor calibration, such as environmental temperature, relative humidity and calibration test equipment. Performance indexes such as zero-point output, hysteresis and coupling error of multi-component force sensor are proposed [3].

According to the characteristics of materials and test signals, multi-component force sensors can be divided into resistance strain type and piezoelectric crystal type. According to the combination of shape and elastic elements, Multi-component force sensors can be divided into two categories: single type and combined type. According to the number of force component perception, the common multi-component force sensors can be divided into three component force sensors and six component force sensors. Various kinds of Multi-component force sensors differ greatly in shape, size and connection mode.

According to JJF 1560-2016, only the environmental factors and test equipment used in the calibration process of the sensor are required, but no specific requirements are put forward for the loading tooling and loading point positions of a variety of Multi-component force sensors being calibrated. However, in the actual calibration test, the loading fixture and loading point position of the calibrated multi-component force sensor will have great influence on the sensitivity, coupling error and other indexes of the multi-component force sensor.

3. Analysis of factors affecting the calibration accuracy of Multi-component force sensor

Laboratory calibration of multicomponent force transducers usually takes the following two forms:

- Use force standard machine to perform single-component force load calibration on multi-component force sensor;
- A special multi-component force combined loading device is used to perform combined loading calibration for multi-component force sensors.

Due to the structural characteristics of multi-component force sensors, there is often coupling error between components when multi-component force sensors perceive the force values in all directions. In order to comprehensively investigate the performance of the sensor under test, improve the calibration accuracy of the multi-component force sensor, and reduce the influence of coupling error, the second calibration method is often used for the combined load calibration of the multi-component force sensor. At present, a variety of special calibration devices have been developed for multi-component combined load calibration. Common multi-component force calibration devices include: superposition two-component or three-component force calibration device, static gravity six-component force calibration device and superposition six-component force calibration device. Among them, the superposition six-component force calibration device can realize the combined loading of six-component forces due to its wide range, wide application and small coupling error, so it is a commonly used multi-component force combined loading calibration device at present [4].

The loading system of the common superposition six-component force calibration device is composed of multiple loading cylinders. Each loading cylinder is distributed on the loading beam and the upper roof of the device. The lower surface of the sensor under test is installed on the moving platform of the calibration device through the lower loading tooling, and the upper surface of the sensor...
under test is installed with the upper loading tooling. During the test, the z-axis position of the sensor under test is adjusted by moving the platform up and down, and z-orientation positioning of the sensor under test is completed with the help of laser displacement sensor. During the test, the horizontal loading cylinder loads the tooling on the sensor under test, which can complete the load calibration of the force components in X and Y directions of the sensor under test. Meanwhile, eccentric loading on the tooling can realize the load calibration of the z-direction torque of the sensor under test. Similarly, the Z-direction loading cylinder installed on the upper roof can complete the load calibration of z-direction force and X-direction and Y-direction torque of the sensor under test through z-direction loading of the loading tooling on the sensor under test [5].

According to the characteristics of the multi-component force loading calibration device and the measured multi-component force sensor, there are the following factors influencing the calibration accuracy for the multi-component force combined loading calibration test:

3.1. Loading sequence
According to JJF 1560-2016, in the process of multi-component force combined load calibration test, a component shall be selected as the main component, and then the secondary component shall be loaded after loading.

A Multi-component force sensor senses a force value in such a way that the force value is applied to the sensitive element, and the sensitive element generates microstrain, output voltage or charge signals. After a principal component is applied to the sensor under test, there is close contact between the sensor under test and the loading cylinder of the loader, and the stiffness of the system is different from the stiffness of the original sensor under test. Loading cylinders of different structures and flexible decoupling devices may have different effects on the output of the sensors under test [6].

$$F_x$$  

$$F_z$$  

Figure 1 Schematic diagram of combined loading test

3.2. Influence of loading position on calibration accuracy
In the process of multi-component force load calibration, $$F_x$$, $$F_y$$ and $$M_z$$ should be laterally loaded. Unlike $$F_z$$, $$M_x$$ and $$M_y$$, which directly apply the force value on the up-loading plane through the up-loading tooling, it is necessary to apply the force value indirectly on the loading plane during the loading process. Due to the design of the loading fixture, the size of the sensor under test, the choice of loading mode and other factors, there may be a deviation between the loading axis and the upper loading plane axis for the lateral loading of the multi-component force sensor.

When the loading axis is inconsistent with the load plane designed for the multi-component force sensor, the stress state is shown in the figure. The load on the upper loading plane includes the lateral force $$F_x$$ and the introduced bending moment $$M_y$$.

$$F_x$$  

$$M_y$$  

Figure 2 Schematic diagram of eccentric loading
According to the knowledge of mechanics, the bending moment introduced is:

\[ M_y = F_x \times L_1 \]  

(1)

Converted to the applied force value, \( M_y \) can be expressed as:

\[ M_y = \int_{L_2}^{L_1} x \times \frac{q}{L_2} dx \]  

(2)

4. Test on the influence of combined loading calibration sequence on the calibration result of multi-component force sensor

Theoretically, the output of the measured multi-component force sensor should be the same under different loading sequence during calibration and operation. However, in practical use, due to the installation mode of multi-component force sensor, different loading fixture and stress condition, and the coupling error of multi-component force sensor itself, the output of multi-component force sensor is often greatly different. Therefore, it is very necessary to carry out metrological calibration tests for multi-component force sensors under different loading orders.

JJF 1560-2016 provides the combined loading test method for multi-component force sensors, that is, firstly determine a group of combined loading directions, then load one of the loading directions as the main component, and then load the other loading direction as the secondary component on the sensor to measure the output of the sensor under test.

In this test, the JR-MPF-Z50Y30X50-01 multi-component force sensor developed by Changcheng Institute of Metrology & Measurement was selected as the measured sensor. The installation method is shown in the Fig. 3.

![Installation diagram of multi-component force sensor combined load calibration](image)

Figure 3 Installation diagram of multi-component force sensor combined load calibration

In the test, referring to JJF 1560-2016, the measured multi-component force sensor is firstly loaded separately in the \( F_z \) direction to obtain the \( Z \) output to the force value of the measured sensor under the condition that there is no other influence quantity. Next, apply \( F_x \) force values of different sizes to the sensor under test, and apply \( F_z \) to the sensor under the condition that the sensor under test is subjected to the \( F_x \) direction load to measure the \( Z \) output force value of the sensor under test under this state. The output of \( F_x \) in this experiment is shown in Fig. 4. The output of \( F_z \) in this experiment is shown in Fig. 5.
Figure 4 The Fx direction output of different load combinations of the sensor under test

Figure 5 The Fz direction output of different load combinations of the sensor under test

From the above data, it can be seen that the output of \( F_z \) under the condition of applying \( F_x \) has a large difference from that under the condition of not applying \( F_x \), among which, the full-range output of \( F_z \) under the condition of not applying \( F_x \) has a difference of 8.47%FS between 30kN lateral force applied by \( F_x \) and that under the condition of not applying \( F_x \), which is far greater than the performance error of the sensor under test.

In addition, the output of the \( F_z \) direction of the sensor under application of \( F_x \) is related to the difference of the output of the \( F_z \) direction of the sensor under application of \( F_x \) and the force value of \( F_x \) applied on the sensor under test, which increases with the increase of the force value of the sub-component, as shown in the figure. At the same time, it can be seen that the linearity of the output of the principal component is almost not affected by the secondary component.

In conclusion, in many points force sensor calibration in each component should be considered in addition to the output of the loading point, still need according to the usage of sensors, such as the stress distribution and the way of loading way, clamping, the larger force sensors to be measured to the sensor calibration experiment combined load calibration tests, and measured sensor based on actual usage to choose the main load components and load component. At the same time, it is necessary to consider the size of the by-loading component as the influence quantity.

5. Test on the influence of loading position on the calibration result of Multi-component force sensor

According to the above analysis, for the measured multi-component force sensor, different loading positions will introduce different coupling error components in the calibration test. In the application of multi-component force sensor, different loading tools and stress conditions will cause different sensitivity output of multi-component force sensor. The sensor error will be introduced when the output is deviated from the output in calibration test.
To verify the influence of load position on the output of Multi-component force sensor. According to JJF 1560-2016, a set of six-component force sensor calibration tests under different loading positions were designed and carried out, and the test results were processed. The test is shown in the figure. In this test, the McS-type sensor produced by HBM company is selected as the sensor under test, and the Fy direction of the multi-component force sensor under test is loaded at different positions. The loading position selects three points of the upper plane, symmetric center and lower plane of the sensor under test. The output data of the sensor under different loading forces at different positions are shown in Table 1.

| Loading force value (kN) | Fx (mV/V) | Fy (mV/V) | Fz (mV/V) | Mx (mV/V) | My (mV/V) | Mz (mV/V) |
|--------------------------|-----------|-----------|-----------|-----------|-----------|-----------|
| 0 | 0 | -0.0002 | 0 | -0.0001 | 0 | 0 |
| 6 | 0.0024 | 0.2355 | -0.001 | 0.0106 | -0.0003 | 0.0006 |
| 12 | 0.0032 | 0.4714 | -0.0019 | 0.0209 | -0.0019 | 0.0014 |
| 18 | 0.0039 | 0.7072 | -0.0029 | 0.0310 | -0.0041 | 0.0024 |
| 24 | 0.0053 | 0.9429 | -0.004 | 0.0410 | -0.0073 | 0.0033 |
| 30 | 0.0072 | 1.1786 | -0.0056 | 0.0511 | -0.0113 | 0.0044 |

According to the data in Table 1, under different loading positions, the multi-component force sensor under test is affected by the load component output, among which the loading point is the upper platform of the sensor under test and the loading point is the lower platform of the sensor under test. The sensitivity deviation of the y-direction full range of the sensor under test is the largest, 0.0095mV/V. Taking the loading point as the full-range sensitivity at the symmetrical center of the sensor under test as the standard value, the output error of the sensor under test reaches 0.81%FS under the maximum deviation, far exceeding the performance error of the sensor itself.

At each loading position, repeatability, hysteresis and straightness indexes of the sensor under test are shown in Table 2. According to several results, it can be seen that when different loading points are selected, the output value of the measured Multi-component force sensor is different to some extent. The repeatability index is almost not affected by the position of the loading point, while the linear index and the hysteresis index are greatly affected by the position of the loading point. In this test, when the measured Multi-component force sensor is loading Fy to the loading point, the errors of the two indexes,
linearity and hysteresis, increase with the downward offset of $F_y$ to the loading point. After analysis, in order to realize loading of the measured multi-component force sensor at different loading positions, L-type loading tooling is needed, as shown in the figure. With the increase of loading force in $y$ direction, the Flexible deformation of L-type tooling results in the deviation of loading force. The influence on the reference force sensor and the measured multi-component force sensor on the loading device leads to the deviation of the linearity and hysteresis of the measured sensor. At the same time, as the position of the loading point is shifted more, according to the relevant knowledge of material mechanics, the flexible deformation of the L-type tooling of the sensor under test is increased, and the linear and hysteresis indexes are shifted more.

![Figure 6 L-type tooling schematic diagram](image)

| Table 2 | Repeatability, hysteresis and linearity of the sensor under test |
|---------|---------------------------------------------------------------|
| The loading point is the platform of the sensor under test | Repeatability (%FS) | Hysteresis (%FS) | Linearity (%FS) |
| 0.12 | 0.10 | 0.05 |
| The loading point is the symmetric center of the sensor under test | Repeatability (%FS) | Hysteresis (%FS) | Linearity (%FS) |
| 0.11 | 0.19 | 0.15 |
| The loading point is the platform under the sensor under test | Repeatability (%FS) | Hysteresis (%FS) | Linearity (%FS) |
| 0.12 | 0.29 | 0.24 |

Under various loading positions, measured sensor coupling error indicators as shown in table 3, according to table 3 shows that the sensor mount point for the measured sensor center of symmetry, the direction of the coupling error indicators is best, it has to do with the structure of the measured sensor decoupling software algorithm design and write about, measured sensor manufacturer, different models of the best position for loading different coupling error indicators. According to the calculation results, the coupling error of the sensor under test mainly occurs in $M_x$, and the generation of $M_x$ coupling error is related to the deviation from the sensor axis. When the loading position is located in the center of the sensor, the coupling error is the smallest, and when it is off the center of the sensor, the coupling error increases. The analysis shows that the direction coupling error is related to the torque value introduced by eccentric loading.

| Table 3 | Coupling error index of sensor under test |
|---------|----------------------------------------|
| Sensor coupling error(%FS) | $F_x$ | $F_y$ | $F_z$ | $M_x$ | $M_y$ | $M_z$ |
| The loading point is the platform of the sensor under test | | | | | | |
According to the above analysis, the output, repeatability, linear hysteresis, coupling error and other indexes of the measured multi-component force sensor are related to the loading position of the measured multi-component force sensor. Due to the different working conditions of the multi-component force sensor in actual use, the calibration scheme should be formulated according to the actual use of the measured sensor during the calibration test. When the calibration test of westward loading is needed, the special tooling should be designed for the sensor under test and the rigidity of the tooling should be improved as far as possible by adding the floor plate and increasing the thickness. When the multi-component force sensor is actually used in the measurement and control field, the factory performance index of the selected sensor should be considered to ensure that the force state of the sensor can give full play to the best sensor performance during the design.

6. Conclusion
Due to the limited test data, each data is only meaningful to the tested object. In the future, more tests should be carried out to obtain the performance rules of each influencing factor in the calibration of multi-component force sensor and obtain the analysis results with general significance of multi-component force sensor.

Considering that multi-component force sensors are widely used in various measurement and control situations, the complexity of their actual operating conditions may be far beyond the scope of discussion in this paper. Therefore, it is necessary to carry out targeted calibration tests for different types of multi-component force sensors in different application situations.

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