Research of Micro-deformation Measurement for High-resolution Space Camera Complex Structured

JIANG Li, WU Tong, MEN Li-zhou, YIN Qing, LIU Ke
Beijing Aerospace Institute for Metrology and Measurement Technology, Beijing, 100076, China
Author’s e-mail: jiangli_929@126.com

Abstract: High-frequency vibration in the process of launching and complex environmental conditions of the outer space generate micro deformation in components of space cameras. As a result, images from the space cameras are blurred. Therefore, it is necessary to measure the micro deformations in components of space cameras in various experiment conditions.

This paper presents a high-accuracy micro deformation measurement method. The method is implemented as follows: (1) fix Invar balls onto a space camera being measured and measure the coordinate for each ball under the standard condition; (2) simulate high-frequency vibrations and environmental conditions like the outer space to measure coordinates for each ball under each combination of test conditions; and (3) compute the deviation of a coordinate of a ball under a test condition combination from the coordinate of the ball under the standard condition and the deviation is the micro deformation of the space camera component associated with the ball. This method was applied to micro deformation measurement for space cameras of different models. Measurement data for these space cameras validated the proposed method.

1. Foreword

With the higher and higher requirements for resolution ratio of space camera of people, the space camera gradually develops towards long-focus and large caliber. This kind of space camera with large size and high resolution ratio is affected by various dynamic loads during the process of launching and travelling in the space. Both the violent vibration and complex space environment will cause the self-deformation among each optical elements of the camera, and lead to blurred images and reduction of resolution ratio [1-3]. Therefore, when conducting the ground experiment, the measurement for complex structure micro-deformation amount of high-resolution space camera is one of the major problems urgently to be solved.

In conclusion, this text proposes a kind of high-precision measurement method for micro-deformation amount of high-resolution space camera. Firstly, multiple metal balls made of tungsten steel are installed on the measured camera as references, to measure the position of center of metal balls under the standard environment; secondly, during the completing process of multiple vibration and environmental experiments, the above measurement process is repeated, and the coordinate of position of center of each metal ball before and after the experiment is obtained; finally, the
measurement data from multiple experiments is analyzed by combing environmental conditions, and the deviation value of center of each metal ball is worked out, namely the micro-deformation amount of camera structure. The result shows that this measurement method is feasible, and the measurement problem about complex structure micro-deformation amount of high-resolution space camera is solved.

2. Measurement scheme

2.1. Selection of measured target

The selection of measured target includes the selection of target structure, shape and material. This text chooses invar as the material of measured target. Because of particularity of aerospace engineering, the selected composite materials usually have characteristics of light weight, high specific strength, low coefficient of thermal expansion and etc., so materials with similar coefficient of thermal expansion are needed, and invar material has this characteristic. The processability of metal ball is very good, whose sphericity can reach 0.1μm, far less than the deformation amount of mechanical structure. Therefore, this text chooses the ball made of invar material as the measured target, and the fixed parts are all made of invar material.

2.2. Measurement procedure

Under the standard environmental conditions, fix the measured target—metal ball on the outside surface of the measured workpiece, measure all the metal balls with three coordinate measuring machine and etc., number them and record the coordinate position of center of each ball, take the position of center of ball as the control point for each part of mechanical structure to monitor the overall structure change. The distribution sketch of measured target ball on the structure is shown as below (Figure 1), and the position of measured ball can be changed according to measurement requirements.

After the change of environmental conditions (including temperature, humidity, atmospheric pressure and etc.), measure position of center of each ball again, conduct coordinate fitting, convert the measurement data before and after the environment change to the same coordinate system for the calculation of position change of each point, and calculate the deviation after change of environmental conditions and under standard environment. Then change the environmental conditions continuously, record the position change of each point under different environments, stat the laws, and calculate the deformation situation of mechanical structure. The flow chart is shown as Figure 2. Improve the original measurement method, replace the traditional method for calculating the deformation amount by measuring the geometric dimension with the method of measuring the standard ball fixed on mechanical structure: (1) reduce the error brought by the machining precision of workpiece; (2) solve the problem that the deformation amount of irregular structure can't be measured with the method of
measuring the geometric dimension.

2.3. Data processing method

Before and after the change of environmental conditions, the workpiece will have certain deformation amount (such as what is shown in Figure 3). As the change of external environment may change the overall location of mechanical structure, the data before and after change aren't under the same coordinate system, and the data of two groups of points needs to be converted to the same coordinate system for comparison and calculation. The mathematical representation of coordinate change is based on matrix theory, and is mainly related with 7 parameters, namely three translation parameters along the coordinate axis (X₀, Y₀, Z₀), three rotation parameters around three coordinate axis (Rₓ, Rᵧ, Rż) and one scale factor k, and each coordinate system is uniquely determined by these seven parameters of coordinate system.

There are two space rectangular coordinate systems, namely O-XYZ and O’-XYZ’. It is known that the coordinates of n points under current coordinate system (O-XYZ) is (Xᵢ, Yᵢ, Zᵢ), and seven parameters (X₀, Y₀, Z₀, Rₓ, Rᵧ, Rż, k) converted according to the coordinate system are also known to us, then the coordinates of n points under the target coordinate system (O’-XYZ’) is worked out as (xᵢ, yᵢ, zᵢ), and the representing method of their matrixes is:

\[
\begin{bmatrix}
    x_i \\
    y_i \\
    z_i
\end{bmatrix} = kM^T \begin{bmatrix}
    X_i - X_0 \\
    Y_i - Y_0 \\
    Z_i - Z_0
\end{bmatrix}
\]

(1)

In the formula, \(M = \begin{bmatrix}
a_1 & a_2 & a_3 \\
b_1 & b_2 & b_3 \\
c_1 & c_2 & c_3
\end{bmatrix}\), \(a_1, a_2, a_3, b_1, b_2, b_3, c_1, c_2, c_3\) and \(c_3\) are trigonometric functions of rotation parameters of three angles, substitute data of each point before and after experiment into formula (1), and seven parameters (X₀, Y₀, Z₀, Rₓ, Rᵧ, Rż, k) can be worked out, namely the measurement data before and after experiment can be converted to the same coordinate system to calculate the deviation and evaluate.

The data processing method in this text is superior to traditional data processing method, which usually uses certain three points as references to establish coordinate system, and compare the data before experiment with that after experiment. The accuracy of this kind of evaluation method requires more for three points as references, but during the actual measurement process, the measurement error of reference points is larger or the deviation values of reference points due to environment are larger, which will bring great influence to the measurement results, so the reliability of this method is worse. This text uses part of points to establish coordinate system (such as what is shown in Figure 4), and calculates the integrated data from multiple experiments by combining the unified equivalent of environmental conditions, which enhances the reliability of method.
3. Analysis of experimental results

3.1. Analysis of uncertainty

During the measurement process, the main sources for uncertainty measurement include: standard uncertainty component introduced by three coordinate measuring machine and standard uncertainty component introduced by environment temperature. The standard uncertainty component introduced by three coordinate measuring machine: the maximum permissible error of indicating value given in calibration certificate of three coordinate measuring machine is \((0.6+L/600)\,\mu m\), including the factor \(k=2\); the standard uncertainty component introduced by environment temperature: the temperature change of three coordinate measuring machine is no more than 0.3°C, and the influence of temperature is little, so it can be ignored. The extended uncertainty of three-dimensional coordinate assignment of spatial point for this measurement method: \(U=(1.2+L/600)\,\mu m\) (\(k=2\)) (in the formula, \(L\) is the maximum size of measured target, with unit of m, and \(k\) is confidence factor).

3.2. Experimental verification

In order to verify the feasibility of the method proposed in this text, measure the micro-deformation amount before and after the mechanical vibration and environmental experiment of simulation sample piece, and compare the deformation data obtained under the simulation environment and given by simulation software, the result is shown as Figure 4.

In the actual application, the test tasks of high-resolution space cameras of multiple models such as "High-resolution No. 4" and "High-resolution No. 5" have been completed according to the method proposed in this text, and the problems which can't be solved with conventional method have been solved. The micro-deformation amount measurement of complex structure, especially the online measurement of micro-deformation amount under complex environment, is the problem which hasn't been solved in geometric quantity measurement filed. The deformation amount of camera structure is worked out through replacing the traditional measurement method with establishing of high-precision structure control point, and calculating the relative position change of coordinate of control point, which has solved the high-precision measurement of micro-deformation amount of this structure.

4. Conclusion

This text proposes a kind of new measurement method by aiming at the major problem urgently to be solved, namely the micro-deformation amount measurement of complex structure of high-resolution space camera. It realizes the measurement of ultra-precision space camera through the method proposed in this text, and verifies the optical simulation result through measurement and change of camera parameters under complex environmental conditions, and the extended uncertainty of three-dimensional coordinate assignment of spatial point for this measurement method is \(U=(1.2+L/600)\,\mu m\) (\(k=2\)).

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