Analysis on calculating process of mechanical precision of devices on satellite

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Abstract. With the gradual complication of the devices on satellite, the mechanical precision of some devices with accuracy requirements on satellite should be predicted after the assembly, in order to conduct the previous design of devices and accuracy assignment of satellite. This paper will discuss main factors which influence the mechanical precision of devices, process design and calculating method. And the position and orientation matrix is used to analyse the influence of error at each stage on mechanical precision of devices after installation. One thruster on satellite is chosen as an example to specify the calculating process and feasibility of this calculating method. This paper proves that the satellite structure assembly has a small impact on mechanical precision. The control method of mechanical precision is put forward at design stage and assembly stage of satellite, and the mechanical precision and error distribution method of devices on satellite is predicted through position and orientation matrix at previous work stage.

1. Introduction

The attitude control of satellite on orbit is collectively completed by gyroscopes, sensors and thrusters. The premise of these devices which operates stable and efficient is that those devices still keeps high quality of mechanical precision after installation. In order to ensure the normal work of satellite, some key devices in satellite have the strict requirement of mechanical precision [1]. Before the installation of those devices asked for mechanical precision, the satellite will experience some stages such as structure assembly, cabins disassembling. These repeated disassembly, coordinate transfer and large-scale test will produce effects on the mechanical precision of device after installation. With the development of satellite assembly technology and the gradual complication of devices on satellite, more and more typical multibody systems appear in satellite [2]. The installation process of those devices is complex and non-testable links are numerous, and how to calculate the mechanical precision of these devices becomes a problem that should be solved urgently [3]

This paper discusses main factors which influence the mechanical precision of devices, process design and calculating method. From the very beginning of satellite manufacturer, the position and orientation matrix is used to analyze the influence of error at each stage, such as satellite structure assembly and satellite precision basement transfer, on mechanical precision of devices after installation. And one thruster on satellite is chosen as an example to specify the calculating process and feasibility of this calculating method.
2. Calculating process of mechanical precision

2.1. Satellite structure assembly error
Satellite of central cylinder will firstly experience structure assembly, then the device assembly. The errors from structure assembly accumulate to device assembly stage, which will influence the mechanical precision of devices. The structure assembly includes propulsion module assembly and service module assembly, the installation process of main panels is shown as follows.

(1) Central cylinder assembly
Take the positioning pin on satellite-rocket separation interface as a standard, the central cylinder is connected to foundation support of structure assembly through bolts. Z-axis of the central cylinder is vertically upward to establish the precision basement of structure assembly.

(2) Horizontal panels assembly
Two horizontal panels are installed to central cylinder which is shown in Fig.1. A holder is fixed to the foundation support of structure assembly, which can assign the parallelism of two horizontal panels with satellite-rocket separation interface. It is assumed that M and N are two installation holes of some device on horizontal panel, because of the leaning within the limit of error, that is to say, two coordinate values of Z-axis under satellite coordinate are different, which will result in the leaning of device after installation. So in the device assembly stage, the mechanical precision of device should consider the inherent errors in the stage of structure assembly stage.

2.2. Satellite precision basement transfer error
In the stage of satellite structure assembly, the satellite mechanical coordinate is determined by three positioning pin in precision turntable. Before the satellite turned into the stage of devices assembly, the basement of satellite should be transferred to reference mirror in satellite. This process is called satellite precision basement transfer, which will use four mounting theodolites to realize, and this process will introduce a certain mechanical error.

The auto collimation measuring error of one mounting theodolite is $\sigma_1=0.5''$, the leveling error of one mounting theodolite is $\sigma_2=0.7''$, the calibration error and milling error of reference mirror are $\sigma_3=3.6''$ and $\sigma_4=1''$. Mounting theodolite system will measure for three times, and RSS method is used to calculate error. Angular measurement error at every time is as follows.

$$\sigma_1 = \sqrt{\sigma_1^2 + \sigma_2^2}$$  \hspace{1cm} (1)

$$\sigma_2 = \sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_3^2 + \sigma_4^2}$$  \hspace{1cm} (2)
\[ \sigma_1 = \sqrt{\sigma_1^2 + \sigma_2^2} \]  

(3)

3σ rule is chosen and measuring accuracy is rounded [4], the angular measurement errors are 0.0008°, 0.004° and 0.0008°. In the practical basement transfer process, mounting theodolite system will measure for three times, and RSS method is used again to calculate error. Angular measurement error is as follow.

\[ \sigma = \sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_3^2} = 0.004157° = 14.965'' \]  

(4)

The angle value above is the worst case in the stage of satellite precision basement transfer. When structure assembly and precision basement transfer completed, satellite turns into the stage of device assembly. The error from structure assembly will also reflect in the mechanical precision of devices.

3. Calculating process design of mechanical precision of devices

Before devices installation, satellite will experience stages of structure assembly and precision basement transfer, as described in the previous section. The errors of these two stages will reflect in the mechanical precision of device. So they will be seen as two point errors and added into the mechanical precision links of devices, shown as Fig.2.

![Figure 2. Calculating process of mechanical precision of devices on satellite.](image)

Shown as Fig.2, when mechanical precision of devices are calculated, there are three coordinate should be considered, satellite coordinate, installation hole coordinate and device coordinate. Build the relationship between these three coordinate through location and orientation matrix and reflect in the mechanical precision of device.

Location and orientation matrix is a block matrix of 3×4. The first three columns present the orientation relationship between two coordinates. The last one column presents the location relationship between two coordinates. When a device is installed to a satellite, the relationship between device coordinate and satellite coordinate will be obtained through mounting theodolite or laser tracker, and the location and orientation matrix is obtained then.

Location and orientation matrix describes the location and orientation relationships between two coordinate [5]. Lead the location and orientation matrix method into the calculating of mechanical precision of device, and treat the structure assembly error and basement transfer error as two errors and add them into the location and orientation matrix between satellite coordinate and installation coordinate in the form of continuous multiplication. So the errors of lifecycle of satellite will be considered into mechanical precision of device. One thruster is taken as an example to explain the mechanical precision method of device based on location and orientation matrix.

4. Example

It is known that one thruster is fixed upon the edge +X+Y of one panel. From structure assembly stage, the influence of installation error, satellite basement transfer error and bracket installation error on
mechanical precision of thruster is considered. This process involves three coordinates, there are satellite coordinate, panel installation hole coordinate and thruster coordinate, shown as Fig.3.

Figure 3. Installation diagram of one thruster.

(1) Relationship between satellite coordinate and panel installation hole coordinate

The origin of satellite coordinate is located in the center of central cylinder, while the origin of panel installation hole coordinate is located in the +X+Y edge of one panel. In the case of theory, the three axes of panel installation hole coordinate are parallel respectively to each axis of satellite coordinate. So it is assumed that in the case of theory, the position of the origin of panel installation hole coordinate in satellite coordinate is (1180mm, 1050mm, 100mm), Euler angle is (0°, 0°, 0°), the theory position and orientation matrix between these two is:

\[
C_{C_s \rightarrow C_i} = \begin{bmatrix}
1 & 0 & 0 & 1180 \\
0 & 1 & 0 & 1050 \\
0 & 0 & 1 & 100
\end{bmatrix}
\]

\(C_{C_s \rightarrow C_i}^{(5)}\)

In practice, it is assumed that the maximum error of structure assembly of one panel is ±1mm, and the satellite basement transfer error is 15″. Then the position changes to (1179.999941mm, 1049.999947mm, 101mm). Let the norm of the axes of satellite coordinate be 1, there are:

\[
\begin{align*}
\hat{x}_s &= (1,0,0) \\
\hat{y}_s &= (0,1,0) \\
\hat{z}_s &= (0,0,1)
\end{align*}
\]

\(C_{C_s \rightarrow C_i}^{(6)}\)

Then the actual angle matrix between satellite coordinate and panel installation hole coordinate is obtained. The position and orientation matrix and Euler angle are obtained through cosine of that actual angle matrix. Then add the satellite basement transfer error of 15” to this Euler angle, the actual position and orientation matrix is obtained.

\[
C_{C_s \rightarrow C_i}^{(7)} = \begin{bmatrix}
0.99999997 & -0.00007272 & -0.00024378 & 1179.999941 \\
0.00007278 & 0.999999968 & 0.000243775 & 1049.999947 \\
0.00024376 & 0.000243793 & 0.999999941 & 101
\end{bmatrix}
\]

(2) Relationship between panel installation hole coordinate and thruster coordinate

Thruster coordinate is located in the top of its bracket. Local enlarge Fig.3, the relationship between panel installation hole coordinate and thruster coordinate is obtained, as Fig.4 shown. It is assumed that in the case of theory, the position of the origin of thruster coordinate in panel installation hole coordinate is (0mm, 64.65mm, -224.64mm). Let the norm of the axes of satellite coordinate be 1, there are:
The theory angle matrix is obtained through the included angles of these six vectors:

$$A_{n\rightarrow b}^T = \begin{bmatrix} 90 & 0 & 90 \\ 74.99999971 & 90 & 14.99999918 \\ 14.99999918 & 90 & 105 \end{bmatrix}$$

Then the theory Euler angle is (-105°, 0°, -90°), the theory position and orientation matrix is:

$$C_{n\rightarrow b}^T = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0.258819 & 0 & 0.96592583 & 64.65 \\ 0.96592583 & 0 & -0.258819 & -244.64 \end{bmatrix}$$

Figure 4. Two coordinates of panel installation hole and thruster.

(3) Relationship between satellite coordinate and thruster coordinate

The position and orientation matrix $C_{n\rightarrow s}^T, C_{b\rightarrow s}^T$ between satellite coordinate and panel installation coordinate are obtained from step (2), and the position and orientation matrix $C_{n\rightarrow b}^T$ between panel installation coordinate and thruster coordinate is also obtained. Then the theory position and orientation matrix between satellite coordinate and thruster coordinate is gained as $C_{n\rightarrow s}^T = C_{b\rightarrow s}^T \cdot C_{n\rightarrow b}^T$. And the actual position and orientation matrix $C_{n\rightarrow s}^R, C_{b\rightarrow s}^R$ considering errors from structure assembly and satellite basement transfer is

$$C_{n\rightarrow s}^T = C_{b\rightarrow s}^T \cdot C_{n\rightarrow b}^T$$

$$C_{n\rightarrow s}^R = C_{b\rightarrow s}^R \cdot C_{n\rightarrow b}^R$$

$$\Delta = C_{n\rightarrow s}^R - C_{n\rightarrow s}^T$$

From the value $\Delta$ of theoretical subtracting actual position and orientation matrix, it can be seen that the influence of error from structure assembly on mechanical precisions of device is very small. If the errors from structure assembly and satellite basement transfer are only considered, while the error from
device assembly is not considered, the maximum angle error of thruster is only 0.00025429°, and the maximum position error is 1mm. Taking one thruster as an example and using the position and orientation method, not only specify the feasibility of this calculating method, but also demonstrate the rationality of precision allocation in the stages of structure assembly and satellite basement transfer.

5. Conclusion

This paper discusses main factors which influence the mechanical precision of devices, process design and calculating method. The position and orientation matrix is used to analyze the influence of errors at each stage, such as satellite structure assembly and satellite precision basement transfer, on mechanical precision of devices after installation. And one thruster on satellite is taken as an example to specify the calculating process and feasibility of this calculating method. This paper proves that the satellite structure assembly has a small impact on mechanical precision of device. The control methods of mechanical precision are put forward at design stage and assembly stage of satellite, and the mechanical precision and error distribution methods of devices on satellite are predicted through position and orientation matrix at previous work stage.

1. Mechanical precision of device after installation is thought ahead, which may reduce the cost of devices and conserve resources of machine work.

2. If it is known that the design precision of some device on satellite is lower, the installation location of device on satellite can be aligned at the design stage. Some location on satellite which has a higher mechanical precision is chosen to make up for the mechanical precision of device.

3. The mechanical precision of device can be calculated ahead through the method of this paper, and compare with test value after installation, which verifies the correctness of design process.

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