Method for generating high-precision calibration force for low thrust measurement

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Abstract. The micro-thrust measurement system plays an important role in the development of micro-nano satellites. The method of obtaining high-precision calibration force is one of the key technologies of the micro-thrust measurement system. The smaller the calibration force error, the higher the calibration accuracy of the system parameters, and the higher the measurement accuracy of the measurement system. In this paper, a high-precision calibration force generation method is obtained through experiments and experiments using magnets and coils.

Keywords: electromagnetic force; micro thrust measurement; calibration.

1. Introduction
Micro-nano satellite is one of the hotspots of current satellite technology research. Micro-nano satellites have high practical value. The use of micro-satellite networking technology can not only effectively reduce costs, but also greatly improve anti-interference and recombination capabilities. However, the distributed satellite system puts forward higher requirements for the relative orbital position maintenance and high-precision attitude control between satellites. The high-precision thrust supply of the thruster is the most important factor for the Wiener satellite to perform high-precision attitude control. Accurate measurement of thrust is of great significance for the further development of thrusters.

The torsion pendulum is considered to be a suitable and effective micro-thrust measurement structure. As a measuring device, its system parameters must be calibrated. High-precision calibration force plays an important role in the calibration of system parameters. The electromagnetic force method is based on the principle that the energized wire is subjected to the amperage force in the magnetic field. It is usually composed of a coil and a permanent magnet. It has the advantages of simple structure, linearly adjustable force, and the like, and is a commonly used form of calibration force.

Due to coil installation, beam rotation, etc., the coil and the permanent magnet will have relative position changes such as relative inclination $\alpha$, radial deviation $d_r$, and axial deviation $d_s$, which affect the constant output of the electromagnetic force $F$. Thereby affecting the calibration accuracy of the system parameters. Fig. 1 shows a schematic diagram of relative inclination $\alpha$, radial deviation $d_r$, and axial deviation $d_s$. At present, regarding the influence of relative position change on electromagnetic force, only the influence of $ds$ on electromagnetic force is studied. In this study, the relative position is within a certain range, that is, in the common envelope formed by the parameter range such as insensitive
angle ($|\alpha| \leq \varphi$), insensitive radial error ($|d_r| \leq L_r$), insensitive axial interval ($|d_s - d_{s0}| \leq L_s$), the relative error of electromagnetic force satisfies a certain error range (usually $\epsilon_f = 1\%$). Thereby, a high-precision constant electromagnetic force is obtained.

Figure 1. Relative inclination, radial deviation, axial deviation

In order to study the insensitive relative position under different working currents, the balance is used to measure the output of electromagnetic force under different conditions. Through the analysis of the electromagnetic force output characteristics under different working current conditions, the insensitive relative position range within the working current range of the electromagnetic force generating device within a certain relative error range is given. Thereby providing a reliable and effective high-precision, wide-range, stable calibration force acquisition method.

2. Experiments equipment setup

As shown in Fig. 2, the designed experimental device is mainly composed of the following four parts. (a) Balance: The measurement was carried out using a Mettler-Toledo XS105DU high-precision analytical balance with a resolution of 0.01g ($\approx 0.1 \mu N$) in the range of 0 to 41g and a resolution of 0.1mg in the range of 41 to 200g. (b) Power supply: Agilent 6644A with 1mA resolution. (c) Electromagnetic force generating device: consisting of a coil and a magnet with a design parameter of 0.001 N/A and an operating current of less than 1 A. (d) Five-dimensional adjustment mechanism: consists of two horizontal stages and one vertical stage and two rotating stages. The coil can be controlled in five degrees of freedom. The minimum adjustment in horizontal and vertical directions is 0.01mm, the minimum adjustment of the angle adjustment is $0.00615^\circ (=8^\circ/1300)$. The installed experimental device is shown in Fig. 3. The magnet is placed on a precision electronic balance and the coil is suspended above the magnet using a five-dimensional adjustment mechanism. The current in the coil is changed by the power source, and the relative position of the coil and the magnet is adjusted at the same time, and the indication value of the balance is recorded, and the change of the indication value of the balance can reflect the change of the electromagnetic force (change of indication value $\times$ local gravity acceleration). By analyzing the relationship between the electromagnetic force and the relative position under different current conditions, the insensitive relative position range within the operating current range of the electromagnetic force generating device is obtained.
Figure 2. Laboratory equipment (a) balance (b) five-dimensional adjustment mechanism (c) magnet and coil (d) power supply

Figure 3. Installed experimental device
3. Results and discussion

3.1. Insensitive axial distance analysis
After adjusting the relative position to zero, study the influence of the axial distance on the electromagnetic force. The current in the control coil is less than 1.0A, and within this interval, the current range is evenly divided into 10 current sampling nodes. For each current sampling node, the balance readings were recorded at a total of 11 positions every 0.5 mm in the axial distance of 0.5 to 5.5 mm, and the average was measured 6 times at each position. It was found that the gravity acceleration in Beijing was 9.8015, which converted the balance reading into electromagnetic force. The relationship between \( F \) and \( d_s \) when \( I=0.1A \) is shown in Figure 4.

![Figure 4. Relationship between axial distance and electromagnetic force at I=0.1A](image)

The relationship between the axial distance and the electromagnetic force under different current conditions is shown in Fig. 5. Due to the small value of the error bar, it is covered by the experimental data points in the figure.

![Figure 5. Relationship between axial distance and electromagnetic force](image)

Taking the electromagnetic force of \( d_s =1.5\text{mm} \) as the reference, calculate the axial distance interval when the relative error of the electromagnetic force is 1\%, and obtain the insensitive axial deviation \( L_s=0.4\text{mm} \), that is, set the insensitive axial distance interval to 1.1~1.9 mm.
3.2. Insensitive angle analysis

Five current sampling nodes are evenly divided in the current range of 0–1A. For each current sampling node, adjust $d_s$ in 0.1mm steps in the 1.1–1.9mm insensitive axial distance interval. At each $d_s$, adjust $\alpha$ back and forth along the positive and negative directions, and measure 6 times at each position. Take the average. Then use the function to fit the recorded data. Taking $I=0.8$A as an example, the change of $F$ with $\alpha$ when $d_e=1.5$mm and 1.9mm is as shown in Fig. 6.

![Figure 6. Relationship between relative inclination and electromagnetic force](image)

3.3. Insensitive radial deviation analysis

Five current sampling nodes are evenly divided in the current range of 0–1A. For each current sampling node, in the range of 1.1–1.9mm insensitive axial distance, adjust $d_s$ in steps of 0.1mm. At each $d_s$, adjust $d_e$ back and forth along the positive and negative directions, and measure 6 times at each position. Take the average and then perform a function fit on the recorded data. Taking $I=0.8$A as an example, the change of $F$ with $d_e$ when $d_s=1.5$mm and 1.9mm is shown in Fig. 8.

![Figure 7. Insensitive angle changes with axial distance](image)
Figure 8. Relationship between radial deviation and electromagnetic force

Taking the electromagnetic force when $d_s=1.5\text{mm}$ and $d_e=0\text{mm}$ as the reference, the change of $L_e$ along the axial distance in the insensitive axial distance interval is as shown in Fig. 9 under the condition that the relative error of the electromagnetic force is 1%. Under the constant current condition, in the range of 1.1~1.9mm insensitive axial distance, $L_e$ decreases first and then increases with the increase of $d_s$. In the current range of 0~1.0A, the size of $L_e$ is 0.70mm.

Figure 9. Insensitive radial deviation with axial distance

3.4. The relationship between current and electromagnetic force

In the range of 1.1~1.9mm insensitive axial distance, $d_s$ is adjusted in steps of 0.1mm. At each $d_s$, the current is loaded by increasing first and then decreasing. First, step by 0.1A, gradually increase from 0.1A to 1A, then gradually reduce from 1A to 0.1A. In the process of gradually increasing or decreasing the control current and returning, sample each current sampling point multiple times. The method of measuring electromagnetic force was repeated, and each sampling point was measured 6 times to obtain 540 sets of data. The data was subjected to a linear regression fitting, and the results are shown in Fig. 10.
Figure 10. The relationship between current and electromagnetic force

The relationship between $F$ and $I$ obtained by fitting is shown in formula (1).

$$F(\mu N) = f(I) = 2607.1256I + 1.1461; I \leq 1A; \varepsilon_f = 1\%;$$

\[
\begin{align*}
|d_s - 1.5| & \leq 0.4\text{mm} \\
|\alpha| & \leq 0.36^\circ \\
|d_e| & \leq 0.70\text{mm}
\end{align*}
\]  

(1)

4. Conclusion

In this paper, the method of obtaining high-precision electromagnetic force is obtained by analyzing the insensitive axial spacing, insensitive angle and insensitive radial spacing. At the same time, the relationship between electromagnetic force and current is calibrated, and the corresponding relation is obtained. The electromagnetic force obtained in this way can meet the performance requirements of the calibration force in the micro-thrust measurement, and also has a certain reference value for the electromagnetic calibration force used in other fields. Considering the influencing factors such as temperature and noise is the next step to be studied.

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