A Method for Calibrating Thrust of Satellite Based on the Attitude Variety On-orbit

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Abstract. The propulsion system of satellites is usually used for orbital controlling and attitude-adjusting. And the thrust of thrusters is always calibrated by ground test. A method of calibrating the small thrust of thrusters used for satellites on-orbit is presented in this paper. The application of this method is based on the variety of the attitude of the satellite. And the rotate speed of reaction wheel, the star sensor, and the scopperil, and other components in satellite are utilized in this method. The ground test of 1N thrusters was also carried out, and the thrust calibration test of the same thrusters was performed on-orbit according to this method described here. Both the test were compared, and the results show that both the data are coincident, which means that the method is fit for calibrating small thrust of satellites on-orbit.

1. Foreword
The propulsion system of satellite is widely used for orbital controlling and attitude-adjusting. When the orbital controlling is performed, one or several thrusters work together to increase or to decrease the velocity of satellite, and the centroid of satellite should be in the direction of resultant thrust. It is because that if the centroid of satellite is not in the direction of force, there will be a disturbance torque to satellite, which will consume some more propellant to eliminate the attitude deviation. On the other hand, the attitude-controlling thrusters, which are always located at the corner of satellites and which force doesn’t go through the centroid of satellites, are used for adjust the attitude of the satellite. At the same time, Small thrust liquid pulsed rocket engines operating in pulsed mode have gained a good reputation in attitude control applications for their potential reliability and efficiency[1].

Some method is used for thrust test in the laboratory[2], but for the satellite on-orbit, the thrust calibration is always performed while the satellite is carrying out orbital controlling, and the thrust is test by the velocity increment of aircraft. While, if some new propulsion technology which may be used for satellites is validated on-orbit, the thruster may not be located through the centroid of the satellites, and the resultant thrust of thrusters may not go through the centroid either. At this time, the calibration method based on the velocity increment isn’t applicative. At the same time, if there is something wrong with the attitude-adjusting thrusters, there should be some diagnosis measures to check the fault. Another method based on the attitude variety on-orbit is available to calibrate the thrust.
2. General Approach

2.1. System Design
The thrust calibration mainly focuses on the thrust of thrusters, and the thrust lies on the pressure of the system. Take monopropulsion system as an example, a simplified, verified system is shown in figure 1. There are 2 thrusters configured in this system. It is assumed that both thrusters are located as attitude-controlling mechanism, which means that its force doesn’t go through the centroid of the satellite.

![Propulsion System Sketch](image)

**Figure 1. The MonoPropulsion System Sketch**

2.2. Calibration Method
By now, the satellite is always designed as a fully 3-axis stabilized craft by the GNC(Guidance, Navigation, Control) system. The thrust calibration is based on the attitude variety of the satellite, so the GNC system of satellite should be applied, and some sensor technology such as reaction wheel(RV), star sensor(SS) and scopperil should be utilized. The demonstrations are described as follows:

a) The thrust calibration is performed by GNC autonomous maneuvering with high precision of autonomy including SS and scopperil measuring the attitude, RV controlling the attitude. And during the calibration, the thrust is validated with the shift of RV’s rotate speed, the magnetic torque should not be utilized to unload the rotate speed of RV.

b) Both impulse test and steady test are performed for thrust test and specific impulse test.

The thrust vector to the fully 3-axis stabilized satellite when the thrusters work can be presented as follows:

\[
F = \begin{bmatrix}
F_x \\
F_y \\
F_z
\end{bmatrix} = \begin{bmatrix}
\cos(\alpha) \\
\cos(\beta) \\
\cos(\gamma)
\end{bmatrix}
\]

(1)

The shift of RV’s rotate speed can be described as \([dn1 \ dn2 \ dn3 \ …]\) by the telemetry data of satellite. There are always 4 reaction wheels fixed in the satellite for a complementary function of attitude controlling, and according to the number, the fixed angle, perform ability of the RVs, the shift of angular momentum is:
\[
\begin{bmatrix}
    dH_x \\
    dH_y \\
    dH_z
\end{bmatrix} = 
\begin{bmatrix}
    a_{11} & a_{12} & a_{13} & a_{14} \\
    a_{21} & a_{22} & a_{23} & a_{24} \\
    a_{31} & a_{32} & a_{33} & a_{34}
\end{bmatrix}
\begin{bmatrix}
    d n_1 \\
    d n_2 \\
    d n_3 \\
    d n_4
\end{bmatrix}
\]  

(2)

At the same time, the influence of the thrust to the attitude of satellite is:

\[
F_z \cdot y - F_y \cdot z = dH_x / dt
\]

\[
F_x \cdot z - F_z \cdot x = dH_y / dt
\]

\[
F_y \cdot x - F_x \cdot y = dH_z / dt
\]

(3)

When calculating the thrust, the vector of the largest angular momentum shift can be utilized. For example, the angular momentum shift of Y axis is the largest, which can be described as follows:

\[
f \cdot [\cos(\alpha) \cdot z - \cos(\gamma) \cdot x] = dH_y / dt
\]

(4)

So the thrust of the thruster can be solved by

\[
f = \frac{d(\Delta H_y)/d(\Delta t)}{\cos(\alpha)z - \cos(\gamma)x}
\]

(5)

From the method described in this chapter, we can know that the shift of RV’s rotate speed is linear to the thrust. And according to the hot-fire test results of thrusters, the chamber pressure of the first few impulses is usually lower than expected[3]. And after the first few impulses, the thrust and specific impulse is equal to designed. In order to calibrate the performance of steady-state test on-orbit, a method utilizing the linear relation can be applied here, and the test data of the number of impulses, the shift of RV’s rotate speed during different stages test will be used:

\[
f = \frac{d(\Delta H_y)/d(\Delta t)}{\cos(\alpha)z - \cos(\gamma)x}
\]

(6)

3. Thrust Calibration

According to the approach presented in the former part, the thrust calibration is performed on-orbit.

3.1. System Design[4]

The propulsion system designed as the system sketch shown in figure 1 is located in a satellite weighting about 4,000kg. This satellite is a fully 3-axis stabilized craft with 4 reaction wheels to adjust the attitude. This propulsion system includes drain valves, propellant tank, latch valve, filter, pressure sensor, and so on. The design object of the system is to generate the moment of force when the thruster works. There are 2 1N monothrusters in the system, and the 2 monothrusters are located in the same surface of the satellite. If one of the thrusters is out of work, another one can still be used to test. In order to reduce the time of unloading the RV’s rotate speed, and in order to perform the calibration of both thrusters, the thrusters are located in the symmetrical position, as shown in figure 2.
3.2. In-Flight Experiment

The propellant was drained into the propellant tank before the satellite was sent to orbit, and the tank was also fed with helium of 1.2MPa. The helium is utilized to push the propellant into the thrusters. The thrusters are designed as the attitude-controlling and orbit-controlling organs. During the thrust calibration, the thrusters are used as the attitude-controlling organs. And during the test, some real-time telemetry data such as the tank pressure, the condition of latch valve, the convolution of RVs, the attitude of the satellite, are obtained from the test and control system (TT&C system).

During the test, impulse test of different impulse number are performed. Among the impulse test, different length of 0.1s/1s*10, 0.1s/1s*20, 0.1s/1s*50 test are performed. The thrust is validated by equation (5) and (6), and the validation is shown in figure 3. From the test, we can know that the thrust ranges from 1.15~1.33N.

3.3. Ground Test

In order to validate the performance of the thrusters, the ground test are performed. Some thrust test of the thruster is carried out, as shown in figure 4. Also, a ground test system using the same components applied in the in-flight system is constructed for hot-firing. The test system is designed as a module, and is put in the vacuum cabin during hot-firing test as shown in figure 5. During the test, the negative step response method is applied[5]. The test result is shown in figure 6. From the test we can know that the thrust is about 1.15N at the pressure of 1.2MPa in the tank.
4. **Test Comparison**

From the test data above, we can know that the calibration results by in-flight experiment and ground test are consistent. At the same time, the thrust validated inflight is a little higher. The main reason may be the pressure difference between the vacuum cabin and the inflight space. The pressure of the
vacuum cabin is higher because of the competence limit of the pump which leads that the cabin pressure cannot be zero, and the gas generated from the propellant increases the pressure of cabin, while the inflight pressure is vacuum. The pressure difference leads to a thrust difference. Another reason may be the devices’ measuring precision and the indetermination of satellite’s centroid.

5. Conclusions
It is described about the method calibrating thrust on-orbit, the method is based on the attitude shift of satellites. The method is presented here, with some data obtained and telemetered to the ground. Also, this method is validated by calibrating the monothrusters on-orbit. Compared with the ground test result, we can know that the thrust is coincident. The conclusions are achieved as follows:

a) Two thrusters located in this method can reduce the time for preparing the test.  
b) This method based on the attitude variety can be utilized to calibrate the small thrust of thrusters in the satellites.  
c) There are some differences between the calibrating results of inflight test and ground test, but the test results are consistent.  
d) Further research on this method such as the method optimization, the precision increase can be carried out.

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