

Testing, modeling and estimation of Taiji-1's in-orbit magnetic parameters

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Received 15 September 2020

Revised 16 October 2020

Accepted 30 October 2020

Published 22 March 2021

Taiji-1's in-orbit magnetic property is significant for the improvement of the satellite's attitude-control performance and the acceleration noise model of gravitational reference sensor. Test data of satellite drifts have been used to construct the model including interaction among the magnetic field; remnant magnetic moment and induced magnetic moment so as to estimate the satellite's magnetic property. Using the global optimization method, the remnant magnetic moment of Taiji-1 is estimated to be $(-1.42 -0.19 -0.06) \text{ Am}^2$.

Keywords: Satellite; magnetic moment; torque.

PACS numbers: 07.87.+v

1. Introduction

Taiji-1 is the first satellite of Taiji research program implemented by Chinese academy of sciences (CAS).¹⁻⁶ The satellite has realized China's first in-orbit drag-free control with one gravitational reference sensor and two sets of electric propulsion.^{7,8}

Taiji-1 is designed not to control its attitude in some tests such as drag-free control. The attitude of satellite is only affected by disturbance torques. It is believed that the magnetic disturbance plays dominant role in the affection by preliminary analysis. Based on the analysis, it is necessary to identify the satellite's in-orbit magnetic property, that could improve the performance of satellite's attitude control and correct the acceleration noise model of gravitational reference sensor.^{9,10}

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[§]For more details, please refer to article 2102002 of this Special Issue.

2. Models and Methods

While performing some in-orbit experiments, Taiji-1's attitude drifts under disturbance torques without control by design. Because of interaction between the magnetic field and the magnetic moment, the magnetic property could be reconstructed after modeling other disturbance torques, calculating local geomagnetic field and using in-orbit housekeeping data. The angular acceleration $\dot{\omega}$ while the satellite drifting with inertia I_{sat} is determined by disturbance torques including gravity gradient torque T_{grv} , magnetic torque T_{mag} , solar pressure torque T_{sol} and atmospheric drag torque T_{atm} ,

$$I_{\text{sat}}\dot{\omega} = T_{\text{grv}} + T_{\text{mag}} + T_{\text{sol}} + T_{\text{atm}},$$

$\dot{\omega}$ can be calculated with angular velocity data which are provided by fiber optic gyroscopes. I_{sat} is measured in the ground testing phase.

The gravity gradient torque is described by

$$T_{\text{grv}} = \frac{3\mu}{r^3}(\mathbf{n}_E \times I_{\text{sat}}\mathbf{n}_E),$$

where μ is the Earth's gravitational constant, r is the distance between the satellite and the geocenter and can be obtained by transferring satellite's position data \mathbf{r}_{WGS} which are provided by GNSS receiver, \mathbf{n}_E is the unit vector in the body coordinates pointing to the geocenter and can be calculated with angle data $(\zeta_{ox}, \zeta_{oy}, \zeta_{oz})$ which are provided by star trackers,

$$\mathbf{n}_E = \frac{\mathbf{R}_{bo}(\zeta_{ox}, \zeta_{oy}, \zeta_{oz})\mathbf{n}_{oE}}{|\mathbf{R}_{bo}(\zeta_{ox}, \zeta_{oy}, \zeta_{oz})\mathbf{n}_{oE}|},$$

where \mathbf{n}_{oE} is a unit vector in the orbit coordinates pointing to the geocenter, \mathbf{R}_{bo} is a transformation matrix between orbit coordinates and body coordinates. The solar pressure torque and atmospheric drag torque can be described by simple model and are lower by more than three orders of magnitude on the 600 km altitude orbit.

After peeling off the above torques, the remnant torque is supposed to be the magnetic torque, and can be described by

$$T_{\text{mag}} = \mathbf{m}_{\text{sat}} \times \mathbf{R}_{bo}(\zeta_{ox}, \zeta_{oy}, \zeta_{oz})\mathbf{R}_{\text{oned}}\mathbf{B}_{\text{ned}},$$

where \mathbf{B}_{ned} is geomagnetic field calculated by World Magnetic Model in the ned coordinates.

The satellite magnetic moment consists of the remnant magnetic moment \mathbf{m}_{rem} and the induced magnetic moment. The induced magnetic moment is usually caused by metallic and anisotropic materials while satellite immersed in the external magnetic field. Hence, the satellite magnetic moment equation above can be expressed by

$$T_{\text{mag}} = (\mathbf{m}_{\text{rem}} + \mathbf{C}_{\text{ind}}\mathbf{R}_{bo}(\zeta_{ox}, \zeta_{oy}, \zeta_{oz})\mathbf{R}_{\text{oned}}\mathbf{B}_{\text{ned}}) \times \mathbf{R}_{bo}(\zeta_{ox}, \zeta_{oy}, \zeta_{oz})\mathbf{R}_{\text{oned}}\mathbf{B}_{\text{ned}},$$

where coefficient matrix \mathbf{C}_{ind} expresses the anisotropic magnetic property. The equation actually changes into an optimization problem with \mathbf{T}_{mag} and \mathbf{B}_{ned} time series data.

3. Results and Discussion

We use the in-orbit housekeeping data from September 13th, 2019 to November 30th, 2019, which contain 126 drifts in experiments. The moment of drifts is shown in Fig. 1. The experiments with 126 drifts include tests of the cold gas propulsion; magnetic torque; gravitational reference sensor and two electric propulsions. Some instruments such as laser and electric propulsions used in experiments may have potential to influence magnetic property significantly. We picked out the drag-free control experiments' data to avoid the definite force disturbance.

The total torque and gravity gradient torque of one drift have been calculated in Fig. 2. The solar pressure torque and atmospheric drag torque have not been plotted with approximate range of 10^{-9} – 10^{-8} Nm. The y -component of gravity gradient torque plays great role because of the satellite's configuration and attitude. The difference between the total torque and gravity gradient torque indicates that the magnetic torque is significant.

The geomagnetic field of one drift is calculated and compared to the measured data provided by magnetometers as shown in Fig. 3. The difference between calculated ones and measured ones implies that the satellite's magnetic property varies under external magnetic field, also indicates that some sort of magnetic materials are applied on the satellite. In the future work, we will try to figure out the kind, position and orientation of magnetic materials.

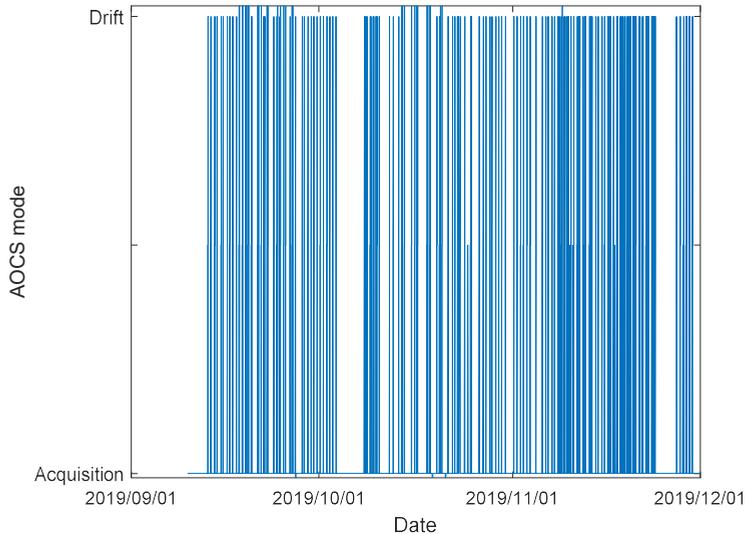


Fig. 1. The moment of 126 satellite drifting data without other AOCS mode.

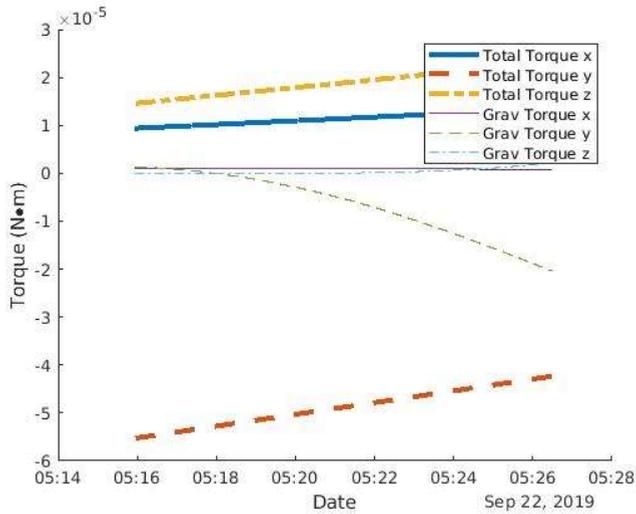


Fig. 2. The calculated total torque and gravity gradient torque.

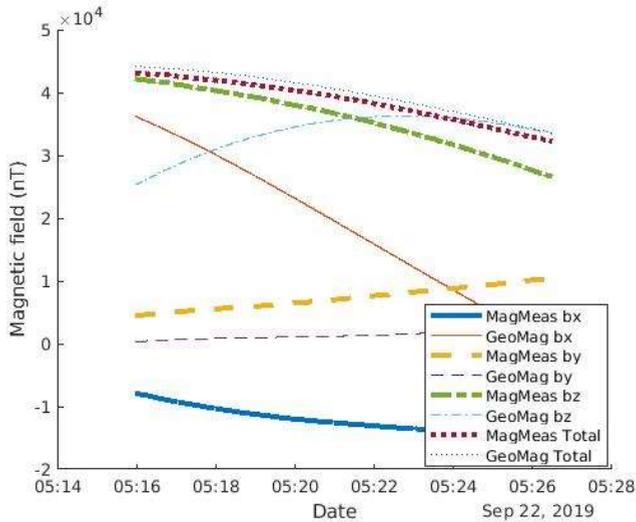


Fig. 3. The measured and calculated geomagnetic field.

The magnetic moment is calculated as shown in Fig. 4. The different values show that the satellite's induced magnetic moment plays dominant role under external magnetic field.

The results of optimization for the satellite's remnant magnetic moment are shown in Fig. 5. The results present approximately a distribution centering on one value because

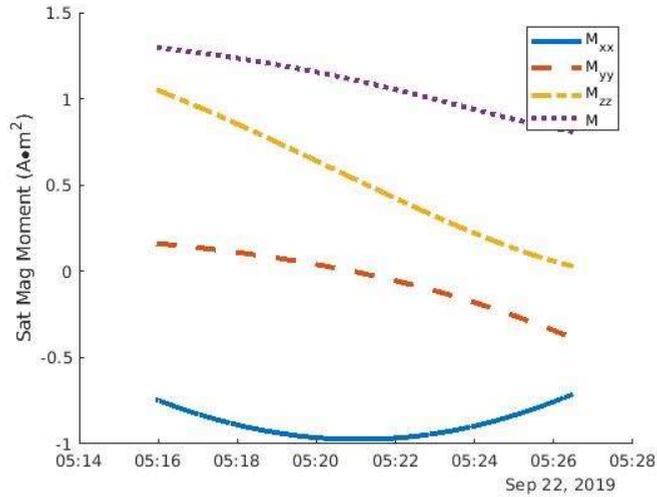


Fig. 4. The calculated magnetic moment.

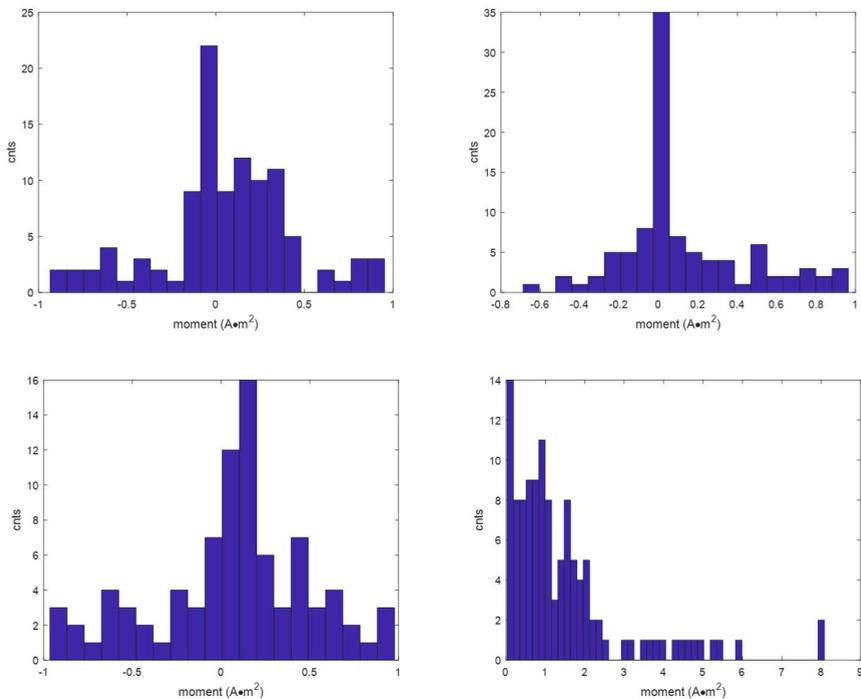


Fig. 5. The results of optimization for the satellite's remnant magnetic moment, components (a-c), total magnitude (d).

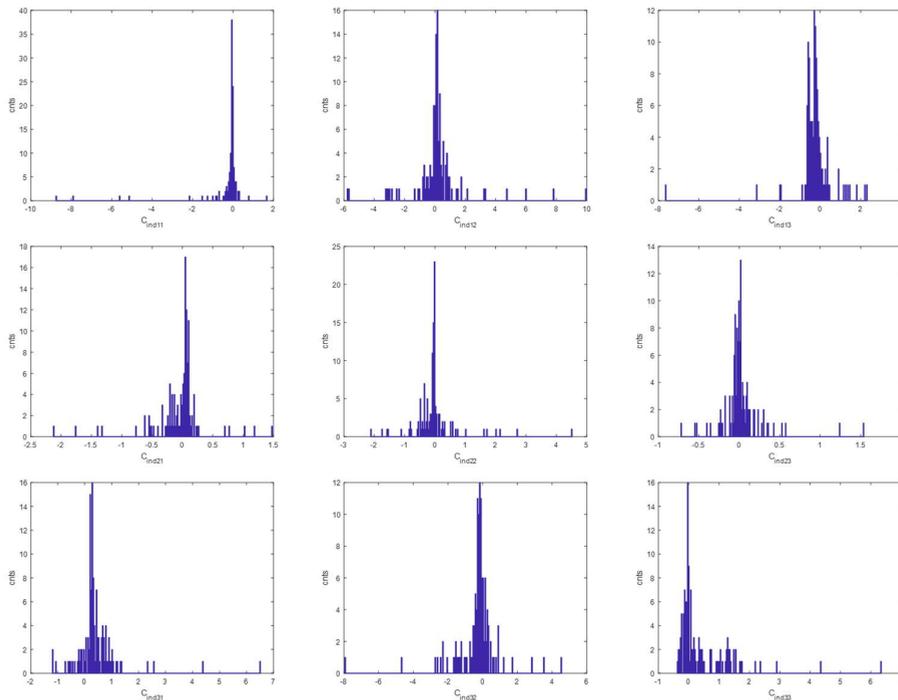


Fig. 6. The results of optimization for the satellite induced magnetic moment coefficient matrix.

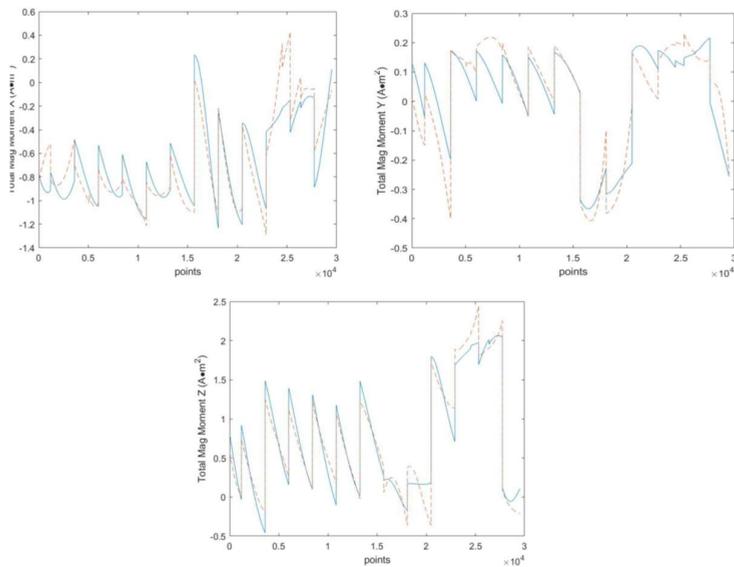


Fig. 7. The optimized (solid) and calculated (dashed) total magnetic moments of 13 tests.

we do not distinguish experiments from corresponding satellite's status. The majority results of the magnetic moment components are in range of $(-0.18, 0.48)$, $(-0.28, 0.39)$ and $(-0.29, 0.69)$ Am² separately. The majority results of the magnetic moment are in range of $(0, 2.44)$ Am².

The results of optimization for the satellite's induced magnetic moment coefficient matrix are shown in Fig. 6. The results present a distribution centering on one value as well.

Furthermore, 13 tests without phase meter, laser or propulsion working and without passing magnetic equator, are picked to be reconstructed Taiji-1's remnant magnetic moment globally. The solution is $(-1.42 -0.19 -0.06)$ Am² and total magnetic moments of the tests are shown in Fig. 7. In the future work, we will make use of the coefficient matrix to study and identify the magnetic materials.

Acknowledgments

We appreciate every Taiji-1 team member's input on the project, also the support of Strategic Priority Research Program of CAS (Nos. XDA15020706 and XDA15020709).

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