Integrated Disturbance Observer Attitude Controller for a Satellite with Rotating Solar Array

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Abstract. In this paper, the response of on-orbit satellite attitude under the influence of flexible satellite's solar array rotation is analysed, and a robust attitude control method based on disturbance observer is proposed. The disturbance torque is estimated and compensated feedforward. The simulation results show that the proposed control method can effectively estimate the external disturbance, and significantly improve the attitude control accuracy and stability.

1. Introduction

Attitude control system is an important part of satellite subsystem, and is the basis of satisfying satellite load pointing and energy supply. During the satellite lifetime, the solar arrays need to rotate to track the sun. Because of the influence of the harmonic torque and friction torque of the solar array driving mechanism, it is usually not stable enough to cause the micro vibration of the sail board. Thus, the attitude control accuracy and stability of the satellite is affected. At the same time, due to the existence of external disturbance torque such as solar pressure, it is necessary to design robust controller to achieve expected tracking performance.

The current compensation is carried to make the solar array drive assembly (SADA) more stable, and the auto disturbance rejection control (ADRC) method is introduced to realize the high stability attitude control under the influence of the satellite solar array driving in [1]. However, the SADA controller is usually independent of the attitude control system, and the current compensation controller is difficult to realize. Combining the advantages of sliding mode variable structure control and disturbance observer, a sliding mode variable structure controller based on disturbance observer is proposed in [2~4], which can not only improve the attitude control performance, but also effectively reduce the chatter phenomenon. However, the structure of the controller is complex and the parameter adjustment is difficult, which is not feasible to the engineering realization.

In this paper, based on the analysis of the micro vibration characteristics of the on-orbit satellite with rotating solar array, a robust proportional differential (PD) controller based on disturbance observer (DO) is designed. By the compensation of solar array disturbing torque, the high precision and stability of satellite attitude are achieved. It is practical significance for the satellite's attitude controller design in the engineering application.

2. Analysis of Disturbance of Solar Array Rotating

The SADA is usually composed of motor, reducer and position sensor. Taking direct driving SADA as an example, its motor adopts two-phase hybrid stepping motor, which is driven by sine cosine subdivision current. The reducer not only meets the requirements of the speed of the solar array, but also strengthens the load moment of the driving mechanism. The unsteadiness of the solar array...
rotation is the main reason that causes the micro vibration, and affects the attitude of the satellite. A large number of studies show that the friction of mechanism and harmonic torque of motor have a great influence on the driving stability of SADA, but it is difficult to accurately model.

By analysing the attitude of satellites in orbit, it is found that the angular velocity of some satellites (with large area solar array) fluctuates obviously when the solar array rotates, which is shown in the fig. 1. It is obvious that the angular velocity noise is mainly the low frequency signal, which is about 0.03 hz. By examining the frequency sources of satellite, the reason of the vibration is that the friction torque of SADA increases at some positions, which results in the micro vibration of the solar array.

Generally, gyroscope and star sensor are used to measure the angular velocity and attitude angle of the satellite, and proportional differential (PD) controller is used for attitude control. In order to eliminate the influence of measurement noise on attitude stability, the system bandwidth is designed to be low. It can restrain the high frequency noise, but not the low frequency ones. It can be seen from the above analysis that the external disturbances are mainly low-frequency noises. The closed-loop system with PD controller can be equivalent to a low-pass filter after. By adjusting the PD parameters, the characteristics of closed-loop system can be changed, but is will lead to other control problems. For example, reducing the system bandwidth will affect the dynamic characteristics of the system, and widening the system bandwidth will increasing the impact of measurement noise.

![Figure 1. The response of roll angular velocity when solar array rotate.](image)

### 3. Mathematical Model of Satellite

The following equations show the dynamic and kinematic model of spacecraft described by the unit quaternion [5]:

\[
J \dot{\omega} = -\omega^\times J \omega + Lu_\omega + d
\]

\[
\dot{q}_0 = -\frac{1}{2} q^T \omega
\]

\[
\dot{q} = \frac{1}{2} (q_0 \omega + q^\times \omega)
\]

where \( \omega = [\omega_1 \ \omega_2 \ \omega_3]^T \) is the angular velocity of satellite with respect to the inertial frame and expressed in the body frame; \([q_0, q^T] = [q_0, q_1, q_2, q_3]^T\) is the attitude of satellite in the body frame with respect to the inertial frame, such as J2000 frame; \(J \in \mathbb{R}^3\) is the symmetric inertia matrix of satellite; \(L \in \mathbb{R}^{3 \times 4}\) is the reaction wheel orientation matrix; \(u_\omega\) is control torque generated by wheels; \(d\) is the external disturbance, including environmental torques and installing error. \(\omega^\times\) is the cross-product operator for a vector \(\omega\):
The attitude tracking error is defined as the deviation between the desired attitude and the real-time attitude. Define $\mathbf{q}_e = \left[ q_{0e}, \mathbf{q}_e^T \right]^T$, which denotes the relative attitude error; and $\mathbf{q}_d = \mathbf{q} - \mathbf{C}\mathbf{q}_d$, which is the relative angular velocity error. By applying the unit quaternion operation rules, and get the derivative. The following equations are got.

$$
\mathbf{q}_e = \left[ q_{0e} \right]
$$

$$
\dot{\mathbf{q}}_e = \frac{1}{2} \mathbf{Q}_w (\mathbf{q} - \mathbf{C}\mathbf{q}_d)
$$

$$
J\dot{\mathbf{q}}_e = -\mathbf{q}^T J\mathbf{q} - Lu + d - J(C\dot{\mathbf{q}}_d - \mathbf{q}_e^T C\mathbf{q}_d)
$$

$$
C = (q_{0e}^2 - q_{0e}^T q_{0e})I_3 + 2q_{0e}q_e^T - 2q_{0e}q_e^T
$$

Where, $\mathbf{q}_d$ is the target angular velocity; $[q_{0d} \ q_{0d}]$ is the target attitude; $\mathbf{C}$ is an attitude rotation matrix. 

Assumption 1: $d(t)$ is a bounded disturbance such that $\|d(t)\| \leq T_d$, $\|\dot{d}(t)\| \leq \sigma$, where $T_d$, $\sigma$ are unknown positive constants, and $\|\|$ is the induced two-norm of a matrix.

4. The Design of Attitude Controller

In order to suppress the influence of disturbance on the attitude control performance, a satellite attitude disturbance rejection controller combined disturbance observer and PD controller is constructed, as shown in Figure 2. The input of controller and disturbance observer can be directly measured by attitude sensor, such as star sensor and gyroscope.

![Figure 2. The diagram of the proposed controller.](image)

The controller estimates the disturbance $d$ by the attitude information of satellite, and compensates the output of PD controller. According to the reference [6,7], the disturbance observer is designed as follows:
\[
\begin{align*}
\dot{d} &= z + kJ\omega \\
\dot{z} &= -kz - k^2J\omega + k(\omega^*J\omega - u)
\end{align*}
\]
(10)

Where, \( \hat{d} \) is the estimation of \( d \), \( Z \) is the intermediate variable, and \( k > 0 \) is the gain of disturbance observer.

Substituting the first formula in equation (10) into the second formula, according to the satellite dynamics equation, the following equation is obtained:

\[
\hat{\dot{d}} = -k(\hat{d} - d)
\]
(11)

Define \( \tilde{d} = \dot{d} - d \), equation (11) changes to be:

\[
\hat{\dot{d}} = -k\tilde{d} + \dot{d}
\]
(12)

By solving equation (12), the following equation is got:

\[
\tilde{d}(t) = \tilde{d}(0)e^{-kt} + \int_{0}^{t} e^{-k(t-\tau)}\hat{\dot{d}}(\tau)d\tau
\]
(13)

Based on the assumption 1 and equation (13), the following Inequality is got:

\[
\left\|\tilde{d}(\infty)\right\| \leq \sigma / k
\]
(14)

It can be seen that the disturbance estimation error of the observer is bounded.

Based on the above analysis, consider the following Lyapunov function \( V \):

\[
V = \frac{1}{2} q_e^T q_e + \frac{1}{2}(1 - q_{0e})^2 + \frac{1}{2} \omega_e^T \omega_e
\]
(15)

Based on the mathematical model, substituting the PD control input into the time derivative of \( V \), it can be given:

\[
\dot{V} \leq -\omega_e^T D\omega_e + \sigma / k \omega_e^T \omega_e \leq -\omega_e^T D\omega_e + \sigma / k
\]
(16)

considering that the disturbance is low-frequency, by choosing the derivative parameter and observer parameter \( k \), the attitude control system is uniformly bounded stable[8].

5. Simulation

The controller is realized by MATLAB Simulink software, and is applied to a small satellite attitude control system. The attitude tracking results are addressed as following. The initial numerical simulation parameters are given in Table 1.

| Parameter name          | value                                                                 |
|-------------------------|----------------------------------------------------------------------|
| Moment of inertia       | \( J = [732.9, 6.0, -2.6; 6.0, 770.8, 1.9; -2.6, 1.9, 1131.3]^T \) |
| Desired attitude        | \([q_d, q_{0d}] = [0 \ 0 \ 0 \ 1]^T, \omega_d = [0 \ 0 \ 0]^T \)       |
| Initial condition       | \( \omega = [0.002 \ 0 \ 0]^T \ \text{rad/s}, \ \vec{q} = [0 \ 0 \ 0 \ 1]^T \) |
| External disturbance    | The above disturbance and \( d = [0.05 \sin(0.2t); 0; 0]^T \ \text{N m} \) |
| Controller parameters   | \( K_p = 5, K_d = 77, k = 5 \)                                      |
| Torque saturation       | 0.075mNm                                                            |

In this simulation, two different controllers are used to demonstrate the effectiveness of the proposed method:
1) The PD controller;  
2) The PD controller with disturbance observer.

**Figure 3.** The response of roll angle and angular velocity (with on-orbit disturbance).

**Figure 4.** The response of roll angle and angular velocity (with sine disturbance).

Fig. 3 shows the response of the roll angle and angular velocity with external disturbing, when adopts two different controllers. It is obvious that the satellite attitude control accuracy and attitude stability have increased by one order of magnitude by the feedforward compensation of disturbance torque. The angle accuracy has increased from 0.1deg to 0.02deg, and the angular velocity accuracy has increased from 0.02deg/s to 0.004deg/s. The estimation accuracy of disturbance observer is about 0.002Nm.

In addition, simulations are designed to examine the performance of other kinds of disturbance, such as sine noise with different frequency. The result is shown in fig. 4. All results show that the proposed controller can improve the control accuracy. For the parameter of disturbance of observer, it is more than about 3 ~ 5 times of the system bandwidth.

**6. Conclusion**

Based on the in-orbit attitude data of satellite under the disturbance of solar array driving, this paper describes the influence of disturbance, designs a PD controller with disturbance observer, and analyses the stability. Via the disturbance observer, the disturbing torque is estimated, and the controller is compensated in real time to eliminate the impact on attitude. Simulation results demonstrate that presented scheme is effective for the estimation and compensation of external disturbance torque derived from solar array driving.

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