Actuator Motor Fault Detection by Nonlinear Sliding Observer

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Abstract. Satellite attitude is so sensitive on orbit that the disturbances induced by the actuator faults are critical. Faults in the actuator motor speed control generates such disturbances and shall be detected in short. Among nonlinear model based observers, a continuous second order sliding mode observer is applied for the detection of disturbance induced by actuator motor faults. Sources of the speed faults are classified based on the frequency spectrums of the observed disturbances and the fault type is then identified.

Introduction

Actuators like reaction wheel, momentum wheel, control moment gyros (CMGs), etc. have been used as primary attitude control actuators for a variety of spacecraft. Slew or reorientation maneuvers are executed by exchanging their angular momentum with spacecraft body.[1] The wheel momentum variation produced by the motor provides the spacecraft with maneuvering capability: torque. However, the vibrational force and torque disturbances induced by wheel faults as wheel bearing wear, misalignment, wheel speed fluctuation, etc. degrade the attitude quality of spacecraft.[2-5] Measures for the detection and isolation of severe faults in actuators shall be thus provided properly.

Model-based observer as one of fault detection and isolation (FDI) algorithms rely mainly on the system dynamic models.[6] Since the spacecraft motion is intrinsically nonlinear in large angle maneuver, a proper nonlinear FDI approach should be adopted.[7,8] Nonlinear sliding mode observer (SMO) can be used for nonlinear FDI. [9-11].

In this paper, a second order nonlinear sliding mode observer is applied for the fault detection of satellite actuators: CMGs. Among various wheel faults, the speed fluctuation faults due to the motor faults are considered. The chattering in conventional sliding observer is avoided by using a continuous observer law suggested in the reference [12]. Magnitude of oscillating disturbance is evaluated very concisely by the frequency compensation approach. Contrary to the reaction wheel case[4,5], in satellite with CMGs the isolating the faults needs consideration of gimbal direction changes. Firstly, the continuous nonlinear sliding mode observer is explained for the detection of general disturbances. Secondly, the observing algorithm is applied for the detection of wheel motor faults. Finally, the fault source is identified by comparing with the spectrums of typical motor faults.

Attitude Control with CMGs

The satellite equipped with \( n \) single gimbal CMGs are governed by following equations:

\[
\begin{align*}
\dot{\omega} + \omega \dot{\omega} - \omega^{\prime} \dot{h} &= u_c + u_i + u_e \\
D \sigma &= -u_c \\
\dot{h} &= A \tau = -u_i
\end{align*}
\]

where \( \omega \) is the satellite angular velocity. Vector \( u_c \) is the control torque produced by steering the CMG’s gimbals as \( \sigma = [\sigma_1, \sigma_2, \ldots, \sigma_n] \), \( u_i \) the wheel internal disturbance due to the actuator faults,
here the wheel speed fault, and $u_e$ the external disturbance torque. The output torque matrix $D$ is composed of output torque vectors $d_i$’s and changes with gimbal angle rotation $\sigma$ as $D=[d_1 \ d_2 \ \ldots \ d_n]$. The nominal wheel momentum $h$ is normally constant but fluctuated in case of the existence of wheel speed malfunction. The internal and external disturbances $u_i$ and $u_e$ are assumed zero on the normal condition. The matrix $A$ is the gimbal configuration matrix composed of the wheel momentum vectors $a_i$’s as $A=[a_1 \ a_2 \ \ldots \ a_n]$. Four CMGs are considered in this study as installed in a pyramid configuration as shown in Figure 1.

![Figure 1. Pyramid configured CMGs on satellite.](image)

**Disturbance Observer Design**

When disturbance is exerted on the satellite body, then the satellite attitude is affected immediately. As a monitoring tool of the anomaly, a state observer can be used as a residual generator. In this section, a nonlinear sliding observer is considered as

$$1\dot{\omega} + \omega I\ddot{\omega} + \dot{\omega}^\tau h = u_e - Iv$$

(2)

where $\dot{\omega}$ is the estimate of $\omega$ and $v$ is the observer switching vector to be designed.

Define the state estimate error as $e = \omega - \dot{\omega}$, then

$$\dot{e} = f + \Gamma^{-1}u_p + v$$

(3)

where $f$ is the system error due to $e$. $u_p$ is either $u_i$ or $u_e$.

The switching term $v$ is designed by second order sliding mode. Let $S$ be a sliding surface satisfying

$$\dot{S} + z_s\dot{S} = \dot{e} + ce$$

(4)

where $z_s$ and $c$ are gains making $S \to 0$. Consider a Lyapunov candidate $V$ as

$$V = \frac{1}{2}(\dot{S}^T\dot{S} + S^TIS)$$

(5)

By choosing $v$ as

$$v = z_s\dot{S} - ce - IS - d\text{sgn}(\dot{S})$$

(6)

then $\dot{V} \leq 0$ and $S, e \to 0$ with selecting a proper gain $d$. However, since the existence of chattering around $S = 0$ surface, the function $\text{sgn}(\dot{S})$ has been occasionally used instead of $\text{sgn}(\dot{S})$. In this paper, we use a different continuous term $d\dot{S}$ instead of $\text{sgn}(\dot{S})$ and consider its performance as suggested in reference [12]. On the sufficiently large gain $d$, a switching law is adapted as $v = z_s\dot{S} - ce - IS - d\dot{S}$. Then $\dot{V}$ becomes
\[ V = \dot{\mathbf{s}}^T \left[ f + I^{-1} u_d - d \mathbf{s} \right] \leq \| \mathbf{s} \| \| f + I^{-1} u_d - d \mathbf{s} \|^2 \]  

(7)

Then \( \dot{V} \leq 0 \) until \( \| \mathbf{s} \| \geq \| f + I^{-1} u_d \| \) and \( V \leq V_0 \). That is, \( V \) and \( \dot{s} \) is bounded small with small initial \( S_0 \), then \( e \to 0 \). Finally, the estimate of disturbance is identified as \( \hat{u}_d \to -I(f + v) \).

**Disturbance Detection**

Here, we prove with some simulations the performance of the designed observer for the detection of various kinds of disturbances.

**Secular Disturbance**

On orbit, the satellite occasionally experience secular disturbance torques, like gravity gradient torque, and solar pressure, etc, which induce the wheel momentum increase and finally saturation.[1] The detection of secular disturbance is thus necessary in real time to provide proper curing actions. The observer designed above can be used as a detector of this type of disturbance. Assume a constant disturbance \( u = [0.1 \ 0 \ 0] \) acts on \( x \)-axis of a satellite during time \( t = (20, 60) \) sec as in Figure 2(c).

![Figure 2](image-url)  

Figure 2. Responses on secular disturbance.

The angular velocity estimate \( \dot{\omega} \) in Figure 2 (b) follows well to the real angular velocity \( \omega \) in (a). The disturbance is detected immediately at \( t = 20 \) sec and the magnitude is also identified exactly in (d). The Lyapunov function \( V \to 0 \) in (f) and the sliding surface state \( \dot{s} \to 0 \) in (e) as expected. The designed observer works well as a secular disturbance detector.

**Oscillating Disturbance**

As satellite rotates around earth, it may be affected by oscillating disturbance like aerodynamic force and earth oblateness, etc. For the precise attitude control, the oscillating disturbance needs to detect. The performance of oscillating disturbance depends on the observer processing frequency. For the detection of high frequency disturbance, the observer frequency shall be greater 5~10 times than the disturbance frequency for more precise prediction. Assume the oscillating disturbance \( u = [0.1 \sin 2\pi f_d t \ 0 \ 0] \) acts on the satellite during time \( t = (20, 60) \) sec on \( y \)-axis. Here, the external disturbance frequency \( f_d = 5 \) Hz, and the observer is set to process every 0.02 sec, i.e., 10 times faster than the disturbance frequency. The time constant of error \( \epsilon \) shall be reduced by using bigger gain \( c \). As shown in Figure 3 below, the oscillating disturbance in (a) is well detected and the magnitude is estimated exactly as in (b).
Actuator Fault Detection and Isolation

Internal Disturbance Due to Wheel Fault

Wheel of control moment gyro rotates normally in constant speed. The maneuver torque is generated by rotating the gimbals. Sustaining the constant speed of wheel is important for precision control of satellite. However, when malfunction occurs in speed control, then the wheel speed may be fluctuated and the attitude quality can be degraded. By detecting immediately the severity of speed fluctuation of wheel, a proper cure can be performed. The disturbance observer shown in the previous section can be used as an internal fault detector.

Assume the wheel 1 in Figure 1 malfunctions during maneuver time \( t = (20, 60) \) sec interval as shown in Figure 4(c). Even though the wheel speed fluctuates and thus generates oscillating disturbance torque, the satellite attitude is finally stabilized with some degradation as shown in Figure 4(a). Different from the case on the external torque exerted on the single axis before, the wheel induced disturbance torque is propagated to the all three axes as shown in Figure 4(d). It is due to the CMG gimbal angles are changed during maneuver as shown in Figure 4(b). We need the isolation of fault from normal wheels.

Fault Isolation

The disturbance effects on the satellite body depending on the gimbal configuration as \( u_d = A \tau \).

Obtained the body disturbance estimate \( \hat{u}_d \), the possible candidate of malfunctioned wheel can be chosen by multiplying \( A^T \) on \( u_d \) as \( \hat{\tau} = A^T \hat{u}_d \), then we can refine candidate response as shown in
Figure 5(a), but still in ambiguity. However, by choosing the wheel axis whose direction is nearest to the $\mu_{D}$, we can finally isolate the fault wheel as shown in Figure 5(b).

**Fault Source Identification**

Malfunctions in wheel speed control may be due to several causes. Structural faults like abnormal power supply, open stator phase, and broken Hall sensors, etc could be major sources of fault. To identify the source of fault, the angular velocity data of the satellite is analyzed by FFT, and the frequency spectrum is then compared with the typical spectrum configurations of the major fault. The typical spectrum configurations of two types of faults in the wheel speed control are obtained using a momentum wheel SRV-451 developed by Spacecraft Control Laboratory in Korea Aerospace University.

**Spectrum in Normal Condition**

When the wheel rotates in the normal speed 3000 rpm, the motor inverter works normally as in Figure 6(a). However, the residual imbalance in wheel generates the disturbance as shown in Figure 6(b).

**Power supply Fault**

When the power cable has an incomplete connection, then the power supply becomes interrupted consistently and the spectrum shows the tendency as Figure 7.

**Motor Phase Fault**

When one of stator coils is cut off, or a phase Hall sensor is broken, then wheel rotates by remaining two-phases and the wheel spectrum shows biased peak configuration as Figure 8.

By comparing the FFT data of Figure 5(b) with these typical spectrum patterns, we can identify the source of motor faults. Here, we have shown only two fault types as examples, however, as accumulating the FFT data of other fault sources more and more, the identification accuracy will be improved.
Conclusions
A continuous nonlinear second order sliding mode observer applied for the detection of wheel speed fault works well with high accuracies. The highly oscillating disturbance can be identified well using frequency compensation. A wheel fault is detected and isolated successfully by applying simple transpose of gimbal configuration matrix. The fault source can be identified by comparing the disturbance spectrum with the ones of the typical motor faults.

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References