Active Fault Tolerant Control for Flexible Spacecraft with Sensor Faults Using Adaptive Integral Sliding Mode

Zhifeng Gao, Bing Han, Moshu Qian and Jing Zhao

1 Introduction

The attitude control system is one of the most important problem in spacecraft design. In modern space related missions, there is a high demand on safety, reliability and performance of spacecraft. In the past few years, the attitude control of spacecraft has attracted extensive interests and attentions by many scientists and engineers, many important results have been reported in the published academic journals [1, 2]. For the high-accuracy attitude control performance of flexible spacecraft, all kinds of advanced attitude control schemes are proposed recently, such as an adaptive fuzzy sliding mode controller is designed in [3] for the attitude stabilization of networked flexible spacecraft with parameter uncertainty and time delay, such that the tracking stability of the closed loop attitude system can be guaranteed. In [4], the attitude regulation control problem is studied for the flexible spacecraft. A dynamic disturbance compensator and a novel robust Lyapunov-based controller are designed.

The above mentioned studies focus on modeling uncertainty, disturbance and vibration to flexible appendages and do not consider the unknown faults. However, faults caused by actuators, sensors or other components, frequently occur in practice attitude control systems, which will deteriorate its performance or even shut-down of the system. Therefore, research into fault tolerant control (FTC) for attitude system has been recognized as one of the important aspects in seeking

Z. Gao (✉) · B. Han · J. Zhao
College of Automation, Nanjing University of Posts and Telecommunications,
Nanjing 210023, People's Republic of China
e-mail: gaozhifeng@njupt.edu.cn

M. Qian
College of Electrical Engineering and Control Science,
Nanjing Tech University, Nanjing 211800, People's Republic of China
e-mail: moshu_qian@126.com

Z. Deng (ed.), *Proceedings of 2017 Chinese Intelligent Automation Conference*,
Lecture Notes in Electrical Engineering 458,
https://doi.org/10.1007/978-981-10-6445-6_3

solution to an improved reliability of spacecraft. In the literature, the categories of FTC and be divide into active and passive methods [5]. Passive FTC is just an extension of robust control. Active FTC needs the feedback from the fault information. The designed controller changes in an active way according to the effects of fault. In [6], A novel fault tolerant attitude tracking control scheme is developed for flexible spacecraft with partial loss of actuator effectiveness fault. a modified fault tolerant control law based on adaptive sliding mode and neural network is proposed. In [7], a FTC method is given to the spacecraft attitude maneuvering control systems against actuator complete failure using feedback controller. In, recent years, sliding mode control has been widely applied for design of FTC as an effective control method to compensate for faults in control system. Until now, to the best of our knowledge, the fault tolerant control problem of spacecraft in sensor faulty case has not been fully investigated yet, which remains challenging and motivates us to do this study.

Inspired by the above background, an active FTC scheme is proposed for a flexible spacecraft attitude systems with unknown sensor faults. Compared to the existing literature, the main contributions of this paper are: (i) Sensor fault can be transformed into the actuator fault form without strict conditions and coordinate. (ii) The proposed approach can achieve the FTC task without fault detection module, which brings convenience FTC design in aerospace Engineering.

2 Problem Statement

The dynamics behavior of flexible spacecraft can be described by Zhang et al. [8],

$$J\ddot{\theta} + \delta^T \ddot{\eta} = u \tag{2.1}$$

$$\ddot{\eta} + D\dot{\eta} + K\eta + \delta\ddot{\theta} = 0 \tag{2.2}$$

where $J \in R^{3\times3}$ is the total inertia matrix of the spacecraft, θ is the attitude angle, which includes roll θ_x, yaw θ_y and pitch θ_z. $\eta \in R^{n\times3}$ stands for the coupling matrix between elastic and rigid dynamics, n is the number of the elastic modes connected to the rigid body, $u \in R^{3\times1}$ is the control torques generating from the flywheels orthogonally mounted on board. D and $K \in R^{n\times n}$ are the damping matrix, stiffness matrix of the appendages and, respectively.

By introducing state variable $x = \begin{bmatrix} \theta & \dot{\theta} \end{bmatrix}^T$, the state space model of flexible spacecraft attitude dynamics with sensor faults is described by,

$$\dot{x} = (A + \Delta A)x + Bu + Bd \tag{2.3}$$

$$y = Cx + f_s \tag{2.4}$$

where $A = \begin{bmatrix} 0 & I_{3\times3} \\ 0 & 0 \end{bmatrix}$, $B = \begin{bmatrix} 0 \\ (J-\delta^T\delta)^{-1} \end{bmatrix}$, $C = \begin{bmatrix} I_4 \\ 0 \end{bmatrix}^T$, $\Delta A = MFE$ is a real time-varying matrices representing parameter uncertainty with M, E being known real constant matrices of appropriate dimensions, and F is an unknown real time-varying matrix satisfying the following inequality $F^TF < I_4$, $d = \delta^T(D\dot{\eta} + K\eta)$ is the disturbance vector caused by elastic vibration of flexible appendages, which satisfies $\|d\| \leq d_0$ and d_0 is a unknown positive scalar. $f_s(t) \in R^{4\times4}$ represents the unknown sensor faults.

Before ending this section, we recall the following assumptions and lemmas, which will be essential to realize the active FTC design later.

Assumption 1 The sensor fault satisfies the following norm bounded constraint: $\|f_s\| \leq l$ and $\|f_s\| \leq l_d$, l and l_d are two unknown positive scalars.

Lemma 1 Hao et al. [9] *consider the following linear system,*

$$x = Ax + B\omega \tag{2.5}$$

$$y = Cx + D\omega \tag{2.6}$$

If there exist a positive scalar γ and a symmetric positive define matrix P, such that the following inequality holds,

$$\begin{bmatrix} A^TP + PA & PB & C^T \\ B^TP & -\gamma^2 I & D^T \\ C & D & -I \end{bmatrix} < 0 \tag{2.7}$$

then above system is stable with a given disturbance attenuation level γ.

3 Sensor Fault Estimation Scheme

In this section, a sensor fault estimation approach will be developed. For this purpose, define a new state variable $z \in R^{4\times4}$, which can be acheived by passing the faulty system output (2.4) through the following virtual filter.

$$\dot{z} = -A_f z + A_f y \tag{3.1}$$

where $A_f \in R^{4\times4}$ is the parameter matrix and it is Hurwitz.

Let $\bar{x} = [x \quad z]^T$, the original faulty system (2.3) and (2.4) can be transformed into the following augment system,

$$\dot{\bar{x}} = (A_a + \Delta A_a)x + B_a u + B_a d + B_a f_s \tag{3.2}$$

$$z = C_a \bar{x} \tag{3.3}$$

where

$$A_a = \begin{bmatrix} A & 0_{6\times4} \\ A_f C & -A_f \end{bmatrix} \quad \Delta A_a = \begin{bmatrix} \Delta A & 0_{6\times4} \\ 0_{4\times6} & 0_{4\times4} \end{bmatrix} \quad B_a = \begin{bmatrix} B \\ 0_{4\times3} \end{bmatrix} \quad D_a = \begin{bmatrix} 0_{6\times4} \\ A_f \end{bmatrix}$$

$C_a = \begin{bmatrix} 0_{6\times4} \\ I_4 \end{bmatrix}^T$. After transformation by this way, the original sensor fault can be treated as actuator fault in system (3.2) and (3.3). The estimated value of sensor fault can be obtained by the above designed adaptive fault estimation observer,

$$\dot{\hat{\bar{x}}} = A_a\hat{\bar{x}} + B_a u + D_a\hat{f}_s + L(z - \hat{z}) \tag{3.4}$$

$$\dot{\hat{f}}_s = KR(z - \hat{z}) - \sigma K\hat{f}_s \tag{3.5}$$

where $\hat{\bar{x}}$, $\hat{f}_s$ and $\hat{z}$ are the estimation of $\bar{x}$, f_s and z respectively. L is the designed observer gain matrix. K is a positive define weighting matrix, σ is a positive constant scalar and satisfies $\sigma > \lambda_{\max}(K^{-1})$.

Denoting $e_x = \bar{x} - \hat{\bar{x}}$, $e_f = f_s - \hat{f}_s$, in the following, the fist main result is given in the form of Theorem 1.

Theorem 1 *Based on the proposed observer* (3.4) and (3.5), *the estimation error dynamics are uniformly ultimately bounded, if there exists asymmetric positive definite matrix P_1 and a matrix Q with appropriate dimensions such that*

$$P_1 D_a = C_a^T R \tag{3.6}$$

$$\begin{bmatrix} P_1 A + A^T P - QC_a - C_a^T Q^T & P_1 M & P_1 B_a \\ M^T P_1 & -\varepsilon I & 0 \\ B_a^T P_1 & 0 & -\varepsilon I \end{bmatrix} > 0 \tag{3.7}$$

The observer gain can calculated by $L = P_1^{-1}Q$. The estimation errors are bounded and converge with a exponential rate greater than $e^{-\frac{k}{h}}$ to the residual set $\Omega : \left\{ e_x, e_f | \lambda_{\min}(P_1)\|e_x\|^2 + \lambda_{\min}(K^{-1})\|e_f\|^2 \le \frac{\delta h}{k} \right\}$.

Proof Choosing a Lyapunov candidate function as follows,

$$V_1 = e_x^T P_1 e_x + e_f^T P_1 e_f \tag{3.8}$$

Under the Assumption 1 and some constraints mentioned above, it is easily obtained that, $2e_f K^{-1}\dot{f}_s \le \lambda_{\max}(K^{-1})(\|e_f\|^2 + l_d^2)$, $2\sigma e_f^T f_s \le \sigma(\|e_f\|^2 + l^2)$, $2e_x^T P_1 \Delta Ax \le \frac{1}{\varepsilon} e_x^T P_1 B_a B_a^T P_1^T e_x + \varepsilon d^T d$.

Then, the derivative of (3.8) satisfies the following inequality relationship,

$$\dot{V}_1 \leq -k(\|e_x\|^2 + \|e_f\|^2) + \delta \quad (3.9)$$

where $k = \min(\lambda_{\max}(\Gamma), \sigma - \lambda_{\max}(K^{-1}))$, $\delta = \lambda_{\max}(K^{-1})l_d^2 + \sigma l^2 + \varepsilon\|x\|^2 + \varepsilon d_0^2$, $\Gamma = -(A_a - LC_a)^T P_1 - P_1(A_a - LC_a) - \frac{1}{\varepsilon}P_1 MM^T P_1^T - \frac{1}{\varepsilon}P_1 B_a B_a^T P_1^T$.

Noting that $V_1 \leq h(\|e_x\|^2 + \|e_f\|^2)$, $h = \max(\lambda_{\max}(P_1), \lambda_{\max}(K_1^{-1}))$, and substituting it into (3.9), it yields $\dot{V}_1 \leq -\frac{k}{h}V_1 + \delta$, which implies that Theorem 1 holds. This completes the proof.

4 Fault Tolerant Controller Design and Stability Analysis

In this section, the compensated output signal $y_c = y - \hat{f}_s$ is used to construct a integral sliding surface as follow,

$$s = G(y_c - y_c(t_0) + \int_{t_0}^{t} y_c(\tau)d\tau) \quad (4.1)$$

where $G = (CB)^+ - Y(I - (CB)(CB)^+)$ and Y is an arbitrary matrix. t_0 represents the initial time of the attitude system.

The designed controller is composed of a linear and a nonlinear part as follows,

$$u = u_l + u_n \quad (4.2)$$

where $u_l = Ny_c$, $u_n = -(\hat{\rho} + \lambda)\frac{s}{\|s\|}$, $\dot{\hat{\rho}} = \frac{1}{v}\|s\|$. N is the designed matrix, λ is a constant scalar and $\hat{\rho}$ is the estimation of the unknown term $\rho = l_d + \|G\|\|\dot{e}_f\| + \|G + N\|\|e_f\|$. $v > 0$ is a constant adaptation gain.

Theorem 2 *If there exist a symmetric matrix P_2 and output feedback gain N satisfy the following linear matrix inequality,*

$$[\Xi]_{34\times 34} < 0 \quad (4.3)$$

where $\Xi_{11} = (\varphi A - BGC)P_2 + P_2(\varphi A - BGC)^T$, $\varphi = I - BGC$, $\Xi_{12} = -BG + BN$, $\Xi_{13} = -BG$, $\Xi_{14} = P_2$, $\Xi_{15} = \varphi M$, $\Xi_{16} = \Xi_{18} = P_2 C^T$, $\Xi_{17} = BN$, $\Xi_{22} = \Xi_{33} = -\gamma_2^2 I$, $\Xi_{28} = I$, $\Xi_{44} = \Xi_{55} = -\mu_2^{-1} I$, $\Xi_{66} = \Xi_{77} = \Xi_{88} = -I$, $\Xi_{i,j}$ are null for others. The asymptotical stability of the system can be guaranteed.

Proof When the system has the ideal sliding mode motion on the sliding surface, i.e. $\dot{s} = 0$, the equivalent control can be designed as,

$$u_{eq} = -G(C(A + \Delta A + I)x + CBd + \dot{e}_f + e_f) + u_n \tag{4.4}$$

Substituting (4.4) into (2.3), the sliding dynamics can be obtained,

$$\dot{x} = ((I - BGC)(A + \Delta A) - BGC + BNC)x + \bar{B}\omega \tag{4.5}$$

$$y_c = Cx + \bar{D}\omega \tag{4.6}$$

where $\omega = [\, e_f \quad \dot{e}_f \,]^T$, $\bar{B} = [\, B(N - G) \quad -BG \,]^T$ and $\bar{D} = [\, I \quad 0 \,]^T$.

By applying Lemma 1 to (4.5) and (4.6), Schur complement and some calculations, the linear matrix inequality condition (4.3) can be obtained.

Consider the following Lyapunov function candidate,

$$V_2 = \frac{1}{2}(s^T s + v\tilde{\rho}^2) \tag{4.7}$$

where $\tilde{\rho} = \rho - \hat{\rho}$ is the adaptive estimation error.

Its derivative follows from (4.2) that,

$$\dot{V}_2 \le (\varepsilon\|x\| - \lambda)\|s\| \tag{4.8}$$

where $\varepsilon = \|GCA\| + \|GC\| + \|NC\| + \|GCM\|\|E\|$. Choosing $\lambda > \varepsilon\beta$ with a given scalar β, then $\dot{V}_2 < 0$. Which means that the system will be stably even in faulty conditions. This completes the proof.

5 Simulation Example

In this section, the good performance of the proposed active fault tolerant control approach is verified by considering a flexible spacecraft attitude control system model which is given by Zhang et al. [8]. Suppose that the sensor fault occurs on the first measurement channel at 10 s and the fault is a time-varying signal. Namely, $f_s = [f_1 \quad 0_{1\times 3}]^T$. The expressions of fault is described as $f_s = 0.8\sin(0.9t)$, when $t > 10s$.

Firstly, Fig. 1 provides evidence that our dynamic sensor estimation scheme has excellent fault estimation capability. Furthermore, the simulation is performed with classical output feedback control strategy. Figure 2a shows the bad effect of sensor fault on the flexible spacecraft attitude system. From Fig. 2b, with the implement of the active FTC scheme designed in this paper, it is not difficult to find that the effect of sensor fault to the closed-loop attitude systems is removed.

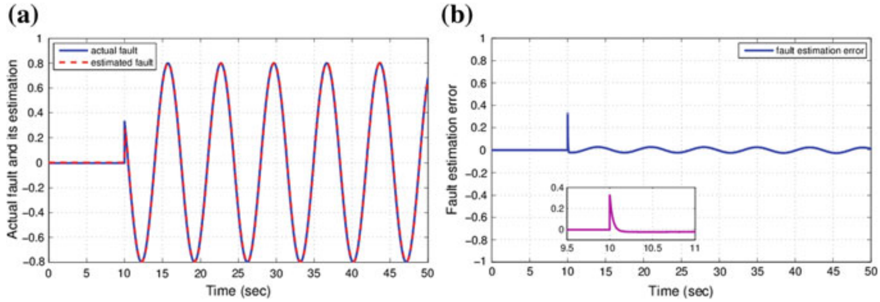

Fig. 1 Sensor fault estimation result (**a**) and its error (**b**)

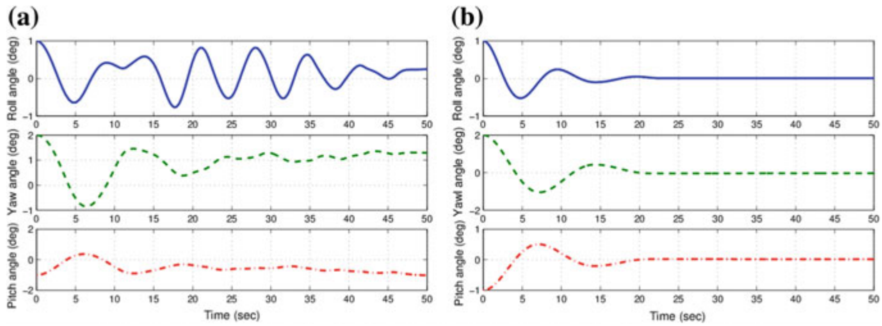

Fig. 2 Attitude angle responses in sensor faulty case using classical output feedback control (**a**) and using active FTC approach designed in this paper (**b**)

6 Conclusion

In this paper, an active FTC strategy for flexible spacecraft under sensor fault case is designed. The sensor fault is transformed into actuator fault form of an augment system and fault estimation is achieve based on an adaptive observer. By applying adaptive integral sliding mode, a FTC controller is proposed, which can ensure the attitude system normal operation although sensor fault occurs. In the finally, simulation results show the excellent performance of our approach.

Acknowledgements This work is supported by NNSF under Grant (61304106, 61403195), the Natural Science Foundation of Jiangsu Province, China (SBK2014042586), the Fundamental Research Funds for the Central Universities (NJ20160051), the Graduate Innovation Research Foundation of Jiangsu Province (1166).

References

1. Zou AM, Ruiter AJD, Kumar KD (2016) Distributed finite-time velocity-free attitude coordination control for spacecraft formations. Automatica 67:46–53
2. Ruiter AJD (2016) Observer-based adaptive spacecraft attitude control with guaranteed performance bounds. IEEE Trans Autom Control 61(10):3146–3151
3. Dong C, Xu L, Chen Y, Wang Q (2009) Networked flexible spacecraft attitude maneuver based on adaptive fuzzy sliding mode control. Acta Astronaut 65:1561–1157
4. Zhong C, Chen Z, Guo Y (2017) Attitude control for flexible spacecraft with disturbance rejection. IEEE Trans Aerosp Electron Syst 53(1):101–110
5. Lan JL, Patton RJ (2016) A new strategy for integration of fault estimation within fault-tolerant control. Automatica 69:48–59
6. Xiao B, Hu QL, Zhang YM (2012) Adaptive Sliding mode fault tolerant attitude tracking control for flexible spacecraft under actuator saturation. IEEE Trans Control Syst Technol 20 (6):1605–1612
7. Zhao D, Yang H, Jiang B, Wen L (2016) Attitude stabilization of a flexible spacecraft under actuator complete failure. Acta Astronaut 123:129–136
8. Zhang R, Qiao JZ, Li T, Guo L (2014) Robust fault-tolerant control for flexible spacecraft against partial actuator failures. Nonlinear Dyn 76:1753–1760
9. Hao LY, Park JH, Ye D (2016) Fuzzy logic systems-based integral sliding mode fault-tolerant control for a class of uncertain non-linear systems. IET Control Theory Appl 10(3):300–311