Spacecraft Attitude Fault-tolerant Control Based on Dynamic Control Distribution

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Abstract: For spacecraft attitude control system, we consider the aircraft's control surface deflection position saturation and rate constraints. Based on the dynamic control allocation method, we put forward redistribution method in the event of actuator stuck and damage failure. Firstly, because of the system modeling error caused by uncertainty and external disturbance, under actuator stuck and damage failure, we put forward the attitude control system mathematical model of angular rate control. We design actuator stuck fault diagnosis device and an adaptive sliding mode observer, respectively. The hidden failures and interference information feedback to the controller and the dynamic control allocation algorithm, in order to realize the fault tolerant control of actuator stuck and damage failure. Copyright © 2014 IFSA Publishing, S. L.

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1. Introduction

Modern aircraft on aerodynamic layout design has been reasonable segmentation to the traditional flap, rudder and elevator, and add more new type control surfaces, such as pitch flap, full motion wingtip, lift flaps, etc., has improved the system reliability and security.

As is known to all, fault-tolerant control is the premise of realization system redundancy control, and new type control surface just lays the foundation for the research of fault tolerant control. But the increase in the design of all kinds of new type of control surfaces on improving the system reliability, also brought various coupling control surfaces. So, how to effectively control instructions assigned to each control manipulation surface into a complete control system design becomes the primary issue. The control allocation technology is considering aircraft control surface deflection under the premise of position and velocity constraint, the control instruction in the form of the optimal target assigned to each control manipulation, to ensure the stability and maneuverability in the process of aircraft flight [1]. Basic control allocation chart is shown in Fig. 1. At present, the control allocation technology is considered that it is the most effective method to solve redundancy control allocation.

The traditional linear control allocation methods mainly include, 1) the pseudo-inverse method. The pseudo inverse method is a widely used method; 2) the multilevel generalized inverse; 3) chain; 4) direct distribution method; 5) the linear programming method [2].

At present, control allocation technology research focus has transformed from the linear static control technology to the dynamic and nonlinear control allocation technology.
Fig. 1. Control allocation structure.

On the other hand, considering the aircraft control surface deflection position and rate constraints, using the rest of the control surfaces to ensure flight safety is a difficult problem. As stated earlier, the control allocation provides relevant theoretical method for its implementation.

According to the fault diagnosis and identification unit get accurate fault information, using the control allocation technology, the optimal distribution of the remaining control to various control surfaces.

According to the fault diagnosis and identification unit online to get accurate fault information, using the control allocation technology, the optimal distribution of the remaining control to various control surfaces. Reference [3] puts forward the dynamic control allocation methods based on predictive control technology. Reference [4] comes up with a new control allocation method, using linear matrix inequality (LMI) toolkit online to solve the optimal actuator control instructions.

2. Problem Description

Considering the parameter uncertainty and external disturbance, it can be expressed as the following nonlinear form

\[
\begin{aligned}
\dot{x}_1 &= f_1(x_1) + g_1(x_1)x_2 \\
\dot{x}_2 &= f_2(x_1,x_2) + g_2(x_1,x_2)u + d(x_1,x_2,t),
\end{aligned}
\]

where

\[
x_1 = \Omega = [\alpha, \beta, \mu]^T \in \mathbb{R}^3, \quad x_2 = \omega = [p, q, r]^T \in \mathbb{R}^3,
\]

\[
u = \delta = [\delta_1, \cdots, \delta_8]^T \in \mathbb{R}^8, \quad f_1(x_1) = f_\Omega,
\]

\[
f_2(x_1,x_2) = -J^{-1}\omega^TJ\omega, \quad g_2(x_1,x_2) = J^{-1}\psi.
\]

Because the control allocation is to realize the optimal allocation maneuvering control, so its main work embodies the attitude angle velocity loop. The controlled object can be considered as follows

\[
\dot{x}_2 = f_2(x_1,x_2) + g_2(x_1,x_2)u + d(x_1,x_2,t),
\]

where \( x = \begin{bmatrix} x_1^T, x_2^T \end{bmatrix}^T \) is written in general form as follows

\[
\dot{x} = F(x) + G(x)u + \eta(x,t),
\]

Suppose that composite interference of system \( \eta(x,t) \) has boundary \( \tilde{\eta} \).

2.1. Actuator Stuck Fault Modeling

Actuator fault can be regarded as damage and stuck two situations. You can get damage fault model [5]

\[
\dot{x} = F(x) + G(x)Du + \eta(x,t),
\]

where \( D = \text{diag}(d_1, d_2, \cdots, d_8) \), \( k_i \) is the \( i^{th} \) manipulated surface damage factor, and is unknown constants. Aircraft rudder loop and control surfaces are usually connected by the mechanical structure. When actuator stuck happens, if the mechanical connection part is normal, then electric hydraulic drive also stuck in a certain position and can't move.

So, actuator mechanism with dynamic properties generally is represented by the following first-order inertia link:

\[
\ddot{u}_i = -\lambda_i (u_i - u_{id}),
\]

where \( u_i \) is the actuator actual output, \( u_{id} \) is the actuator output commands. Due to the actual system actuator loop response speed is much faster than the system itself, so you can use singular perturbation theory to order reduction. Failure and stuck fault can be expressed as

\[
u_i = \sigma_i d_i u_{id} + (1 - \sigma_i)\bar{u}_i,
\]

where \( \sigma_i = \text{or} 1, \text{ } 0 \) is the stuck fault, 1 represents control surfaces stuck fault.

We can get fault model of stuck fault and failure [6]

\[
\dot{x} = F(x) + G(x)D\Sigma u + G(x)D(1 - \Sigma)u + \eta(x,t),
\]

where \( \Sigma = \text{diag}(\sigma_1, \sigma_2, \cdots, \sigma_8) \). Here in fact \( u \) can be calculated by displacement sensor or through light
code disc. The purpose of fault tolerant control is to calculate the actuator displacement instructions $u_c$.

2.2. Manipulation of the Physical Constraints

Due to the actual system has a deflection position and rate constraints, so it is necessary to design the controller. So its location constraints can be expressed [7]

$$u_{\min} \leq u_c \leq u_{\max},$$

(8)

The rate constraints can be expressed

$$\dot{u}_{\min} \leq \dot{u}_c \leq \dot{u}_{\max},$$

(9)

Using an order Euler equation discretized (9)

$$\dot{u}_{\min} T + u_c(k) \leq u_c(k+1) \leq \dot{u}_{\max} T + u_c(k),$$

(10)

where $T$ is the sampling period. Therefore, the limit of rate saturation can be approximate to the deflection at each sampling time. In combination with rate constraint and saturation constraint of deflection position, we can unify definition to satisfy the following constraints, namely

$$u(k+1) \leq u_c(k+1) \leq \overline{u}(k+1),$$

(11)

3. Fault-tolerant Control System Design

This section presents the robust fault-tolerant control design thinking. The design is divided into three parts, fault diagnosis and identification unit, pseudo control law and control allocation algorithm. The proposed scheme block diagram is shown as in Fig. 2.

3.1. The Design of Fault Detection and Diagnosis Unit

In this section, the design of fault detection and diagnosis unit has two functions. One is the rapid diagnosis stuck fault of control surfaces, the other is damage fault information and interference information hiding in the adaptive sliding mode observer [8].

For the convenience of the following expression, (4) can be rewrite as

$$\dot{x} = F(x) + G(x)\dot{d} + \eta(x,t),$$

(13)

where $U = \text{diag}(u_1, \cdots, u_k)$, $\dot{d} = [\dot{d}_1, \cdots, \dot{d}_8]^T$, the observation error is $e = z - x$, so we design an observer as follows

$$\dot{\hat{d}} = \text{Proj}_{\mathcal{Z}_d \mathcal{D}} \left\{ -2\gamma (U^T G^T(x) Pe) \right\},$$

(15)

where

$$\overline{u}(k+1) = \min\left[u_{\max}, \dot{u}_{\max} T + u_c(k)\right],$$

$$\underline{u}(k+1) = \max\left[u_{\min}, \dot{u}_{\min} T + u_c(k)\right].$$

(12)

Considering under the constraint of (11), how to realize control allocation problem and fault-tolerant control system design under the control surface damage and stuck.
where \( \gamma > 0 \), \( P = P^T > 0 \), \( P \) is the solution of \( A^T P + PA = -Q \). When \( Q = Q^T > 0 \), \( A \) is a Hurwitz matrix. \( \text{Proj} \) is the projection operator, it can ensure the estimate between the minimum \( d \) and maximum \( \tilde{d} \). The sliding mode design is,

\[
v(t) = \begin{cases} \frac{-P \varepsilon}{\|P \varepsilon\|} m(t) & \text{if } \|P \varepsilon\| \neq 0 \\ 0 & \text{otherwise} \end{cases},
\]

(16)

where \( \varepsilon \) is close to the constant 0. Time-varying parameters \( m(t) \) is gotten by the following adaptive law

\[
m(t) = \Gamma \varepsilon^T e, \quad m(0) > 0,
\]

(17)

The damage factor estimation error is \( \tilde{d} = \tilde{d} - d \), by observer (14) and (4), observation error dynamic equation is obtained

\[
\dot{e} = Ae + G(x)U \tilde{d} + \nu(t) - \eta(t),
\]

(18)

By introduced into stuck fault estimation, observer (14) can be written as the following form

\[
\dot{z} = A(z - x) + F(x) + G(x) \hat{d} \sigma_e + G(x) \hat{d} (I - \Sigma) u + \nu(t)
\]

(19)

where \( \hat{d} = \text{diag}(\tilde{d}_1, \tilde{d}_2, \ldots, \tilde{d}_8) \), \( \Sigma = \text{diag}(\sigma_1, \sigma_2, \ldots, \sigma_8) \).

3.2. Pseudo Control Law Design

Due to (19) belong to the drive system, and the position saturation and rate constraints on the control input, so in the design of control law must be divided into two parts, pseudo control law and control distribution respectively.

Pseudo control law design is how to solve the following dynamic equation [9]

\[
\dot{z} = Ae + F(x) + \tau + G(x) \hat{d} (I - \Sigma) u + \nu(t),
\]

(20)

And the control allocation part is for the following equation to get the optimal control instruction \( u_c \)

\[
\gamma - J = \gamma - u_c(k)^T W^2 u_c(k)
\]

\[
= -[\tau_{des}(k) - G(k) \hat{d}(k) \Sigma(k) u_c(k)]^T W^2 [\tau_{des}(k) - G(k) \hat{d}(k) \Sigma(k) u_c(k)],
\]

(26)

By (21), pseudo control law design is relatively simple. There are many methods to use such as dynamic inversion control, backstepping control, dynamic surface control, sliding mode control, the design method based on inner and outer ring. In this section, the control law design is based on inner and outer ring.

Step 1: attitude angle loop control law is designed to be as follows

\[
x^d = -g_1(x) \left[ K_1 E_1 + f_1(x) - x^e \right],
\]

(22)

where \( E_1 = x_1 - x^e_1 \), we are prepare to design a positive matrix \( K_1 \), \( x^e_1 \) is the output of attitude angle setting value \( x^d_1 \) after the smooth. \( x^e_1 \) is obtained through the following filter

\[
\dot{X}_1 = X_2 \\
\dot{X}_2 = -2 \lambda X_1 - \lambda^2 (X_1 - \nu),
\]

(23)

where \( \lambda > 0 \), \( \nu \) is the filter input. If the input of the filter is \( \nu = x^d_1 \), then \( X_2 \) is required \( x^e_1 \).

Step 2: the attitude angle velocity loop control law is designed to be as follows

\[
\tau_{des} = - \left[ KE_2 + f(x) + G(x) \hat{d} (I - \Sigma) u + \nu(t) - x^e_2 \right],
\]

(24)

where \( E_2 = z - x^e_2 \), we are preparing to design a positive matrix \( K_2 \). \( x^e_2 \) is the output of attitude angle setting value \( x^d_2 \) after the smooth. So, to get the optimal \( u_c \) control allocation problem, we make the actual \( \tau = G(x) \hat{d} \Sigma u_c \) and \( \tau_{des} \) equal.

3.3. Control Allocation

By the above analysis, we can get the following expression

\[
\gamma - J > 0,
\]

(25)

Namely
Inequality (26) can be converted into the following LMI form:
\[
\begin{bmatrix}
    R(\chi) & C(\chi) \\
    C(\chi) & B(\chi)
\end{bmatrix} > 0, \quad (27)
\]

where \( R(\chi) = R(\chi)^T \), \( B(\chi) = B(\chi)^T \).

The use of Schur complement lemma [10, 11] can obtained
\[
B(\chi) > 0, \quad (28)
\]
\[
R(\chi) - C(\chi)B(\chi)^{-1}C(\chi)^T > 0, \quad (29)
\]

The actuator position and rate constraints are as follows
\[
u_e(k) - \bar{u}(k) \geq 0, \quad \bar{u}(k) - u_e(k) \geq 0, \quad (30)
\]

Inequality (31) is a suitable control allocation solution, using the real-time optimization result \( u_e(k) \) as the actuator instruction. (31) can solve the problem of the critical real-time flight controlling.

**4. Simulation Verification**

Using the simulation prove the validity of the proposed method, X-33 has four control surfaces, two rudders, two flaps, the inside flap and the lateral flap on the left and right side. Namely, \( u = \delta = [\delta_{rei}, \delta_{lei}, \delta_{rfl}, \delta_{lfl}, \delta_{rvt}, \delta_{lvt}, \delta_{reo}, \delta_{leo}]^T \). Where \( \delta_{rei}, \delta_{lei} \) are right and left medial flap, \( \delta_{rfl}, \delta_{lfl} \) are right and left flaps. \( \delta_{rvt}, \delta_{lvt} \) are right and left rudders. \( \delta_{reo}, \delta_{leo} \) are right and left lateral flaps. On each control surface the rudder loop dynamic equation is:
\[
\frac{u_{r}}{u_{ci}} = \frac{40}{s + 40}
\]

By setting the attitude angle tracking value \( \chi^d \), control gain is \( K_1 = \text{diag}(1,1,1) \). Considering there is 1 % of rotational inertia parameter perturbation.

Joint inequality (27) and (28), then control allocation problem can be turned into the minimization problem solving LMI constraints, online to obtain the optimal control law \( u_e(k) \) can be calculated by the following inequality (31)
\[
\gamma \begin{bmatrix} W_u \mu_i(k) \\ W_r \mu_i(k) \\ \tau_{des}(k) - G(k)\hat{D}(k)\hat{\Sigma}(k)u_e(k) \end{bmatrix}^T W_r > 0 \quad (31)
\]

Namely, \( \Delta J \in \left[(1-1\%) J, (1+1\%) J\right] \), the external disturbance of angular rate ring is \( [\text{sin}(r), 1.5\text{sin}(0.1r), 1.5\text{cos}(0.1r)]^T \), the initial value of angular rate is \( x \in [0,0.0]^T \) deg/s.

Angular rate loop control gain matrix of pseudo control law is \( K_2 = \text{diag}(1,1,1) \), the adaptive sliding mode observer gain matrix is \( A = \text{diag}(-2,-2,-2) \), \( P = \text{diag}(10,10,10) \), \( m(0) = 0.001 \). Not fault-tolerant control of attitude angle and angular rate response curve is shown in Fig. 3. It can see that the system can no longer be stable after 5 s when the fault happens.

Attitude angle and angular rate of the fault tolerant control system response curve are shown in Fig. 4. The proposed technology based on control allocation fault-tolerant control can realize fault tolerance control. Each control surface deflection angle is shown in Fig. 5.

By the simulation result shows that the proposed fault tolerant control method has good fault tolerance control capabilities. The control allocation technology ensures that each control surface deflection instructions are optimal results. To the actual manipulation, the fault-tolerant control technology research does not fully consider saturation constraint of the position and velocity.
Fig. 3. Attitude angle and angular rate response curve of not fault tolerant.

Fig. 4. Fault-tolerant control of attitude angle and angular rate response curve.
5. Conclusions

Due to parameter uncertainty and disturbance of aircraft, we consider robust fault-tolerant control problem. Combined with the control allocation technology, in the presence of the position and velocity saturation constraint, LMI is used to calculate the optimal control surface deflection instructions.

The design of fault-tolerant control system does not need accurate information such as the damage of fault information and interference, but implied in the design of adaptive sliding mode observer, and the implied information feedback of real-time LMI algorithm for pseudo control law and online distribution, so as to realize the robust fault-tolerant control.

Finally, the design method is applied to the spacecraft attitude stability and tracking control, realizes the flight attitude robust fault-tolerant control, and has achieved good control performance.

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