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The Aircraft Attitude Robust Inversion Fault-tolerant Control Based on Observer

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Abstract: For attitude control system, based on instruction filter back-stepping techniques, a robust fault-tolerant control method is proposed. Firstly, attitude control system mathematical model is given, on this basis, the attitude control system under the modeling errors caused by uncertainty, external disturbances and control surfaces faults are considered. The fault tolerant control design involves two main units, one is auxiliary system design, the other is controller design using the auxiliary system. Finally, the simulation results show that the proposed method can make the tracking performance for flight control system. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Attitude, Instruction filter, Back-stepping, Fault tolerant, Tracking.

1. Introduction

The flight control system failure is mainly composed of actuators, sensors, structural failure. In order to improve the safety and reliability, control system fault tolerant control (FTC: Fault tolerant control) must be considered [1].

Because the object exists uncertainty and disturbance, even if the diagnosis information is accurate, when designing the controller still want to consider the robustness and anti-interference problem of controller. In this paper, the robust fault-tolerant controller design framework is shown in Fig. 1.

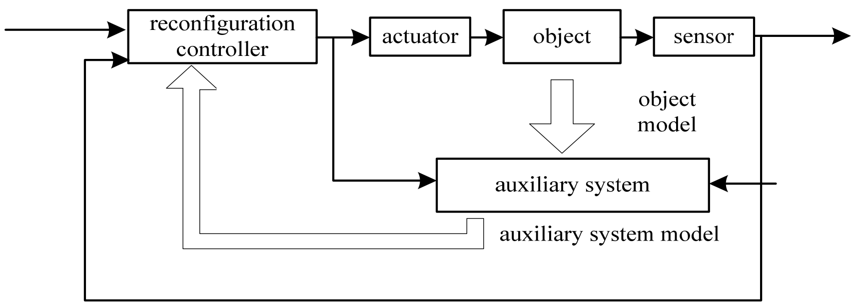

Fig. 1. The proposed design method block diagram.

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In this paper, the proposed fault-tolerant control method merely designs a robust fault-tolerant control. An auxiliary system reconfiguration controller is designed based on the auxiliary system dynamic model. Relative to traditional method in design is more simple and convenient.

Based on instruction filtering inversion method [2], this paper proposes a robust fault-tolerant control system based on instruction filtering inversion design.

2. Control Surface Fault Model

According to the aircraft X-33 aerodynamic configuration, considering the specific flight environment, a reasonable hypothesis and appropriate axes, a simplified model can be used to design attitude control system. Fault tolerance control law is calculated on the original model simulation, and test the validity of the fault-tolerant control system.

2.1. Attitude Model Description

This paper focuses on the fault tolerant flight control system design, only the factors of flight movement play a major role. It can effectively reduce the complexity of the problem.

Therefore, the attitude angle motion equations of the X-33 aircraft are [3, 4]

$$\dot{\alpha}=q-\left(p\cos\alpha+r\sin\alpha\right)\tan\beta+\frac{G_e}{r_e^2V\cos\beta}\cos\gamma\cos\mu+\frac{1}{MV\cos\beta}\left(-L-T_x\sin\alpha+T_z\cos\alpha\right) \quad (1)$$

$$\dot{\beta}=p\sin\alpha-r\cos\alpha+\frac{G_e}{r_e^2V}\cos\gamma\sin\mu+\frac{1}{MV}\left(Y-T_x\cos\alpha\sin\beta+T_y\cos\beta-T_z\sin\alpha\sin\beta\right) \quad (2)$$

Track roll μ motion expression can be determined by reference [5]:

$$\dot{\mu}=\dot{\phi}_c\cos\gamma\sin\chi-\dot{\lambda}(\cos\gamma\cos\chi\cos\phi_c+\sin\gamma\sin\phi_c)+\dot{\chi}\sin\gamma-\dot{\alpha}\sin\beta+p\cos\alpha\cos\beta+q\sin\beta+r\sin\alpha\cos\beta \quad (3)$$

Angular velocity loop motion equation is

$$\begin{bmatrix}\dot{p}\\ \dot{q}\\ \dot{r}\end{bmatrix}=\begin{bmatrix}\dfrac{\left(I_y-I_z\right)qr+l_A}{I_x}\\ \dfrac{\left(I_z-I_x\right)pr+m_A}{I_y}\\ \dfrac{\left(I_x-I_y\right)pq+n_A}{I_z}\end{bmatrix}+\begin{bmatrix}\dfrac{1}{I_x}&0&0\\ 0&\dfrac{1}{I_y}&0\\ 0&0&\dfrac{1}{I_z}\end{bmatrix}\boldsymbol{M}_c, \quad (4)$$

where I_x, I_y, I_z are the spacecraft inertia moments, I_{xy}, I_{yz}, I_{zx} are the inertia moments, $\boldsymbol{M}_c=\boldsymbol{\psi}\delta(t)$, $\boldsymbol{\psi}$ are the control allocation matrix.

In summary, X-33 attitude dynamic equation is

$$\begin{cases}\dot{\boldsymbol{\Omega}}=\boldsymbol{f}_\Omega+\boldsymbol{g}_1\boldsymbol{\omega}\\ \dot{\boldsymbol{\omega}}=-\boldsymbol{J}^{-1}\boldsymbol{\omega}^{\times}\boldsymbol{J}\boldsymbol{\omega}+\boldsymbol{J}^{-1}\boldsymbol{\psi}\boldsymbol{\delta}\end{cases}, \quad (5)$$

where $\boldsymbol{f}_\Omega=[f_\alpha, f_\beta, f_\mu]^T$.

$$f_\alpha=\frac{G_e}{r_e^2V\cos\beta}\cos\gamma\cos\mu+\frac{1}{MV\cos\beta}(-\hat{q}SC_{L,\alpha}-T\sin\alpha) \quad (6)$$

$$f_\beta=\frac{G_e}{r_e^2V}\cos\gamma\sin\mu+\frac{1}{MV}(\hat{q}SC_{Y,\beta}\beta\cos\beta-T\cos\alpha\sin\beta) \quad (7)$$

$$\begin{aligned}f_\mu=&-\frac{G_e}{r_e^2V}\cos\gamma\cos\mu\tan\beta+\\ &+\frac{1}{MV}\hat{q}SC_{Y,\beta}\beta\tan\gamma\cos\mu\cos\beta+\\ &+\frac{1}{MV}\hat{q}SC_{L,\alpha}\left(\tan\gamma\sin\mu+\tan\beta\right)+\\ &+\frac{T}{MV}\left[\sin\alpha\left(\tan\gamma\sin\mu+\tan\beta\right)-\right.\\ &\left.-\cos\alpha\tan\gamma\cos\mu\sin\beta\right]\end{aligned}, \quad (8)$$

$$\boldsymbol{g}_1=\begin{bmatrix}-\tan\beta\cos\alpha&1&-\tan\beta\sin\alpha\\ \sin\alpha&0&-\cos\alpha\\ \sec\beta\cos\alpha&0&\sec\beta\sin\alpha\end{bmatrix}, \quad (9)$$

2.2. Control Surface Damage Failure Model

Considering the control surface damage fault, in fact the control action u_i^{Ξ} of each channel is [6]:

$$\begin{aligned}&u_i^{\Xi}=\sigma_i u_i,\quad \sigma_i\in[\underline{\sigma}_i,\bar{\sigma}_i]\\ &0<\underline{\sigma}_i\le 1,\bar{\sigma}_i\ge 1,\quad i=1,\cdots 8\end{aligned}, \quad (10)$$

where σ_i is the damage factor. When $\underline{\sigma}_i=\bar{\sigma}_i=1$, failure did not happen.

The actual control channel is

$$u^{\Xi}=[\sigma_1u_1,\cdots,\sigma_8u_8]=\Xi u, \quad (11)$$

where $\Xi=\mathrm{diag}[\sigma_1,\cdots,\sigma_8]$, the X-33 control surface damage model is

$$\begin{cases}\dot{x}_1=f_1(x_1)+g_1(x_1)x_2\\ \dot{x}_2=f_2(x_1,x_2)+g_2(x_1,x_2)\Xi u+d(x_1,x_2,t)\end{cases}, \quad (12)$$

3. Active Fault Tolerant Control Design

In view of the mentioned in the second part, this section presents the proposed robust fault-tolerant control design.

It is shown in Fig. 2.

Dynamic equation and attitude angle loop equation using observer design an instruction filtering inversion control method, fault and compound interference implied in the observer. Dynamic controller based on state observer has robustness and fault tolerance.

For the convenience of fault-tolerant controller design, the observer equation can also be expressed as

$$\dot{z}_2 = Ae + f_2(x_1, x_2) + g_2(x_1, x_2)\hat{\Xi}u + \hat{W}^T\Phi(x), \quad (13)$$

where $\hat{\Xi} = \text{diag}[\hat{\sigma}_1, \cdots, \hat{\sigma}_8]$. The two tracking error vectors are $E_1, E_2 \in R^3$, filter output is x_1^c, x_2^c.

$$\dot{E}_1 = f_1(x_1) + g_1(x_1)x_2 - \dot{x}_1^c, \quad (14)$$

$$\dot{E}_2 = A\tilde{x}_2 + f_2(x_1, x_2) + g_2(x_1, x_2)\hat{\Xi}u + \hat{W}^T\Phi(x) - \dot{x}_2^c, \quad (15)$$

The first step: first of all, x_2^d is ideal control input of attitude angle ring.

Then we choose the Lyapunov function $V_1 = \frac{1}{2}E_1^T E_1$, and get the derivative of V_1.

$$\dot{V}_1 = E_1^T \dot{E}_1 = E_1^T \left(f_1(x_1) + g_1(x_1)x_2 - \dot{x}_1^c \right), \quad (16)$$

Attitude angle loop controller is

$$x_2^d = -g_1^{-1}(x_1)\left[K_1 E_1 + f_1(x_1) - \dot{x}_1^c \right], \quad (17)$$

where K_1 is the positive constant matrix.

In order to solve the traditional inversion control existing differential expansion and restriction problem, reference [7, 8] introduced instruction filtering. Instruction filtering thought is a virtual control volume x_2^d is obtained by a quadratic constraint filter x_2^c and $\dot{x}_2^c$. A compensator corrects filter residuals between output and input, as shown in Fig. 3.

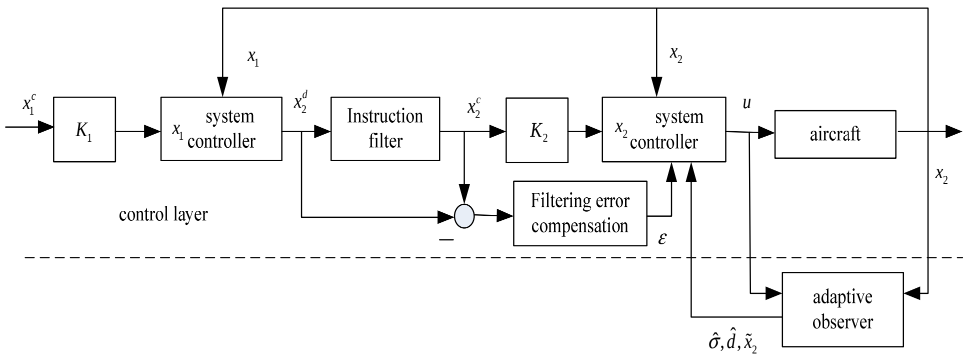


Fig. 2. The proposed robust fault-tolerant control of flight control system block diagram.

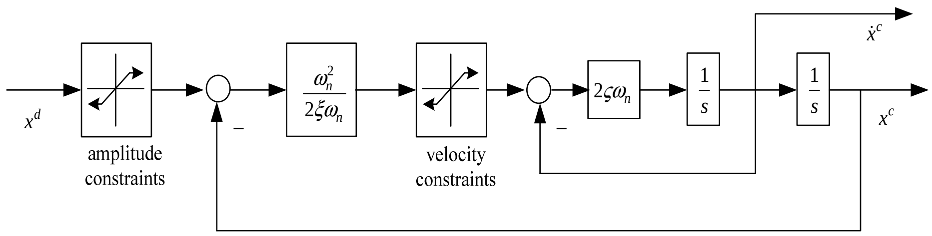


Fig. 3. The instruction filter structure diagram.

State equations of constraint instruction filter are:

$$\begin{Bmatrix} \dot{z}_1 \\ \dot{z}_2 \end{Bmatrix} = \begin{bmatrix} z_2 \\ 2\xi\omega_n \left[S_R \left(\frac{\omega_n^2}{2\xi\omega_n} (S_M(y) - z_1) \right) - z_2 \right] \end{bmatrix}, \quad (18)$$

where ξ, ω_n are the damping and bandwidth of filter respectively, and $y = x^d$, $\begin{bmatrix} z_1 \\ z_2 \end{bmatrix} = \begin{bmatrix} x^c \\ \dot{x}^c \end{bmatrix}$.

The second step: considering observer equations, at the same time we choose the Lyapunov function

$$V_2 = \frac{1}{2}\bar{E}_1^T \bar{E}_1 + \frac{1}{2} E_2^T E_2 , \qquad (19)$$

The design of angle velocity loop controller is

$$u = -\left(g_2(x_1,x_2)\hat{\Xi}\right)^{-1}\left(K_2E_2 + Ae + f_2(x_1,x_2) + \hat{d}(x,t) - \dot{x}_2^c + g_1^T(x_1)\bar{E}_1\right) \qquad (20)$$

where K_2 is the positive constant matrix.

$$\dot{V}_2 = -K_1\bar{E}_1^T\bar{E}_1 - K_2E_2^TE_2 - \bar{E}_1^T g_1(x_1)\tilde{x}_2 \ , \qquad (21)$$

4. Simulation and Verification

X-33 aircraft has four control surface, two rudders, two flaps, left and right two inboard ailerons, outboard ailerons.

Namely

$$u = \boldsymbol{\delta} = [\delta_{\text{rei}}, \delta_{\text{lei}}, \delta_{\text{rfl}}, \delta_{\text{lfl}}, \delta_{\text{rvr}}, \delta_{\text{lvr}}, \delta_{\text{reo}}, \delta_{\text{leo}}]^T ,$$

where $\delta_{\text{rei}}, \delta_{\text{lei}}$ are the right, left medial flap, $\delta_{\text{rfl}}, \delta_{\text{lfl}}$ are the right and left flap, $\delta_{\text{rvr}}, \delta_{\text{lvr}}$ are the right and left rudder. $\delta_{\text{reo}}, \delta_{\text{leo}}$ are the right and left lateral flaps.

Instruction filter parameter selection is shown in Table 1.

Table 1. Instruction filter parameter selection.

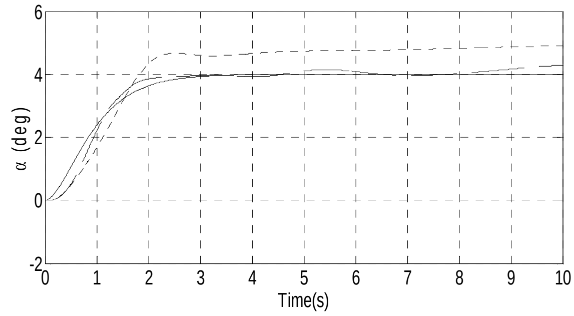
	ω_n	**Saturation constraint**	**Velocity constraints**
p	2×10^{10}	±20 rad/s	±20 rad/s^2
q	2×10^{10}	±20 rad/s	±20 rad/s^2
r	2×10^{10}	±20 rad/s	±20 rad/s^2

We assume that the following control surface damage failure: the right medial aileron, the left flaps, the right rudder failure are respectively 40 %, 20 %, 40 %.

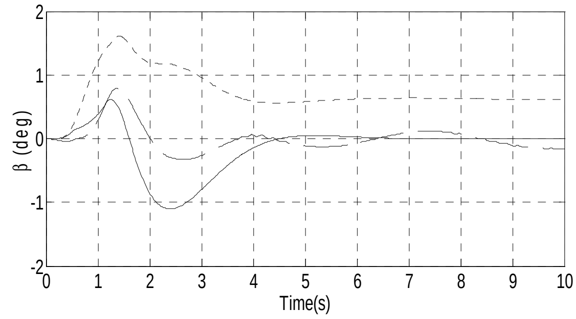
Flight control system uses the proposed method in the paper, the traditional fault-tolerant control method [9], not fault-tolerant control method.

Then we can get the attitude angle response curve. The simulation results are shown in Fig. 4 and Fig. 5.

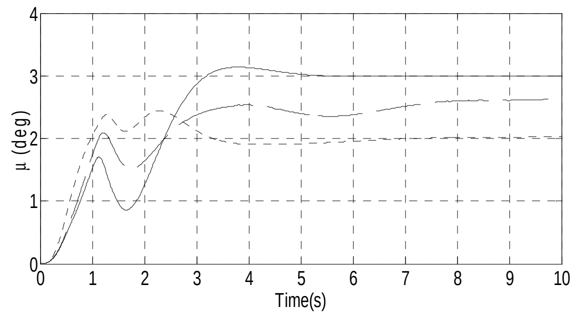
It can be seen from Fig. 4 under fault condition, the proposed fault-tolerant control method effect is superior to the traditional fault-tolerant method. Therefore, the paper proposed method is superior to the traditional fault-tolerant control method, for uncertain system with external disturbance has obvious characteristics of fault tolerance.



(a) Attack angle response curve



(b) Sideslip angle response curve

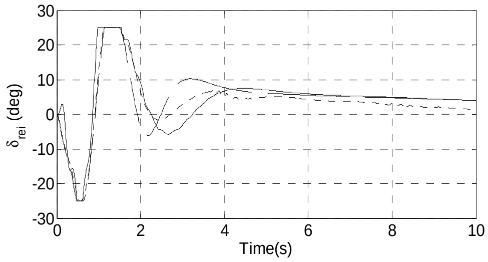


(c) Track roll angle response curve

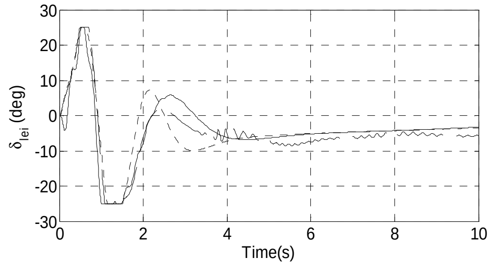
Fig. 4. The attitude angle response curve (— — — for the traditional active fault-tolerant control method, ······ for non fault-tolerant control, — for the proposed method).

5. Conclusions

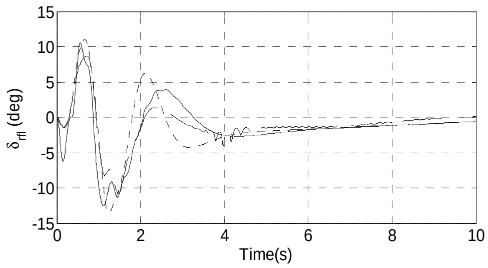
Due to disturbances and parameter uncertainty, considering the control surface damage problem of robust fault-tolerant control, we design a new type of robust fault-tolerant control framework. Based on adaptive neural network observer, we design the instruction filter inversion fault-tolerant control system. Firstly, we give aircraft X-33 attitude dynamic equation and set up the control surface fault model. Instruction filter inversion method is used to design angle loop controller and angular velocity loop controller. The design of fault-tolerant control system does not require accurate fault and interference information, which are implied in the adaptive neural network observer design. It can feedback real-time hidden information to the controller, and can realize the robust fault-tolerant control. Finally, the design method is applied to the control surface fault in spacecraft attitude control, flight attitude robust fault-tolerant control is realized.



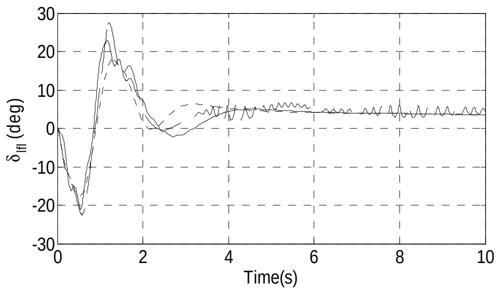
(a) Right inboard aileron deflection curve



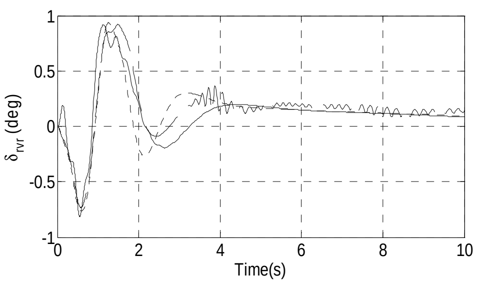
(b) Left inboard aileron deflection curve



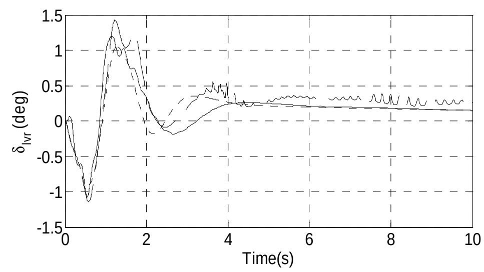
(c) Right side flap deflection curve



(d) Left side flap deflection curve



(e) Right rudder deflection curve



(f) Left rudder deflection curve

Fig. 5. Control surface deflection angle (− − − for the traditional active fault tolerant control method, ······ for non fault-tolerant control, —for the proposed method).

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