Sensors & Transducers, Vol. 178, Issue 9, September 2014, pp. 270-275

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Aircraft Attitude Distributed Fault-tolerant Control Based on Dynamic Actuator

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Received: 25 June 2014 /Accepted: 29 August 2014 /Published: 30 September 2014

Abstract: For attitude control system, based on decentralized fault-tolerant control framework, actuators damage and stuck fault detection and identification unit are designed for the flight control system. And observer-based auxiliary system unit is also designed. The auxiliary system implies control surface damage faults and disturbances information. Firstly, we give the attitude control system under actuator stuck, lose of effectiveness, and control surface damages faults. Secondly, a multi-observer is designed for actuator fault detection and identification using a decision-making mechanism to determine current actuator failure modes. Then, an adaptive sliding mode observer is designed for implicit control surface damages and interference information. The reconfigurable controller can achieve fault tolerant using the information of adaptive sliding mode observer. Finally, the simulation results show the effectiveness of the proposed method.

Keywords: Attitude control, Decentralized, Fault-tolerant, Sliding mode, Observer.

1. Introduction

Aircraft fault is mainly composed of actuators, control surfaces, caused by the failures of sensors and the structure. In order to improve the safety and reliability, on the aerodynamic layout design has been reasonable division the traditional flap, rudder and elevator, at the same time also makes the attitude control system be a drive system.

Based on state or parameter estimate, fault detection and recognition technology is the most commonly used method of flight control system. It is a kind of method based on the model. References [1] introduces the current mainstream method, have observer method, the multiple model method, artificial intelligence methods. The attention of many researchers based on state observer and observer method already has changed from the traditional linear to nonlinear systems [2].

For driving system, due to the input number is greater than the output, it is difficult to get enough excitation signal to obtain the correct fault information. Now FDI method mainly aims at a single type fault. For multiple type faults, it is difficult to find a suitable FDI. During its flight, the most likely caused multiple types cascading failure by a tiny fault. This aircraft must be considered in the process of various faults of FDI problems at the same time.

Based on the above discussion, references [3] put forward a kind of distributed fault-tolerant control framework, structure diagram is shown in Fig. 1. Based on the framework, the flight control system of FDI unit is divided into two parts.

One is the actuator damage and stuck identification, another auxiliary system is used to implicit control surface failure and disturbance based on observer.

A reconfigurable fault-tolerant controller is designed flight control system of fault-tolerant control.

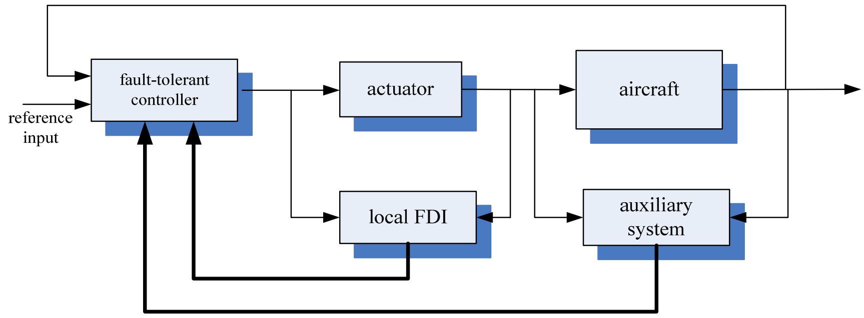


Fig. 1. Distributed fault-tolerant control chart.

2. Fault Modeling

Considering the presence of parameter uncertainty and external disturbance, the nonlinear form is shown below [4]:

$$\begin{cases} \dot{x}_1 = f_1(x_1) + g_1(x_1)x_2 \\ \dot{x}_2 = f_2(x_1,x_2) + g_2(x_1,x_2)u + \eta(x_1,x_2,t) \end{cases}, \quad (1)$$

where $x_1 = \boldsymbol{\Omega} = [\alpha,\beta,\mu]^T \in R^3$, $x_2 = \boldsymbol{\omega} = [p,q,r]^T \in R^3$, $u = \boldsymbol{\delta} = [\delta_1,\cdots,\delta_8]^T \in R^8$, $f_1(x_1) = \boldsymbol{f}_\Omega$, $f_2(x_1,x_2) = -\boldsymbol{J}^{-1}\boldsymbol{\omega}^{\times}\boldsymbol{J}\boldsymbol{\omega}$, $g_2(x_1,x_2) = \boldsymbol{J}^{-1}\boldsymbol{\psi}$. $\eta(x_1,x_2,t)$ is the composite interference. Assuming that composite interference $\eta(x_1,x_2,t)$ is bounded.

Firstly, control surface failure model is [5]

$$\begin{cases} \dot{x}_1 = f_1(x_1) + g_1(x_1)x_2 \\ \dot{x}_2 = f_2(x_1,x_2) + g_2(x_1,x_2)Du + \eta(x_1,x_2,t) \end{cases}, \quad (2)$$

where $D = \mathrm{diag}(d_1,d_2,\cdots,d_8)$, d_i is the damage factor. Secondly, considering the actuator dynamic for a first order transfer function is shown in the following type

$$\dot{u}_i = -a_i(u_i - u_{ci}), \quad i = 1,\cdots,8, \quad (3)$$

The real output of the actuator is u_i, the actuator output instructions are u_{ci}.

Actuator fault can be shown by the following form:

$$\dot{u}_i = -a_i\sigma_i(u_i - k_i u_{ci}), \quad i = 1,\cdots,8, \quad (4)$$

where $k_i \in [o,1]$ and $o << 1$. When $\sigma_i = 0$, it is i^{th} actuator stuck. $\sigma_i = 1$ is the actuator stuck. Specifically, actuator stuck and failure is unlikely to occur at the same time. (4) also can be expressed as follows

$$(4) \overset{\Delta}{=} \begin{cases} \dot{u}_i = 0, stuck \\ \dot{u}_i = -a_i(u_i - k_i u_{ci}), failure \end{cases}, \quad (5)$$

Using the theory of singular perturbation order reduction, failure and stuck are shown as

$$u_i = \sigma_i k_i u_{ci} + (1-\sigma_i)\bar{u}_i, \quad (6)$$

We get the actuator failure and stuck, then control surface damage failure model is

$$\begin{cases} \dot{x}_1 = f_1(x_1) + g_1(x_1)x_2 \\ \dot{x}_2 = f_2(x_1,x_2) + g_2(x_1,x_2)DK\Sigma u_c + g_2(x_1,x_2)D(I-\Sigma)u + \eta(x_1,x_2,t) \end{cases} \quad (7)$$

where $\Sigma = \mathrm{diag}(\sigma_1,\sigma_2,\cdots,\sigma_8)$, $K = \mathrm{diag}(k_1,k_2,\cdots,k_8)$.

In fact, by displacement sensor or through light code disc, fault-tolerant control objective is to obtain the actuator displacement instruction u_c.

3. Fault-tolerant Control System Design

This section of fault-tolerant control system design is mainly divided into three parts, the actuator fault detection and identification unit, based on state observer auxiliary system design, based on the instruction filtering inversion fault-tolerant control algorithm. In this section, the proposed scheme diagram is shown in Fig. 2.

3.1. Actuator Fault Detection and Identification Units

Based on observer of fault diagnosis in this section, the designed actuator fault detection and identification units quickly detect fault and identify fault type.

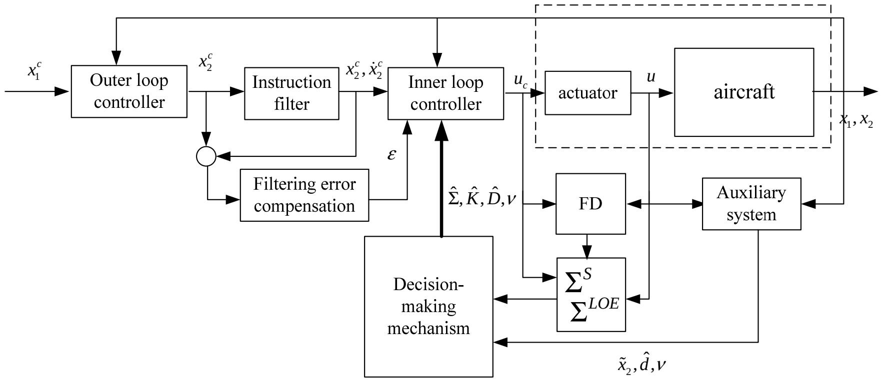


Fig. 2. The proposed method structure chart.

3.1.1. Actuator Fault Detection

When the aircraft may fly long distances statically, control surface deflection angle is in stationary state. If there is no excitation signal Δu_c continuously, it will affect the fault recognition results. Therefore, we need to design excitation signal u_c and make each angle change to the aerodynamic characteristics fully. Of course, imposed by excitation signal does not affect the normal aircraft to complete the task. Δu_c should be far less than the normal amount of control surface deflection. In order to detect actuators fault, fault detection observer is designed as follows [6]

$$\dot{u}_i^o = -a_i(u_i - u_{ci}) - \lambda_i(u_i^o - u_i), \quad i = 1, \cdots, 8, \quad (8)$$

where u_i^o is the control surface deflection, $\lambda_i > 0$. Residual signal is $u_i^e = u_i^o - u_i$, the design threshold is $\bar{\varepsilon}_i > 0$, the fault detection time is T_d.

When $\left|u_i^e\right| > \bar{\varepsilon}_i$

$$T_d \overset{\Delta}{=} \inf \bigcup_{i=1}^{8} \left\{ t > T_0 : \left|u_i^e\right| > \bar{\varepsilon}_i \right\}, \quad (1)$$

When $\left|u_i^e\right| \le \bar{\varepsilon}_i$, it is no fault. Conversely, it has failure.

3.1.2. Based on Multi-observer Actuator Fault Identification

Based on adaptive technique, we design two group observers for actuator stuck and fault identification. The designed observer is shown as follows [7]

$$\Xi_i^S : \begin{cases} \dot{u}_i^s = -a_i\hat{\sigma}_i(u_i - u_{ci}) - \lambda_i^s(u_i^s - u_i) \\ \hat{\sigma}_i = \mathrm{sign}\left(a_i\tilde{u}_i^s(u_i - u_{ci})\right) \end{cases}, \quad (10)$$

$$\Xi_i^{LOE} : \begin{cases} \dot{u}_i^l = -a_i(u_i - \hat{k}_i u_{ci}) - \lambda_i^l(u_i^l - u_i) \\ \dot{\hat{k}}_i = \mathrm{Proj}_{[o,1]}\left\{-\gamma^l a_i \tilde{u}_i^l u_{ci}\right\} \end{cases}, \quad (11)$$

where $\lambda_i^s > 0$, $\lambda_i^l > 0$, $\tilde{u}_i^s = u_i^s - u_i$, $\tilde{u}_i^l = u_i^l - u_i$. γ^l is the constant.

3.1.3. Decision-making Mechanism

Decision-making mechanism aim is to distinguish that the current actuator fault is stuck or failure. The error $\tilde{u}_i^j, j = s, l$ between the observer and actuator judges the fault types. Decision-making mechanism is

$$I_i^j(t) = c_1\left\|\tilde{u}_i^j(t)\right\|^2 + c_2\int_{t_0}^{t}\exp\left(-\lambda_1(\tau - t_0)\right)\left\|\tilde{u}_i^j(t)\right\|^2 d\tau, \quad (12)$$

where $c_1 > 0, c_2 > 0, \lambda_1 > 0$. According to performance index determine the most appropriate observer. If the observer makes performance index is minimum, we can judge the fault type at the moment. The current fault parameter values are obtained by the fault judging result.

$$\hat{\sigma}_i, \hat{k}_i = \begin{cases} \hat{\sigma}_i, 1, if I_i^s(t) is \min mum \\ 1, \hat{k}_i, if I_i^l(t) is \min mum \end{cases}, \quad (13)$$

3.2. Based on Adaptive Sliding Mode Observer Design Auxiliary System

Due to the control surface fault and compound interference coupling, flight attitude control is a typical driving system. Based on the design of adaptive sliding mode observer, an auxiliary system of the control surface fault information and external disturbances are implied. Observer is designed as follows. Observation error is $e = z - x_2$. According to angular rate circuit, an observer is designed as [8]

$$\dot{z} = A(z - x_2) + f_2(x_1, x_2) + g_2(x_1, x_2)U\hat{d} + \nu(t), \quad (14)$$

where $\hat{d} = [\hat{d}_1, \cdots, \hat{d}_8]^T$ is the estimate value of control surface damage factor. By the following adaptive law

$$\dot{\hat{d}} = \text{Proj}_{[\underline{d}_i, \overline{d}_i]}\left\{-2\gamma_1 U^T g_2^T(x_1, x_2)Pe\right\}, \quad (15)$$

where $\gamma_1 > 0$, $P = P^T > 0$. P is the solution of $A^T P + PA = -Q$. Where $Q = Q^T > 0$, namely A is the Hurwitz matrix. The estimate value is set between the minimum $\underline{d}_i$ and maximum $\overline{d}_i$. The sliding mode design is:

$$\nu(t) = \begin{cases} -\dfrac{Pe}{\|Pe\|}m(t) & \text{if } \|Pe\| \neq 0 \\ 0 & \text{otherwise} \end{cases}, \quad (16)$$

Time-varying parameter $m(t)$ is updated by adaptive law

$$\dot{m}(t) = \Gamma e^T e, \quad m(0) > 0, \quad (17)$$

Estimation error of damage factor is $\tilde{d} = \hat{d} - d$. By the observer equation (16) and (17), observation error dynamic equation is obtained

$$\dot{e} = Ae + g_2(x_1, x_2)U\tilde{d} + \nu(t) - \eta(t), \quad (18)$$

Continuous sliding mode item is [9]

$$\nu(t) = -\frac{Pe}{\|Pe\| + \rho}m(t), \quad (19)$$

where $\rho = \rho_0 + \rho_1\|e\|$. ρ_0, ρ_1 is normal number.

Based on the observer (18) and (19) equations, we can get following equations.

$$\begin{cases} \dot{x}_1 = f_1(x_1) + g_1(x_1)x_2 \\ \dot{z} = Ae + f_2(x_1, x_2) + g_2(x_1, x_2)\hat{D}u + \nu(t) \end{cases}, \quad (20)$$

where $\hat{D} = \text{diag}(\hat{d}_1, \hat{d}_2, \cdots, \hat{d}_8)$. By equation (6) and proposition 1, we can get following expressions.

$$\begin{aligned} u_i &= \sigma_i k_i u_{ci} + (1 - \sigma_i)\overline{u}_i \\ &= \hat{\sigma}_i \hat{k}_i u_{ci} + (\sigma_i - \hat{\sigma}_i)(k_i - \hat{k}_i)u_{ci} + (\sigma_i - \hat{\sigma}_i)\hat{k}_i u_{ci} + \hat{\sigma}_i(k_i - \hat{k}_i)u_{ci} \\ &\quad + (1 - \hat{\sigma}_i)\overline{u}_i - (\sigma_i - \hat{\sigma}_i)\overline{u}_i \\ &= \hat{\sigma}_i \hat{k}_i u_{ci} + (1 - \hat{\sigma}_i)\overline{u}_i + \tilde{\sigma}_i \tilde{k}_i u_{ci} - \tilde{\sigma}_i \hat{k}_i u_{ci} - \hat{\sigma}_i \tilde{k}_i u_{ci} + \tilde{\sigma}_i \overline{u}_i \\ &= \hat{\sigma}_i \hat{k}_i u_{ci} + (1 - \hat{\sigma}_i)\overline{u}_i - \sigma_i \tilde{k}_i u_{ci} - \tilde{\sigma}_i(\hat{k}_i u_{ci} - \overline{u}_i) \\ &= \hat{\sigma}_i \hat{k}_i u_{ci} + (1 - \hat{\sigma}_i)\overline{u}_i - \varphi_i^T \varpi_i \\ &= \hat{\sigma}_i \hat{k}_i u_{ci} + (1 - \hat{\sigma}_i)u_i - \varphi_i^T \varpi_i \end{aligned} \quad (21)$$

Fault model of control surface damage is

$$\begin{aligned} \dot{x}_1 &= f_1(x_1) + g_1(x_1)x_2 \\ \dot{z} &= Ae + f_2(x_1, x_2) + g_2(x_1, x_2)\hat{D}\hat{K}\hat{\Sigma}u_c \\ &\quad + g_2(x_1, x_2)\hat{D}(I - \hat{\Sigma})u - \sum_{i=1}^{8} g_{2i}(x_1, x_2)\varphi_i^T \varpi_i + \nu(t) \end{aligned} \quad (22)$$

4. Simulation and Verification

X-33 aircraft has four control surfaces, 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: δ_{rei}, δ_{lei} are the right, left medial flap. δ_{rfl}, δ_{lfl} are the right and left flap. δ_{rvr}, δ_{lvr} are the right and left rudder. δ_{reo}, δ_{leo} are the right and left lateral flaps.

Attitude angle and angular rate response curve of not fault-tolerant control is shown in Fig. 3. When the fault happens, the system can no longer be stable after 5 s. Attitude angle and angular rate response curve of fault-tolerant control system is shown in Fig. 4. Deflection angle of each control surface is shown in Fig. 5.

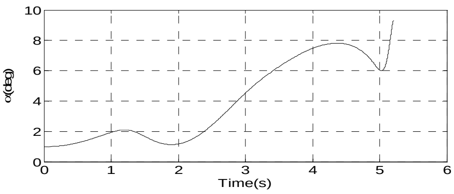
From the simulation results, we can see that the fault tolerant control method in the paper has good fault-tolerant control ability. Due to the presence of disturbance and the system itself is a drive system, can't really estimate the control surface damage factor. Based on adaptive sliding mode observer, implied information also realizes fault-tolerant control. This method can detect the fault rapidly, identify fault and estimate the fault value.

5. Conclusions

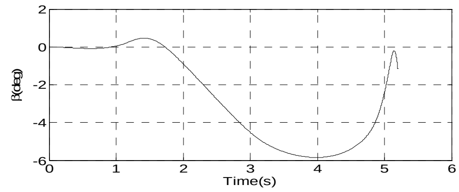
Based on distributed fault-tolerant control framework, this paper designed actuator fault detection and identification unit. It is used to get real-time systems fault information. For attitude angular velocity loop designed adaptive sliding mode observer, the designed observer has very strong robustness. Don't need to know the upper bound. It will imply control surface damage fault and interference information. Finally the application of the method of the design in the actuator and control surface fault attitude stability control and tracking control of the aircraft, realize the flight attitude robust fault-tolerant control, achieved good control effect.

Acknowledgements

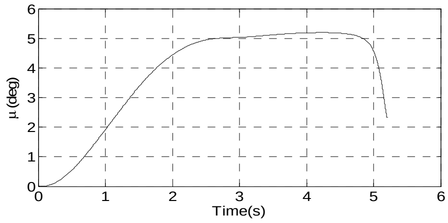
This work was supported by Qing Lan Project of Jiangsu province, 333 Project of Jiangsu province, Aeronautical Science Foundation of China (No. 20111052010), the National 863 Program (No. 2007AA01Z404), Universities Natural Science Research Project of Jiangsu Province (No. 13KJD520005), Modern Educational Technology in Jiangsu province (2013-R-26144).



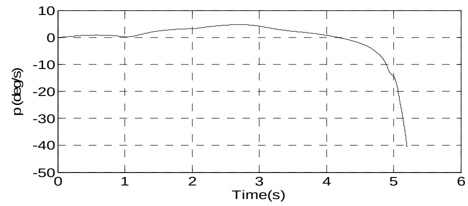
(a) Attack angle response curve



(b) Sideslip angle response curve

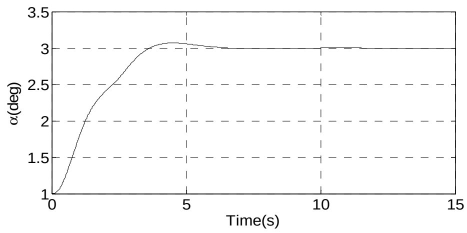


(c) Track roll angle response curve

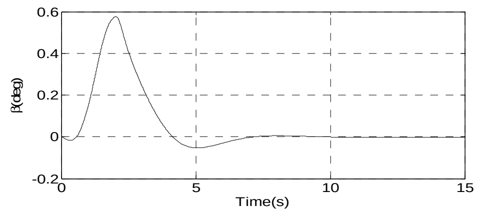


(d) The roll angle velocity response curve

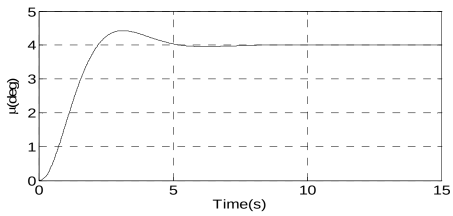
Fig. 3. Attitude angle and angular rate response curve under not fault-tolerant control.



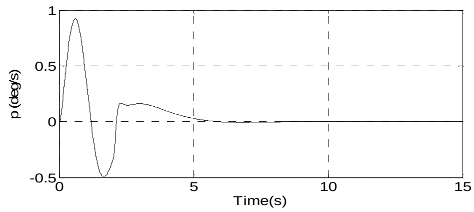
(a) Attack angle response curve



(b) Sideslip angle response curve

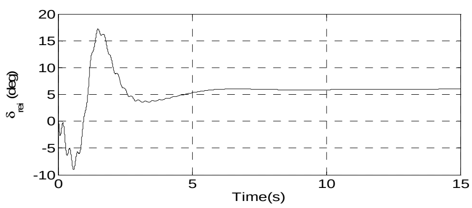


(c) Track roll angle response curve

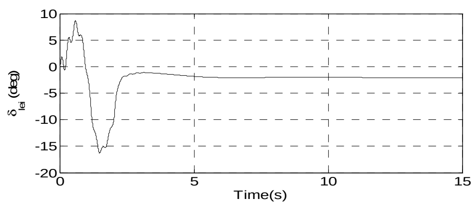


(d) The roll angle velocity response curve

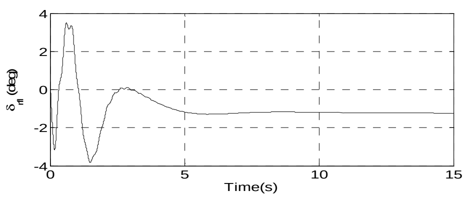
Fig. 4. Attitude angle and angular rate response curve.



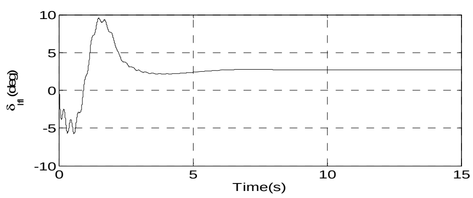
(a) The right inside aileron deflection curve



(b)The left inside aileron deflection curve



(c) The right side of the flap deflection curve



(d) The left side of the flap deflection curve

Fig. 5. Each control surface deflection angle response curve.

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