ADAPTIVE RECONFIGURABLE FLIGHT CONTROL SYSTEM USING MULTIPLE MODEL MODE SWITCHING

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Abstract: An adaptive reconfigurable flight control system using the mode switching of multiple models is studied. The conventional mode switching method may not guarantee the stability and the performance of the system. In this study, modified adaptive mode switching and decision logic are proposed to improve the adaptiveness of the transient dynamics of a system while maintaining the stability of the closed-loop system in the overall flight envelope. Fixed parameter models and adaptive models are used for mode switching, and a re-initialized adaptive model is also considered. Proper fixed system models are determined by considering various flight conditions with possible aircraft fault models. The mode switching control system is designed based on the selected models for reconfiguration. Numerical simulations are performed to validate the effectiveness of the proposed method.

Keywords: Adaptive Control, Multiple Models, Reconfigurable Flight Control System, Mode Switching, MIMO System

1. INTRODUCTION

In accordance with the development of advanced mechanical and electrical techniques, recently developed systems can be designed to have high performance. As systems become complicated, they are more vulnerable to the various faults. The fault of an aircraft can cause a loss of lives as well as economic losses. To avoid this tragedy, fault tolerant flight control technologies have been studied to increase the reliability and survivability of an aircraft. Reconfigurable flight control system is one of the fault tolerant flight control approaches. A reconfigurable flight control system restructures the flight control system to accommodate the faulty system automatically in the event of various failures such as control surface damage, actuator faults, sensor faults, and so on. When the fault occurs, aerodynamic coefficients are changed and unexpected nonlinearities can be generated. Therefore, a lot of researches have been performed to design the reconfigurable flight control systems using various control theories such as robust control, adaptive control, and intelligent control law.

Usually a linear system model obtained by linearizing a nonlinear aircraft model at a specific trim condition is used to design a flight control system. It is well known that linear controllers provide good performance near the trim condition. To guarantee the desired performance for the wide range of flight conditions, linear controllers should be designed for many different trim conditions, and a gain scheduling technique should be used (Huang and Stengel, 1990; Chandler, 1995). However, it is difficult for the linear controller to guarantee the stability and to maintain good performance in the full flight envelope. To overcome the shortcoming of the conventional control system, a lot of researches on

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alternative nonlinear control laws have been performed. Dynamic inversion technique is one of them (Menon, *et al.*, 1987). However, the dynamic inversion technique is not easy to implement because an accurate system model is required, and the inverse dynamics encompassing the full flight envelope has to be evaluated (Maybeck and Stevens, 1997).

In this study, new adaptive mode switching and decision logic are introduced to improve the performance of the transient dynamics of a system and to maintain the stability of the closed-loop system in the wide flight envelope (Narendra and Balakrishnan, 1997; Bošković and Mehra, 2000; Lee, 2004). Fixed parameter models, a free running adaptive model, and a re-initialized adaptive model are used for mode switching. In order to guarantee reconfigurability for the control surface damage, several fixed models are selected based on various flight conditions and possible faulty system models.

This paper is outlined as follows: Section II describes the equations of motion for the aircraft model and fault aircraft model. Section III deals with the basic concept of the model reference adaptive control (MRAC) law. Section IV proposes a modified multiple model adaptive controller using a free adaptive model, fixed models, and a re-initialized adaptive model. Section V presents numerical simulations using the high performance aircraft to analyze the feasibility and performance of the proposed control method. Finally, Sec. VI presents the conclusion.

2. EQUATIONS OF MOTIONS FOR AIRCRAFT

The decoupled longitudinal and lateral-directional equations are used in this study.

2.1 Aircraft Dynamics

A linearized longitudinal aircraft model is given by

$$\dot{x} = A_{long}x + B_{long}u \tag{1}$$

$$y = C_{long}x \tag{2}$$

where $x = \begin{bmatrix} v_T & \alpha & q & \theta \end{bmatrix}^T$, and $u = \begin{bmatrix} \delta_{th} & \delta_e \end{bmatrix}^T$.

The longitudinal states v_T, α, q, θ are velocity, angle of attack, pitch angular rate, flight path angle, respectively; and the controls δ_{th} and δ_e are engine thrust and elevator input. The system matrices consist of aerodynamic coefficients as follows (Stevens and Lewis, 1992).

$$A_{long} = A_1^{-1}A_2 \tag{3}$$

where

$$A_1 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & V_T - Z_{\dot{\alpha}} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & -M_{\dot{\alpha}} & 0 & 1 \end{bmatrix},$$

$$A_2 = \begin{bmatrix} X_v + X_{T_v}\cos\alpha_e & X_\alpha & -g_0\cos\gamma_e & 0 \\ Z_v - X_{T_v}\sin\alpha_e & Z_\alpha & -g_0\sin\gamma_e & V_T + Z_q \\ 0 & 0 & 0 & 1 \\ M_v + M_{T_v} & M_\alpha & 0 & M_q \end{bmatrix},$$

and

$$B_{long} = \begin{bmatrix} X_{\delta_{th}}\cos\alpha_e & X_{\delta_e} \\ -X_{\delta_{th}}\sin\alpha_e & Z_{\delta_e} \\ 0 & 0 \\ M_{\delta_{th}} & M_{\delta_e} \end{bmatrix} \tag{4}$$

$$C_{long} = \begin{bmatrix} 0 & 0 & 1 & 0 \end{bmatrix} \tag{5}$$

A linearized lateral-directional aircraft model is given by

$$\dot{x} = A_{lat}x + B_{lat}u \tag{6}$$

$$y = C_{lat}x \tag{7}$$

where $x = \begin{bmatrix} \beta & \phi & p & r \end{bmatrix}^T$, and $u = \begin{bmatrix} \delta_a & \delta_r \end{bmatrix}^T$.

The lateral-directional states β, ϕ, p, r are sideslip angle, roll angle, roll angular rate, pitch angular rate, respectively; and the controls δ_a and δ_r are aileron input and rudder input. The system matrices consist of aerodynamic coefficients as follows.

$$A_{lat} = \begin{bmatrix} \dfrac{Y_\beta}{V_T} & \dfrac{g\cos\theta_e}{V_T} & \dfrac{Y_p}{V_T} & \dfrac{Y_r}{V_T} \\ 0 & 0 & \dfrac{\cos\gamma_e}{\cos\theta_e} & \dfrac{\sin\gamma_e}{\cos\theta_e} \\ \mu L_\beta + \sigma N_\beta & 0 & \mu L_p + \sigma N_p & \mu L_r + \sigma N_r \\ \mu N_\beta + \sigma L_\beta & 0 & \mu N_p + \sigma L_p & \mu N_r + \sigma L_r \end{bmatrix} \tag{8}$$

$$B_{lat} = \begin{bmatrix} \dfrac{Y_{\delta_a}}{V_T} & \dfrac{Y_{\delta_r}}{V_T} \\ 0 & 0 \\ \mu L_{\delta_a} + \sigma N_{\delta_a} & \mu L_{\delta_r} + \sigma N_{\delta_r} \\ \mu N_{\delta_a} + \sigma L_{\delta_a} & \mu N_{\delta_r} + \sigma L_{\delta_r} \end{bmatrix} \tag{9}$$

$$C_{lat} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \tag{10}$$

2.2 Fault Model

When a fault occurs to an elevator, aileron or rudder, the system is assumed to be affected according to the damaged area of an actuator as follows.

$$\dot{x} = A_f x + B_f u + Ef \tag{11}$$

where A_f and B_f are faulty system matrices, which can be represented by $A_f = A + \Delta A$ and

$B_f = B + \Delta B$ where ΔA and ΔB are the changed matrices occurred by aileron and rudder's fault; Ef is the changed matrix occurred by elevator's fault as follows (Kim, 1998).

$$Ef = \begin{bmatrix} X_{\delta_e} \\ Z_{\delta_e} \\ 0 \\ M_{\delta_e} \end{bmatrix} \left(\frac{1-\zeta_e}{\zeta_e} \right) \delta_{trim} \tag{12}$$

$$\Delta A_{ail} = (\zeta_a^{'} - 1) \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ \mu L_\beta & 0 & \mu L_p & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{13}$$

$$\Delta B_{ail} = (\varsigma_a - 1) \begin{bmatrix} \frac{Y_{\delta_a}}{V_T} & 0 \\ 0 & 0 \\ \mu L_{\delta_a} + \sigma N_{\delta_a} & 0 \\ \mu N_{\delta_a} + \sigma L_{\delta_a} & 0 \end{bmatrix} \tag{14}$$

$$\Delta A_{rud} = (\zeta_r^{'} - 1) \begin{bmatrix} \frac{Y_\beta}{V_T} & 0 & \frac{Y_p}{V_T} & \frac{Y_r}{V_T} \\ 0 & 0 & 0 & 0 \\ \mu L_\beta + \sigma N_\beta & 0 & \mu L_p + \sigma N_p & \mu L_r + \sigma N_r \\ \mu N_\beta + \sigma L_\beta & 0 & \mu N_p + \sigma L_p & \mu N_r + \sigma L_r \end{bmatrix} \tag{15}$$

$$\Delta B_{rud} = (\varsigma_r - 1) \begin{bmatrix} 0 & \frac{Y_{\delta_r}}{V_T} \\ 0 & 0 \\ 0 & \mu L_{\delta_r} + \sigma N_{\delta_r} \\ 0 & \mu N_{\delta_r} + \sigma L_{\delta_r} \end{bmatrix} \tag{16}$$

3. MODEL REFERENCE ADAPTIVE CONTROL

Consider a linear discrete-time MIMO system given by

$$A(z^{-1}) y(k) = B(z^{-1}) z^{-d} u(k) \tag{17}$$

where z^{-1} and d are shift operator and known integer corresponding to the relative degree, and $u(k)$ is an input, $y(k)$ is an output. The system can be described as

$$A(z^{-1}) = I + A_1 z^{-1} + \cdots + A_n z^{-n} \tag{18}$$

$$B(z^{-1}) = B_0 + B_1 z^{-1} + \cdots + B_m z^{-m} \tag{19}$$

with known orders n and m. Assume that the exact values of the coefficients $A_i (i = 1, \cdots, n)$ and $B_j (j = 0, \cdots, m)$ are unknown and are subject to abrupt changes, while $\det(B_0) \neq 0$ (Maybeck and Stevens, 1997; Narendra and Xiang, 2000).

The objective of the MRAC is to generate the appropriate input $u(k)$ at each step k to make the system output $y(k)$ follow a given reference signal $y_r(k)$. Using coefficient matrices, inputs and outputs, new parameters are described as follows (Fujinaka and Omatu, 1999).

$$\hat{\theta}(k) = [\hat{B}_0(k) \ \cdots \ \hat{B}_m(k) \ -\hat{A}_1(k) \cdots \ -\hat{A}_n(k)]^T \tag{20}$$

$$\begin{aligned} w(k) = [&u_1(k) \ \cdots \ u_i(k) \ \cdots \ u_1(k-m-d+1) \\ &\cdots \ u_i(k-m-d+1) \ \cdots \ y_1(k) \ \cdots \ y_j(k) \\ &\cdots \ y_1(k-n+1) \ \cdots \ y_j(k-n+1)]^T \end{aligned} \tag{21}$$

The adaptive law of an estimation vector $\hat{\theta}(k)$ is updated by

$$\hat{\theta}(k) = \hat{\theta}(k-1) + \frac{P(k-1) w(k-1) e(k)}{\lambda + w(k-d)^T P(k-1) w(k-d)} \tag{22}$$

where the identification error $e(k)$ and a time-varying matrix $P(k)$ are generated by

$$e(k) = y(k) - \hat{\theta}^T (k-1) w(k) \tag{23}$$

$$P(k) = \left[P(k-1) - \frac{P(k-1) w(k-1) w(k-1)^T P(k-1)^T}{\lambda + w(k-1)^T P(k-1) w(k-1)} \right] \frac{1}{\lambda} \tag{24}$$

A forgetting factor λ is used to make the system adapt to a faulty system faster (Åström and Wittenmark, 1995). The control input $u(k)$ is updated by

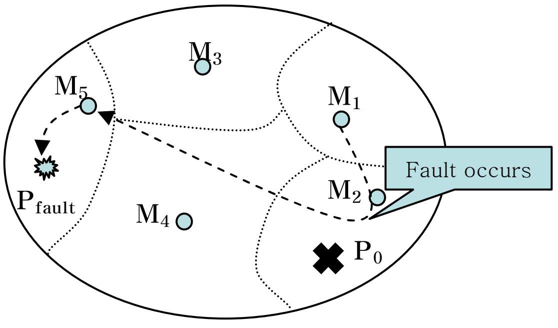
$$u(k) = [\hat{B}_0(k)]^{-1} [y_r(k+d) - \bar{\hat{\theta}}(k)^T \bar{\varpi}(k)] \tag{25}$$

4. MULTIPLE MODEL ADAPTIVE CONTROL

4.1 Multiple Model Adaptive Control

Even though the system output tracking could be achieved by the MRAC scheme, the performance in the transient response at the beginning of the operation or after an abrupt change such as control surface damage, actuator/sensor faults may not be satisfactory. Therefore, the typical adaptive controller cannot generate a proper control input that makes a system follow a reference model. To overcome this shortcoming in the transient response, a multiple model approach for parameter estimation has been proposed. This method can guarantee the stability of the overall system (Narendra and Balakrishnan, 1997).

The multiple models, switching and tuning (MMST) technique is based on the concept of describing the dynamics of the system using different models according to the broad operating range. Fixed models can be selected by considering the current system model or the various system models under the different conditions. Figure 1 shows the overall control system structure of the multiple model adaptive control scheme based on the parameter estimation.



P_0 : Nominal System , **P_{fault}** : Faulty System

Fig. 1 Concept of Multiple Model Adaptive Control

The basic idea is to use the on-line estimates of the aircraft parameters to decide which controller to choose in a particular flight condition. Let us assume that the system dynamics abruptly changes from the nominal system P_0 to the faulty system P_{fault} in the parametric set. The parametric set consists of corresponding system model subsets; $M_1, \ldots, M_5$. When a fault occurs, the multiple model adaptive control looks for the most similar model to P_{fault} among fixed models. In this example, M_5 is selected, and then adaptive control parameters are initialized with the corresponding model. After the parameters are changed, MRAC is updated until the adaptive controller reaches P_{fault}.

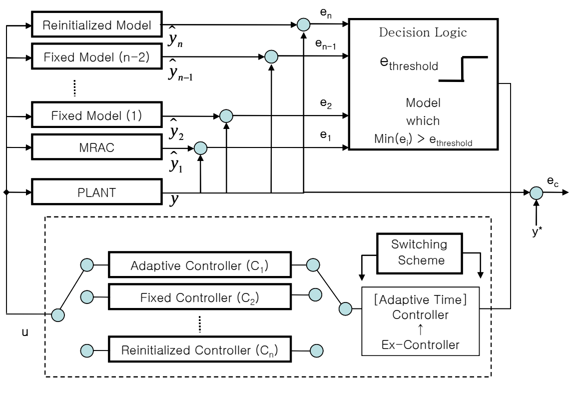


Fig. 2 Multiple Model Adaptive Control

4.2 Reinitialized Adaptive Control

A large number of fixed models are required to guarantee the stability and good steady-state performance. Therefore, the reinitialized adaptive control scheme has been proposed (Narendra and Xiang, 2000).

When mode switching is applied, the selected model initializes the reinitialized adaptive model, and this free-running adaptive model is operating in parallel with fixed models. This approach can improve the performance of the controller. Figure 3 shows the concept of the re-initialization procedure. If a selected model is a certain fixed model, the re-initialized model is initialized by the parameters of the selected fixed model.

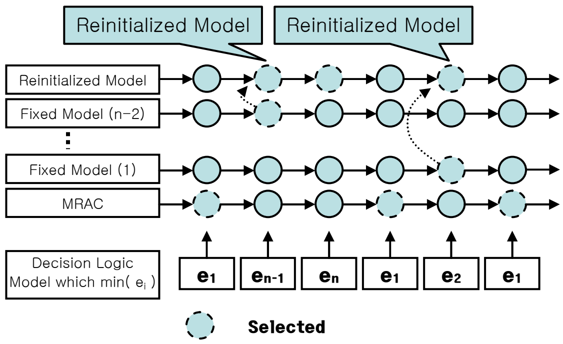


Fig. 3 Re-initialization Procedure

4.3 Switching Scheme and Decision Logic

Output errors are generated by comparing the estimated system with the adaptive model, fixed models, and re-initialized model. The model which has a minimum error norm will be chosen to make the control input. However, even thought the error is at a minimum, the frequent mode switching may disturb the system and make the system chatter. To deal with this problem, an adaptive time concept is proposed. When the system is switched to a fixed model, a reinitialized adaptive model selected by the fixed model is maintained for an adaptive time until the adaptive system sufficiently adapts to a new system.

Furthermore, if the adaptive model error norm $|e_1(k)|$ is larger than a threshold value $e_{\text{threshold}}$, then the switching logic is used to choose a proper fixed model that minimizes the error norm. This concept brings the system more stability by reducing the unnecessary transient change.

5. NUMERICAL SIMULATION

The control objective is to make the system output y follow the prescribed desired command y_r even when the aerodynamic coefficients vary and the control surface effectiveness decreases due to the control surface damage. Numerical simulations are performed to verify the performance of the proposed reconfigurable flight control system.

5.1 Longitudinal Aircraft Model

The F-16 aerodynamic data and the engine model in steady-level flight are used as a longitudinal linear aircraft model. For the simulation, the equilibrium condition at the speed of 700 ft/s and a sea level is considered (Stevens and Lewis, 1992). It is assumed that 22% of an elevator is damaged at 15 seconds during the maneuver. Four fixed models are set to 20%, 40%, 60% and 80% damaged elevator models. White noise is considered for system uncertainty.

Figure 4 shows the response of the flight path angle of an adaptive controller without fixed models. When the actuator fault occurs, the system violently vibrates and cannot follow the reference signal properly. In Fig. 5, the numerical result with a forgetting factor is shown. Figure 6 shows the simulation result of the adaptive controller, fixed models, and reinitialized model with the proposed switching and tuning concepts. The system response follows the reference input well. Moreover, the adaptation time has reduced. In Fig. 7, the mode switching history is shown. Decision logic selects the most similar model with the faulty system at 15 seconds. By switching the re-initialized model with threshold value during the adaptive time, it is assured that the performance of a re-initialized adaptive controller has been improved.

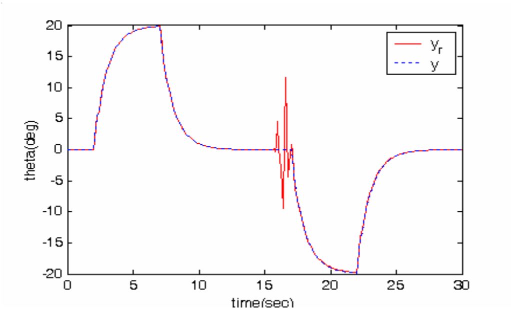


Fig. 4 Flight Path Angle (Single Adaptive Model)

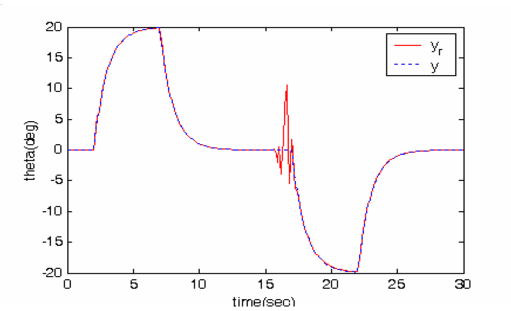


Fig. 5 Flight Path Angle (Single Adaptive Model with Forgetting Factor)

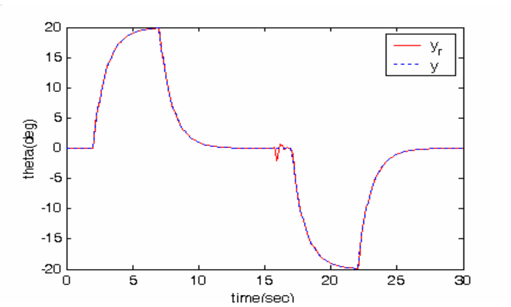


Fig. 6 Flight Path Angle (Multiple Adaptive Models with Forgetting Factor)

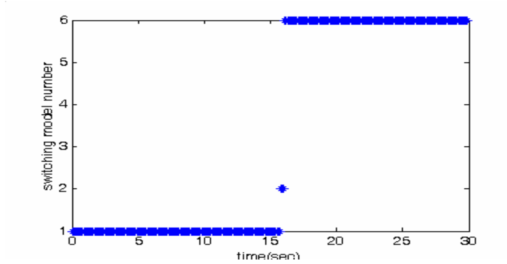


Fig. 7 Mode Switching History

5.2 Lateral-Directional Aircraft Model

F-16 model is also considered as a lateral-directional linear aircraft model under the same environmental condition used in the longitudinal model. It is assumed that 22% of a rudder is damaged at 5 seconds; then 52% of an aileron and 72% of a rudder are damaged at 20 seconds. Fifteen fixed models are combined with 25%, 50% and 75% damaged aileron and rudder models.

Figures 8-9 show the responses of roll angle and sideslip angle with a single adaptive controller. When the actuator faults occur at 5 seconds and 20 seconds, the system vibrates violently. Figures 10-11 show the simulation results of the adaptive controller, fixed models, and reinitialized model with a forgetting factor. The system responses follow the reference input well and the system is very stable. In Fig. 12, the mode switching history is shown. By switching the re-initialized model with threshold value during the adaptive time, it is assured that the performance of re-initialized adaptive controller has been improved.

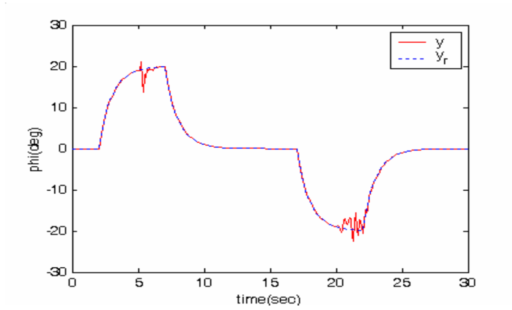


Fig. 8 Roll Angle (Single Adaptive Model)

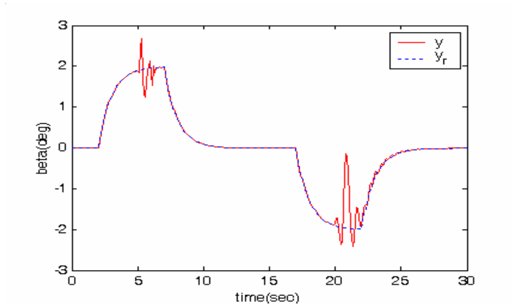


Fig. 9 Sideslip Angle (Single Adaptive Model without Forgetting Factor)

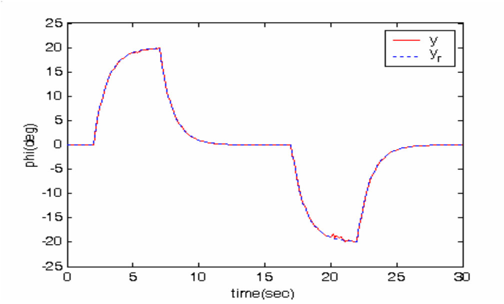


Fig. 10 Roll Angle (Multiple Adaptive Models with Forgetting Factor)

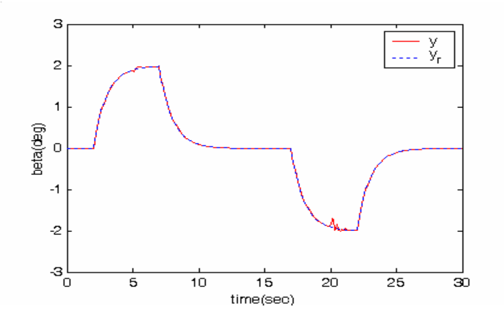


Fig. 11 Sideslip Angle (Multiple Adaptive Models with Forgetting Factor)

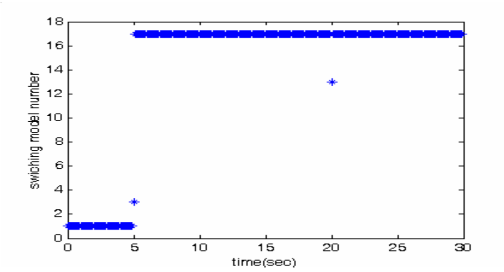


Fig. 12 Mode Switching History

6. CONCLUSION

The mode switching based adaptive reconfigurable flight control system using multiple models is proposed. When faults occur, the single adaptive control system has the shortcomings of a longer adaptation time and lack of stability. The frequent mode switching method may not guarantee the performance of the system and destabilize the system. In this study, the forgetting factor, adaptive time and error threshold value are adopted to overcome the problems. The proposed method also reduces the adaptation time. Residuals are generated at every moment by comparing the system information and the estimated value of each fixed model, and then decision logic selects the best model and its corresponding controller. In the switching scheme, threshold conception is involved. Mode switching is performed when the error exceeds the threshold. This method prevents the system from being unstable by the abrupt change of control. Numerical simulations are performed to verify the effectiveness of the proposed reconfigurable control law.

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