Application Research of MRAC in Fault-Tolerant Flight Controller

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Abstract

Damage, failure, and other configuration variety of aircraft would make the model parameters changed uncertainly, and lead to unknown deviations of the equilibrium points and unexpected coupling characters. One type of fault-tolerant flight controller which contains model reference adaptive theory is released for dealing with these problems. Design requirement for fault-tolerant flight controller is discussed and one structure of controller is presented. The reconstruction simulation for serious shift of center of gravity which could not detected by FDI system demonstrates this type of controller can complete the reconfiguration task without failure information, and demonstrated the validity of this structure.

Keywords: MRAC; fault-tolerant flight controller; control law; reconstruction; robustness

Nomenclature

- $X_{cg}$: the position of gravity centre
- $\bar{q}$: dynamic air pressure
- $K_p$: proportional gain
- $K_i$: integral gain
- $K_d$: derivative gain
- $C_{mac}$: longitudinal stabilizing moment coefficient
- $an_{CMD}$: acceleration command
- $an_{bas}$: acceleration output of airplane with baseline controller

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1. Introduction

High safety is the primary condition of aircraft system operating. Evaluating the safety of the flight control system is the most important part of achieving safe flight. When the unforeseeable dynamic characteristics changes, such as structure damage of the aircraft occurring, control surface failure, or the position of center of gravity shifting, the conventional controller cannot adjust control parameters according to the control error, being likely to lead to disastrous consequences. The fault-tolerance flight control system can reconstruct the control law according to control deviation, and still maintain the satisfying performance, at least possess the ability of safety returning, which will greatly improve the safety level of aircraft system [1-2].

Fault-tolerant control can be divided into passive fault-tolerant control and active fault-tolerant control according to its realization methods. Passive fault-tolerant control is a kind of high robustness scheme, using fixed controller to ensure the low sensitivity to system fault. The attention of constructing active fault-tolerant control is to redesign a new controller according to expected control characteristics after fault taking place, in order to stabilize the system newly. It is clear that the latter design has more developing place and application potential.

Based on whether depending on fault information provided by Failure Detection and Identification (FDI) system, active fault-tolerant control is divided as direct reconfiguration control and indirect reconfiguration control [3]. Because of the accurate fault information provided by FDI system, it is reasonable to require the reconfiguration to complete faster [4], and the flying qualities recover better. Some reconfiguration method could rapidly switch corresponding control law designed beforehand offline when fault occurs.

On 29 April 2013, a Boeing 747-400 which operated by National Airlines between the British military base Camp Bastion in Afghanistan and Al Maktoum Airport in Dubai, crashed moments after taking off from Bagram, killing all seven people on board. On 2 June 2013, investigators from the Ministry of Transport and Civil Aviation of Afghanistan confirmed the load shift hypothesis; three armored vehicles and two mine-sweeping vehicles came loose and rolled backwards onto the rear bulkhead, damaging the aircraft and pushing the center of gravity outside its rear limit. Consequently, the aircraft became uncontrollable, pitched up sharply and stalled, and crashed moments later. In this failure condition, the direct reconstruction control would not work if it was chosen; but the indirect reconstruction control which doesn't rely on FDI has the potential of taking the control, therefore it is the fault-tolerant control's developing direction in the future.

Model Reference Adaptive Control (MRAC) is kind of control method which follows a desired response from a reference model. It has the advantages of simple structure, reconfiguration fast and stable. The general idea behind Model Reference Adaptive Control (MRAC) is to create a closed loop controller with parameters that can be updated to change the response of the system. The control parameters are updated based on this error [6]. The goal for the parameters is to converge to ideal values that cause the plant response to match the response of the reference model.

A state feedback multivariable MRAC scheme is developed for such a linear model, with adaptive compensation of the uncertain dynamics offset as well as system parametric uncertainties in [7], and NASA GTM were used in simulation study and the result was verified. Multivariable MRAC is also used in asymmetrical.

In the control system design, linear design method based on linear time-invariant systems is more mature. However, the stability, security and the performance of design results will have some uncertainty because of the nonlinear characteristic of the controlled object and changes in flight environment.

To solve the problems above, this paper presents a fault-tolerant flight controller containing adaptive control modules derived theoretically. For a certain type of aircraft, longitudinal overload fault-tolerant flight controller is designed to evaluate the effectiveness of major failure reconfiguration when a serious backward shifting of the center of gravity cannot be monitored by FDI. The reasonableness of results has also been assessed.
2. The design requirements of the fault-tolerant controller

When the system goes wrong, the reachable set of control force (generalized force, including force and moment, similarly hereinafter) shrinks or offsets\(^{[14]}\). The task of reconfiguration is to make control force from every actuator rapidly point to the position which can balance the system as soon as possible. If the position is out of the reachable set, the reconfiguration cannot be done. Even though the position is in the reachable set but close to the border, the reconfiguration is also likely to fail. When the deviation between the failed and the original system is small, the range of the reachable set will be large. What’s more, it is easier to complete their, and the reconfigured system is much closer to the original system. Like the key actuators (elevators, rudders, ailerons), the auxiliary actuators (flaps, resistance plates, engines) can also be used to extend the control boundary.

The fault-tolerant ability is closely related to the reachable set of control force and moment. If the range of the reachable set is large, it is easier to reconfigure and maintain a higher quality of flight. In addition, execution rate also impacts the fault-tolerant ability. Therefore, although the auxiliary actuators can extend the control boundary, they can only be used for static reconfiguration for their slow execution rate, except for some special systems whose auxiliary actuators are particularly designed (e.g. Propulsion Controlled Aircraft, PCA).

The design requirements of fault-tolerant flight controller is, when the system fails, to make the fault system avoid entering the potentially catastrophic state within a short time scale by mobilizing all actuators. Within a long time scale, each actuator is configured, in accordance with the static and dynamic requirements, to promote the flight quality. Then, according to the final results of the assessment, decide to continue to complete the task, or homing, or forced landing.

3. The structure of the fault-tolerant controller

The effectiveness of conventional controllers under normal flight conditions has been verified, which is not expected to be abandoned out of engineering reliability. So here proposes an adaptive control method to enhance the conventional adaptive controller’s structure. A typical fault-tolerant flight controller consists of two parts: One part is baseline controller, to achieve normal flight conditions and complete control task under a lower uncertainty state; The other is adaptive controller, as a supplement to the baseline controller, to achieve precise control target under normal conditions. Whereas the system is in fault conditions, it reconfigures the control system to reach a normal state, or at least partial controllable state. On the other way, the adaptive controller does not work when the system’s error is in the normal range and the adaptive controller gets involved when the deviations of system control exceed the threshold.

The total input of the aircraft system is

\[ u = u_{\text{bas}} + u_{\text{ada}} \]  

(1)

where \( u \) is the output of fault-tolerant flight control system, \( u_{\text{bas}} \) is the output of baseline controller, \( u_{\text{ada}} \) is the output of adaptive controller.

The fault-tolerant flight control block diagram is shown in Fig. 1.
3.1. The baseline controller

Considering the controlled objects as decoupling system, the nominal controller consists of independent controllers for the longitudinal and the lateral/directional dynamics. Usually, a nominal controller designed with classical method can achieve satisfying performance.

For control design purposes, the aircraft nonlinear plant is linearized about a trim point \((X_0, U_0)\) as

\[
\begin{align*}
\dot{x}_p &= A_p x_p + B_p u \\
y_p &= C x_p + Du
\end{align*}
\]

(2)

where \(x_p\) is the state, \(u\) is the input, \(A_p\) is the system matrix, \(B_p\) is the input matrix. The state \(x_p\) consists of angle of attack \(\alpha\), sideslip angle \(\beta\), airspeed \(V\), roll rate \(p\), pitch rate \(q\), yaw rate \(r\), and three Euler angles \(\psi, \theta, \phi\). The control input \(u\) consists of the left elevator deflection \(\delta_{el}\), the right elevator deflection \(\delta_{er}\), the left aileron deflection \(\delta_{al}\), the right aileron deflection \(\delta_{ar}\), the rudder deflection \(\delta\), the throttle input to the left engine \(\delta_{thl}\), the throttle input to the right engine \(\delta_{thr}\).

We design the PI controller system with multivariable state feedback, and get the control law as

\[
u = K_p (\Delta x_p) + \frac{1}{T_i} \int_0^t \Delta x_p dt
\]

(3)

where \(K_p\) is the gain matrix, \(\Delta x_p\) is the error between the target state and the actual state, \(T_i\) is the integration time constant.

The baseline controller output is

\[
u_{bas} = Gu = G K_p (\Delta x_p) + \frac{1}{T_i} \int_0^t \Delta x_p dt
\]

(4)

where \(G\) is output allocation matrix, it makes the control surfaces deviates normally, namely \(\delta_{el} = \delta_{er}\), \(\delta_{al} = -\delta_{ar}\), \(\delta_{thl} = \delta_{thr}\).
3.2. The adaptive controller

The second component of the fault-tolerant controller is adaptive controller whose output is $u_{adu}$. In normal flight state, $u_{adu}$ exists for increasing the robustness of aircraft system. The LTI systems used for control design are accurate approximations to the aircraft dynamics, and its dynamics are weakly coupled. $u_{adu}$’s accessing can increase the control accuracy. However, many failures and uncertainties will lead to strong coupling, e.g. one side of the elevator jammed. In such a case, the baseline controller will generate control error, or even lost the control. At this moment, the adaptive component of the controller needs to be activated.

4. MRAC method with measurable state variable

We also use aforementioned plant model

$$\dot{x}_p = A_p x_p + B_p u + f_0$$  \hspace{1cm} (5)

where $f_0$ is the disturbance variable which introduced by fault.

We choose reference model with good characteristics

$$\dot{x}_m = A_m x_m + B_m r$$  \hspace{1cm} (6)

where $x_m$ is the reference model state, $r$ is the input (e.g. $\alpha_{CMD}$, $\beta_{CMD}$, $p_{CMD}$, etc.), $A_m$ is reference model matrix, $B_m$ is the input matrix, The state $x_m$ consists of angle of attack $\alpha$, sideslip angle $\beta$, airspeed $V$, roll rate $p$, pitch rate $q$, yaw rate $r$, and three Euler angles $\psi, \theta, \phi$ as $x_p$.

The control target is

$$\lim_{t \to \infty} |x_p - x_m| = 0$$ \hspace{1cm} (7)

We design the controller with adjustable variables state feedback and feedforward controllers:

$$u = Kr + Fx_p + \theta_d$$  \hspace{1cm} (8)

So the actual closed-loop system is

$$\dot{x}_p = A_p x_p + B_p (Kr + Fx_p + \theta_d) + f_0$$ \hspace{1cm} (9)

Adjust $F$, $K$ and $\theta_d$, controlled plant will match reference model when $x_p$ equals to $x_m$, so we get equations

$$\begin{cases}
A_m = A_p + B_p F^* \\
B_m = B_p K^* \\
0 = B_p \theta_d^* + f_0
\end{cases}$$ \hspace{1cm} (10)

where $F^*$, $K^*$ and $\theta_d^*$ are steady state value of $F$, $K$ and $\theta_d$.

One Lyapunov function is chosen as

$$V = \frac{1}{2} e^T P e + tr \left( \dot{F}^T \phi_1 \phi_1^T F \right) + tr \left( \dot{F}^T \phi_2 \phi_2^T F \right) + tr \left( \dot{F}^T \phi_3 \phi_3^T F \right) + tr \left( \dot{\phi}_1 \phi_1^T \phi_1 \right) + tr \left( \dot{\phi}_2 \phi_2^T \phi_2 \right) \hspace{1cm} (11)$$

We get the update law of $F$ and $K$ with Lyapunov’s second method

$$\dot{F} = \phi_1 B_m^T P e x_p^T$$
$$\dot{K} = \phi_2 B_m^T P e y_r^T$$
$$\dot{\theta}_d = \phi_3 B_m^T P e$$ \hspace{1cm} (12)

where $P$ is a positive definite symmetric matrix, and satisfies $A_m^T P + P A_m = -Q$, $Q = Q^T > 0$. $\Gamma_1$, $\Gamma_2$ and $\Gamma_3$ are gain matrices of feedback and feedforward update laws and satisfy $\Gamma_1 > 0$, $\Gamma_2 > 0$, $\Gamma_3 > 0$. $e = x_p - x_m$, $e$ is the state.
error between controlled plant and reference model.

4.1. Reference model

Due to the nonlinearities, the dynamics set by the linear reference model may differ from those of the actual controlled plant. Therefore, we need to examine different reference models that expand the region of the application. One of such choices is to use a closed-loop full nonlinear reference model, as shown in Fig. 2. This complexity results in high requirements for software and hardware when doing real-time simulation and verification \[16\].

![Reference Model](image)

Fig. 2. The equivalent reference model

It is important to determine whether the reference model we choose can be followed by actual aircraft system. If the plant with failure, damage or uncertainty is still controllable, unsuitable reference model will result in instability, which is triggered by the controller but not the plant.

If the reference model results from the linearization of the vehicle's dynamics at a particular trim point, the adaptive controller will be activated when such a model describes the vehicle's dynamics inaccurately. In such a case, nonlinearities instead of parametric uncertainty, could unexpectedly trigger adaptive controller under nominal flying conditions. This creates a larger range of flying control envelope in the case of unchanged original baseline controller.

In the design of the nominal controller, we get the satisfying closed-loop system in normal flying condition with classical method. Naturally, we consider the designed closed-loop system as the reference model, at least the baseline of that, to be the target model for reconfiguration.

4.2. Adaptive rate

The derivation above shows that, in the LTI framework, closed-loop stability is guaranteed for any adaptive rate of update laws satisfying $\Gamma > 0$. And the theory shows, the larger the adaptive rate the faster the adaptation and the better the performance. But in realistic application, because of the existence of nonlinearities and time delays in physical plant, this is not the case. Large adaptive rate will induce high frequency oscillations, or even lead to instability. The suitable adaptive rate we choose for the controller is based on simulation. The requirement can not
only finishes the reconfiguration in acceptable time, but also not exceed the boundary of oscillating, which ensures the aircraft keep small attitude deviation in the process.

5. Simulation Case

Overload tracking control is often used in tracking tasks. In a fighter aircraft, if an accelerometer is placed close to the pilot’s station, aligned along the body z-axis, and used as the feedback sensor for control of the elevator, the pilot has precise control over his z-axis.

If 1 g is subtracted from the accelerometer output, the control system will hold the aircraft approximately in level flight with no control input from the pilot. If the pilot blacks out from the g-load, and relaxes any force on the control stick, the aircraft will return to 1 g flight.

Other useful features of this system are that the accelerometer output contains a component proportional to alpha and can inherently stabilize an unstable short-period mode, and the accelerometer is an internal sensor that is less noisy and more reliable than an alpha sensor.

Using some linearized dynamical model with the accelerometer 4.6m forward of the pilot’s station, and the flight station of $h = 0$, $\bar{P} = 143.55 Mpa$, $X_{cg} = 0.35 \overline{\sigma}$, $\dot{\psi} = \dot{\theta} = \dot{\psi} = r = 0$, and the output equation is found to be

$$a_n = 0.0039813v_T + 16.262\alpha + 0.97877q - 0.048523\delta_e$$

(13)

where the unit of $a_n$ is $m/s^2$, the unit of $\alpha$ and $q$ are radian, the unit of $\delta_e$ is degree.

Simply, the design work based on short-period model is described as

$$\begin{bmatrix} x_p \\ y_p \end{bmatrix} = A_p x_p + B_p u, \quad x_p = \begin{bmatrix} \alpha \\ q \end{bmatrix}, \quad y_p = \begin{bmatrix} q \\ a_n \end{bmatrix}$$

(14)

where $A_p = \begin{bmatrix} -1.0189 & 0.90506 \\ 0.82225 & -1.0774 \end{bmatrix}$, $B_p = \begin{bmatrix} -0.0021499 \\ -0.17555 \end{bmatrix}$, $C_p = \begin{bmatrix} 0 & 57.296 \\ 16.262 & 0.97877 \end{bmatrix}$, $D_p = \begin{bmatrix} 0 \\ -0.048523 \end{bmatrix}$.

The structure of the baseline controller is illustrated in Fig. 3.

![Fig. 3. The structure of the baseline acceleration controller](image)

By adjusting the control gain, better tracking features can be obtained when $K_p = 1$, $K_I = 2.5$, $K_q = 0.07$, as shown in Fig. 4.
It is shown by the simulation, nominal controller could track acceleration command very well without accessing adaptive controller.

Regard current aircraft and controller as a whole, and consider this system as the reference model. In order to decrease the calculation quantity of the adaptive controller, the order of the equivalent reference model needs to be reduced by ignoring the non-dominant poles. It is illustrated that the response characteristics of the reduced order reference model is close enough to the original model, as Fig. 5.

The unexpected changed position of the centre of gravity may cause severe depravation. Specially, when the centre of gravity shifts behind the focal point, the value of $X_{cg}$ varies from positive to negative and $C_{nit} > 0$, and the aircraft becomes unstable. Because of the robustness of the nominal flight controller, it still has ability of retaking control. But it is shown in Fig. 6 that the PID nominal controller cannot follow the command well.
Now we add the adaptive controller to the nominal controller. After tuning the adaptive rates, the rapidity and convergence can be satisfied with $\Gamma_1 = 0.17 I_2^2, \Gamma_2 = 0.23 I_2^2, \Gamma_3 = 1$.

There are three obvious adapting periods in the whole process. At 1 second, the increasing output error between the plant and the reference model activates the adaptive controller. Then the gain in the adaptive controller varies to follow the output of the reference model. At 2 second, the error activates the adaptive controller again, small amplitude oscillation occurring during the process of gain adjustment, and the error converges rapidly, which happens again at 6 second. But the amplitude oscillation is smaller. When there is no obvious adjusting process later, it is indicated that the reconfiguration is basically finished. So, under the fault condition, the fault-tolerance flight controller with adaptive control modules can still be able to achieve the basic performance of the original control and meet the requirements of rapidity and convergence.

After the fault system modeled and the parameters tuned ($K_p = 5, K_i = 3, K_d = 0.15$), we can get the result of control ability, very close to what is shown in Fig. 4.

In order to reduce the tracking error, the proportional gain needs to be expanded times, which will arouse slightly shock. But the result close to the original control system characteristics can also be obtained by adjusting the baseline controller’s PID parameters. This is because that the control model used is still a linear model and this failure mode is relatively simple without multi-channel coupling phenomenon. Note that adjusting the PID parameters to get better results needs two conditions: First is that the controlled object’s fault information is completely known and modeled; Second is that repeated simulation adjustment is allowed offline. When a real failure occurs, both the two conditions will not work.

6. Conclusions

Based on the conventional control method, the complex control scheme of Baseline Controller and Adaptive Controller given in the text, supported by adaptive modules, extends the range of instruction trace control and reduces the risk of new control system’s development, prone to be accepted in engineering. Backward shifting of the center of gravity cannot be monitored, and in this failure mode, simulation results show that the baseline controller has a greater tracking error. If the control needs to be improved, the gain must be adjusted again under the premise of fault information obtained. However, the fault-tolerant flight controller with adaptive modules described in this article, in the case of unknown fault information, can implement real-time reconfiguration to obtain better control resilience with strong robustness.

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