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An Observer Based Multivariable Adaptive Reconfigurable Control Method for the Wing Damaged Aircraft*

Wang Yao, Yang Lingyu, Zhang Jing and Shen Gongzhang

Abstract— **Focusing on the abrupt parameter variation of the aircraft dynamic characteristics brought by the wing damage, an observer based multivariable reference adaptive control(O-MRAC) method is presented. Firstly, The Multivariable Model Reference Adaptive Control (M-MRAC) method is studied to compensate the abrupt variations in the state matrix, control matrix and the constant uncertainty. In order to improve the tracking speed and precision, the Compensation Observer Unit(COU) based on Extended State Observer(ESO) is introduced and combined with the M-MRAC. Finally NASA Generic Transport Model (GTM) is taken as an example and several cases about different damage occasions are taken into consideration. Three-channel attitude simulations are presented and the results illustrate that the impact due to the parameter variations is significantly reduced, and the outputs tracks the desired trajectories rapidly and stably under uncertain damage.**

Key words: structure damaged aircraft; O-MRAC; Extended State Observer; abrupt parameters variations

I. INTRODUCTION

All aspects of the safety and reliability are attached great attention to ensure the aviation security. Structural damage is a main reason to the control loss of the aircraft, which will seriously affect the flight safety. It may cause a sudden variation of aircraft's quality, center of gravity and aerodynamic characteristics. Moreover, the symmetry of the whole structure will be destroyed and a strong coupling between lateral and longitudinal dynamics will occur. The whole flight control system will be difficult which may cause a terrible accident. So a real-time stable reconfigurable controller is eager, in order to suppress the abrupt variations and ensure the flight performance. It has been a hot but difficult problem in the flight control research area.

Adaptive control of structural damaged aircraft has become an important subject in the field of flight safety. In 2006, NASA launched IRAC plan, its main purpose was to improve the stability of the structural damaged aircraft and the possibility of safe landing. In this project, a series of adaptive control such as the neural networks and multivariable reference adaptive control(M-MRAC) method were adopted to design the reconfigurable control law[1]. The NASA General Transport Model(GTM)[2] was taken as the research plant and a variety of different damage cases were studied.

In order to adapt to the structure and parameter variations caused by damage, the M-MRAC method has gradually become a focus of research. Lombaerts used online system identification in the nonlinear dynamic inversion scheme, and verified this method with a structural damaged Boeing 747 Model in [3]. To deal with the presence of rapidly varying, Yucelen and Calise proposed a derivative-free model reference adaptive control method in [4]. Nguyen proposed a recursive least-squares-based adaptive control for the wing damaged aircraft in [5]. Lavretsky proposed a Combined/Composite Model Reference Adaptive Control(CMRAC) method in [6][7]. Liu Y and Tao G studied the linearization process of the nonlinear aircraft model and designed an MRAC controller for the wing damaged aircraft which is based on the LDS decomposition of high-frequency gain matrix in [8][9]. These methods above suppress the unmodeled dynamics effectively and get a better transient response.

However, the adaptive controller often needs a period of time for the adjustment when there's a variation. There is no guarantee of the closed-loop performance during this period and turbulence maybe accompanied, which can also be seen obviously in [3]-[9]. To a strong nonlinear system with uncertainty such as an aircraft, strong disturbance will appear instantly once damaged. It may inspire a complex process of unmodeled dynamics, then leading to an accident. So it is an important issue to make the damaged aircraft stable rapidly and provide the guarantee for the convergence of the adaptive controller.

Extended state observer (ESO) is the key part of the Active Disturbance Rejection Controller(ADRC). It takes the modeling error and the external disturbance as a unified interference which can be estimated and compensated online by the observer. ESO is based on the state error, and generates the compensation signal directly, so that it has a more rapid response speed. Besides, ESO has a simple calculation and can reduce the system overshoot [10].

In this paper, we combined the MRAC with ESO on the basis of full study and put forward the O-MRAC method. The Compensation Observer Unit(COU) based on ESO is introduced to compensate the disturbance more quickly and accurately. Then the controller in three channels is designed and its effectiveness is verified that the performance has an obvious improvement.

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The paper is organized as follows. Section II contains the dynamic analysis of the damaged aircraft model. In Section III, the linearization process and the dynamics coupling items are studied. In Section IV, an O-MRAC controller method is introduced which consists of the MRAC controller and the Compensation Observer Unit. In Section V, simulations are presented based on GTM both under normal and damaged conditions. Results illustrate that the O-MRAC controller has a desirable performance.

II. Linear Model Of The Damaged Aircraft

The nonlinear system of aircraft can be described as

$$\begin{aligned} \dot{x}(t) &= f(x(t), u(t)) \\ y(t) &= Cx(t) \end{aligned} \tag{1}$$

where u, y represent the input and output vectors, and

$$\begin{aligned} x(t) &= [V, \alpha, q_b, \theta, \beta, r_b, p_b, \phi, \psi] \\ u(t) &= [\delta_e, \delta_r, \delta_a]^T \end{aligned} \tag{2}$$

Similarly the nonlinear system with damage can be described as

$$\begin{aligned} \dot{x}(t) &= f_d(x(t), u(t)) \\ y(t) &= Cx(t) \end{aligned} \tag{3}$$

Linearization is a common method for nonlinear systems to develop a control design. We linearize the system (1) and damaged system (3) at (x_0, u_0) and can obtain the linearized normal aircraft system

$$\begin{aligned} \dot{x}(t) &= A_n \Delta x(t) + B_n \Delta u(t) + f_0(x_0, u_0) \\ \Delta y(t) &= C \Delta x(t) \end{aligned} \tag{4}$$

and the damaged system

$$\begin{aligned} \dot{x}(t) &= A_d \Delta x(t) + B_d \Delta u(t) + f_d(x_0, u_0) \\ \Delta y(t) &= C \Delta x(t) \end{aligned} \tag{5}$$

where $\Delta x(t) = x(t) - x_0$, $\Delta u(t) = u(t) - u_0$, $\Delta y(t) = y(t) - Cx_0$

$$A_n = \left.\frac{\partial f}{\partial x}\right|_{(x,u)=(x_0,u_0)}, B_n = \left.\frac{\partial f}{\partial u}\right|_{(x,u)=(x_0,u_0)}$$

$$A_d = \left.\frac{\partial f_d}{\partial x}\right|_{(x,u)=(x_0,u_0)}, B_d = \left.\frac{\partial f_d}{\partial u}\right|_{(x,u)=(x_0,u_0)}$$

and $f(x_0, u_0) = 0$, $f_d(x_0, u_0)$ is the unknown constant disturbance.

According to (4) and (5), the structural damaged aircraft model can be described with the following type as (6)

$$\begin{aligned} \dot{x} &= (A_n + \Delta A)x + (B_n + \Delta B)u + \Delta f \\ y &= Cx \end{aligned} \tag{6}$$

where $\Delta A = A_d - A_n, \Delta B = B_d - B_n, \Delta f = f_d - f_0$.

III. O-MRAC Controller Design

Structural damage brings a sharp parameter variation and strong uncertainty, which makes it difficult to use fixed controllers to guarantee the performance at the damage moment and after. The control law should be adjusted in real-time to adapt the model changes caused by damage. The adaptive method is an effective means, by which the parameters of the controller can be automatically adjusted to recover the control performance. However, the adaptive method is always based on a slow and continuous change while the structural damage is an abrupt and significant variation. It is necessary to stabilize the damaged object in time to ensure the regulations of the adaptive method. So we put forward the O-MRAC method. The main idea of O-MRAC is to combine the M-MRAC with the COU. The M-MRAC based on LDS decomposition is used for the inner loop to make the output tracking the reference in time, and the COU based on ESO is used for the outer loop to estimate the disturbance and improve the response speed.

A. General Structure

The general structure of O-MRAC control law is shown in Fig.1. The M-MRAC is used in the inner loop which consists of the reference model, the adaptive servo, and the controller. Then on the basis of inner loop, the outer loop disturbance compensation controller is introduced.

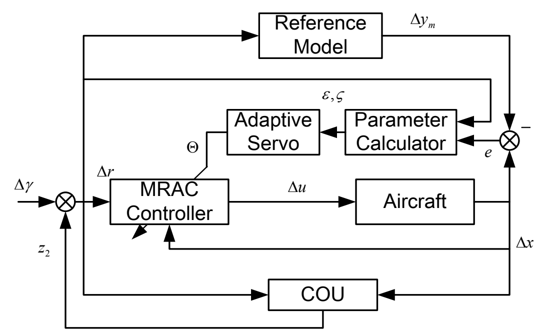

Figure 1. General structure of O-MRAC control law

The characteristics of O-MRAC are as follows:

1. The inner loop MRAC controller and the outer loop COU are both structural independent, so that they can be designed separately. The outer loop COU has no effect on the stability of the inner loop MRAC controller.

2. The outer loop COU based on ESO can directly act to the object so that it can reflect the mutation quickly.

3. The output of COU is designed as the input of inner loop MRAC controller, which can accelerate the convergence.

4. The ESO is susceptible to the noise disturbance. To reduce this effect, the outer loop can be disconnected under the condition of convergence. This point is supposed to be a further research.

B. Inner loop MRAC controller

The control objective is to generate Δu to make the outputs track the specified reference signal

$$\Delta y_m(t) = W_m(s)[\Delta r](t) \in R^m \tag{7}$$

Then each part of the system will be introduced next.

1) M-MRAC Control law

To compensate the constant uncertainties $\Delta A, \Delta B, \Delta f$, we choose the state feedback controller structure as

$$\Delta u(t) = K_1(t)\Delta x(t) + K_2(t)\Delta r(t) + K_3(t) \quad (8)$$

where K_1, K_2 are the estimates of the nominal parameter matrices K_1^*, K_2^* which satisfy the matching equations

$$C(sI - A - BK_1^*)^{-1}BK_2^* = W_m(s), K_2^{*-1} = K_p \quad (9)$$

K_3 is selected by using Laplace final-value theorem and used to compensate the disturbance Δf . So we have the closed-loop system as

$$\Delta y(s) = C(sI - A - BK_1^*)^{-1}BK_2^*\Delta r(s) + \Delta(s) \quad (10)$$

where

$$\Delta(s) = C(sI - A - BK_1)^{-1}(B\frac{K_3^*}{s} + \frac{\Delta f}{s}) \quad (11)$$

According to the Laplace final-value theorem, we obtain

$$\lim_{t\to\infty} e(t) = \lim_{s\to 0} s\Delta(s) = DK_3^* + d \quad (12)$$

where

$$\begin{aligned} &D = -C(A + BK_1^*)^{-1}B, d = -C(A + BK_1^*)^{-1}f_0 \\ &K_3^* = -D^{-1}d \end{aligned} \quad (13)$$

Then we define the parameter matrix

$$\Theta(t) = [K_1(t), K_2(t), K_3(t)]^T \quad (14)$$

2)Parameter calculator

This unit is mainly designed to process the error signal and obtain the corresponding parameters for the adaptive servo.

First we should present two important parameter matrices, i.e. the interactor matrix $\xi_m(s)$ and the high-frequency gain matrix Kp , and we have

$$\lim_{s\to\infty} \xi_m(s)G(s) = Kp \quad (15)$$

where $G(s)$ is the transfer function matrix, $\xi_m(s)$ is a stable and reversible matrix.

Then, to design the M-MRAC controller, two key conditions must be satisfied [8]. First, the interactor matrix $\xi_m(s)$ could be the same for $G(s)$ and $G_d(s)$. Secondly, all leading principal minors of the high-frequency matrix Kp are finite and nonsingular, and their signs do not change when the damage occurs.

D_s in the adaptive servo is obtained through the LDS decomposition of the high-frequency gain matrix according to [9].

$$Kp = L_s D_s S \quad (16)$$

where $S = S^T > 0$, L_s is a lower triangular matrix and $D_s = diag\{sign[\Delta_1]\gamma_1, ..., sign[\frac{\Delta_M}{\Delta_{M-1}}]\gamma_M\}$ $\gamma_i > 0$

To make the error signal converge in time, substitute the control law (8) into the system(6). Then we define $w(t) = [\Delta x^T(t), \Delta r^T(t), 1]^T$ and obtain

$$\Delta x(t) = (A + BK_1^{*T})\Delta x(t) + BK_2^* r(t) + BK_3^* + f + B\tilde{\Delta} \quad (17)$$

where

$\tilde{\Delta} = (K_1^T(t) - K_1^*)\Delta x(t) + (K_2^T(t) - K_2^*)\Delta r(t) + (K_3^T(t) - K_3^*)$

Then we process the error signal by using these equations as follows

$$e(t) = y(t) - y_m(t) \quad (18)$$

$$L_s^{-1} - I = \begin{bmatrix} 0 & 0 & \dots & 0 \\ \lambda_{21}^* & 0 & \dots & 0 \\ \lambda_{31}^* & \lambda_{32}^* & \dots & 0 \\ \dots & \dots & \dots & \dots \\ \lambda_{M-1,1}^* & \dots & 0 & 0 \\ \lambda_{M,1}^* & \dots & \lambda_{M,M-1}^* & 0 \end{bmatrix} \quad (19)$$

$$\bar{e}(t) = \xi_m(s)h(s)[e](t) = [\bar{e}_1(t), \dots, \bar{e}_m(t)]^T \quad (20)$$

$$\eta_i(t) = [\bar{e}_1(t), \dots, \bar{e}_{i-1}(t)]^T \in R^{i-1}, i = 2, \dots, M \quad (21)$$

$$\lambda_i^* = \left[\lambda_{i1}^*, \dots, \lambda_{ii-1}^*\right]^T, i = 2, \dots, M \quad (22)$$

$$\xi(t) = \Theta^T(t)\zeta(t) - h(s)[\Theta^T w](t) \quad (23)$$

$$\zeta(t) = h(s)[w](t) \quad (24)$$

$$h(s) = \frac{1}{f(s)} \quad (25)$$

where $f(s)$ is a stable and monic polynominal of degree equals to the degree of $\xi_m(s)$.

Then the error-estimation signal is

$$\varepsilon(t) = \bar{e}(t) + [0, \lambda_2^T(t)\eta_2(t), \lambda_3^T(t)\eta_3(t), \dots, \lambda_m^T(t)\eta_m(t)]^T + \rho(t)\xi(t) \quad (26)$$

where $\lambda_i(t)$ is the estimate of λ_i^* , $\rho(t)$ is the estimate of $\rho^* = D_s S$.

3) Adaptive servo

The adaptive laws are selected as

$$\begin{cases} \dot{\lambda}_i(t) = -\dfrac{\Gamma_{\lambda i}\varepsilon_i(t)\eta_i(t)}{m^2(t)} & \Gamma_{\lambda i} = \Gamma_{\lambda i}^T > 0, i = 2, 3, \dots, m \\ \dot{\Theta}^T(t) = -\dfrac{D_s\varepsilon(t)\zeta^T(t)}{m^2(t)} & \\ \dot{\rho}(t) = -\dfrac{\Gamma\varepsilon(t)\xi^T(t)}{m^2(t)} & \Gamma = \Gamma^T > 0 \end{cases}$$

(27)

where a series of parameters are obtained through (18) -(26), and

$$m^2(t) = 1 + \zeta^T(t)\zeta(t) + \xi^T(t)\xi(t) + \sum_{i=2}^{m} \eta_i^T(t)\eta_i(t) \quad (28)$$

$\varepsilon(t)$ is computed from (26), $\Gamma_{\lambda i}$ and Γ are adaptation gain matrices. The stability properties of the control law (8) and adaptive law (27) have been verified in [11].

C. Compensation Observer Unit

According to the analysis above, the aircraft model and M-MRAC controller are described as

$$\begin{aligned} \Delta\dot{x} &= A\Delta x + B\Delta u + f \\ u &= K_1\Delta x + K_2\Delta r + K_3 \end{aligned} \quad (29)$$

Then

$$\Delta\dot{x} = (A + BK_1)\Delta x + BK_2\Delta r + BK_3 + f \quad (30)$$

And the reference model is

$$\Delta\dot{x} = A_m\Delta x + B_m\Delta r \quad (31)$$

The form of the inner loop with MRAC included is as (32)

$$\begin{aligned}\Delta\dot{x} &= \left(A_m + \Delta A'\right)\Delta x + \left(B_m + \Delta B'\right)\Delta r + \sigma \\ &= A_m\Delta x + B_m\Delta r + g \\ g &= \Delta A'\Delta x + \Delta B'\Delta r + \sigma\end{aligned} \tag{32}$$

To make (29) track the reference model, the observer can be designed as

$$\begin{aligned}\dot{z}_1 &= z_2 + A_m z_1 + B_m\Delta r - \beta_1 f_{(e)} \\ \dot{z}_2 &= -\beta_2 f_{(e1)}\end{aligned} \tag{33}$$

So that the observer can response instantly once damage. Then the actual closed-loop system will change gradually with the effect of adaptive law. At last, $g \to 0$, the closed-loop system tends be the expectation model (31). Where

$$f_{(e)} = e = z_1 - \Delta x \tag{34}$$

$$f_{(e1)} = fal(e, 0.5, \delta) \tag{35}$$

fal is a continuously exponential function with a linear section near the origin, which has the form as

$$fal(e,\alpha,d) = \begin{cases} ed^{\alpha-1}; |e| \le d \\ |e|^{\alpha}\,\mathrm{sgn}(e); |e| > d \end{cases} \tag{36}$$

Its purpose is to prevent the appearance of high frequency oscillation [12]. Then, the state variables can be estimated very well by selecting the parameters β_1 and β_2 properly.

$$z_1 \to \Delta x, z_2 \to g \tag{37}$$

Set $\Delta u_{ad} = B_m^+ z_2$, thus the reference input is $\Delta r = \Delta\gamma - \Delta u_{ad}$. Then we substitute it into (32) and can obtain

$$\Delta\dot{x} = A_m\Delta x + B_m(\Delta r - B_m^+ z_2) + g \tag{38}$$

IV. System Simulation

Single wing-tip broken is a typical asymmetric structural damage condition. In this paper, we select a 5.5% dynamically scaled GTM model with the damage case as the loss of outboard left wing tip. The damage rate is taken as 15%. According to the linearization results above, it can be verified that both in normal and damaged conditions, the transfer function matrices $G(s)$ and $G_d(s)$ are strict proper and have full rank, and all the zeros have negative real-part. The interactor matrix is selected as

$$\xi_m(s) = \frac{1}{55}\begin{bmatrix} s^2+13.5s+55 & 0 & 0 \\ 0 & s^2+13.5s+55 & 0 \\ 0 & 0 & s^2+13.5s+55 \end{bmatrix} \tag{39}$$

and is unchanged after damage.

Then we can obtain the high-frequency gain matrix for the normal and damaged cases

$$K_{p1}(s) = \begin{bmatrix} -0.0154 & 0 & 0 \\ 0 & -0.01011 & 0.001162 \\ 1.818e-6 & 0.003304 & 0.01406 \end{bmatrix} \tag{40}$$

$$K_{p2}(s) = \begin{bmatrix} -0.01541 & -5.455e-6 & 0.0004218 \\ 1.822e-6 & -0.01013 & 0.0009364 \\ 8.011e-5 & 0.003326 & 0.01129 \end{bmatrix} \tag{41}$$

obviously they are finite and nonsingular.

The signs of first leading principal minor are

$$\begin{aligned} sign(\Delta_{1Kp1}) &= sign(\Delta_{1Kp2}) = -1 \\ sign(\Delta_{2Kp1}) &= sign(\Delta_{2Kp2}) = 1 \\ sign(\Delta_{3Kp1}) &= sign(\Delta_{3Kp2}) = 1 \end{aligned} \tag{42}$$

there is no sign change. So that the two key conditions mentioned in IV are satisfied.

Then we choose $f(s) = (s+20)^2$, $\Gamma_{\lambda 2} = 10$, $\Gamma_{\lambda 3} = [10, 10]$, $\Gamma = diag\{100, 100, 100\}$, $D_s = diag\{-400, -200, 100\}$ for the control law(8) and the adaptive law (27). We select β_1 as a diagonal matrix with the diagonal element is 100 and β_2 with the diagonal element is 5000 to generate the observer (33).

Then directly apply the M-MRAC and O-MRAC controller to the nonlinear aircraft model. We take two cases of simulations as follows.

1) Case.1

To make a reasonable flying trajectory, a step input given in 10 seconds is selected as $\Delta r(t) = [5^\circ, 5^\circ, 8^\circ]^T$ which generates the reference pitch, yaw and roll angles of 5, 5and 8 deg. Damage occurs in 25 seconds when the response has already been in a steady state. Simulation results are shown in Fig. 2-8.

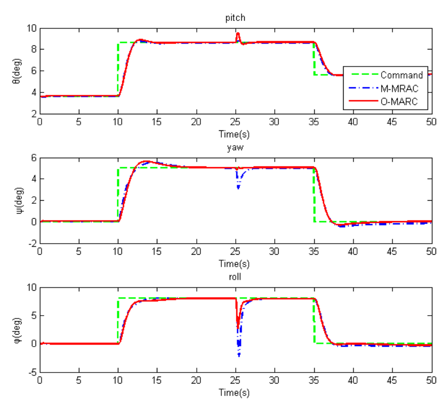

Figure 2. Response curves of pitch, yaw and roll angles in Case.1

As shown in Fig.2, three-channel attitude angles approach to the commands after a small wave, and the tracking errors are converge to zero. When the damage occurs at 25s, tracking errors converge to zero again after a small-scope fluctuation within a short period of time. From the zoomed in version we can see obviously that comparing with the M-MRAC controller, the O-MRAC has a smaller-scope fluctuation and a more rapidly response speed with the same adaptive parameters.

The responses of each rudder are given in Fig.3. Obviously each rudder bias has a faster response and quickly reaches the steady-state value after damage under the O-MRAC control method. Fig.4-6 depict the adaption of parameter matrices $\Theta(t)$, $\lambda(t)$, $\rho(t)$. The parameters achieve a steady-state value after a short period of adaptive adjustment at the beginning. And each parameter reaches new steady-state values after a small wave when damage occurs. Fig.7 shows the output of COU. From Fig.7 we can see that the observer responses instantly when wing-tip damaged. The output converges to zero in a very short period of time to make a rapid inhibition of disturbance, which ensures a fast response speed and good tracking accuracy.

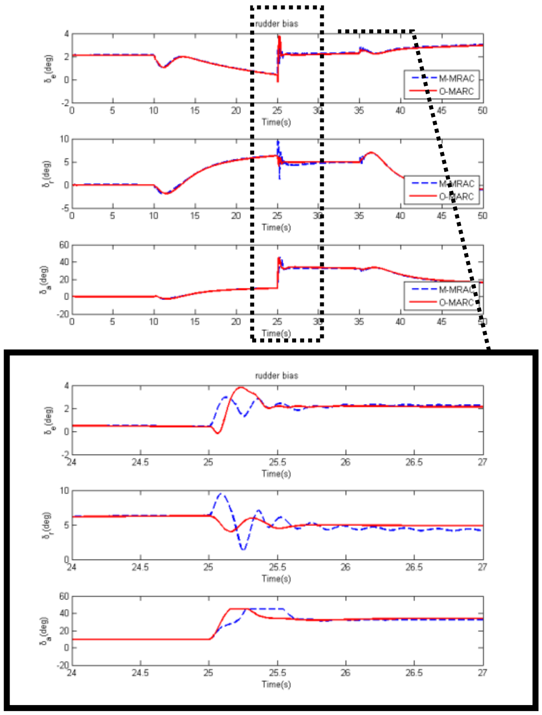

Figure 3. Response curves of elevator, rudder and aileron

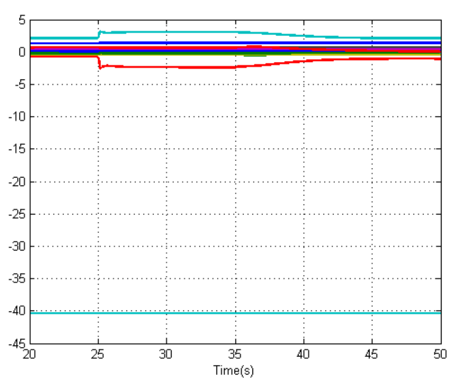

Figure 4. Adaptation of $\Theta(t)$

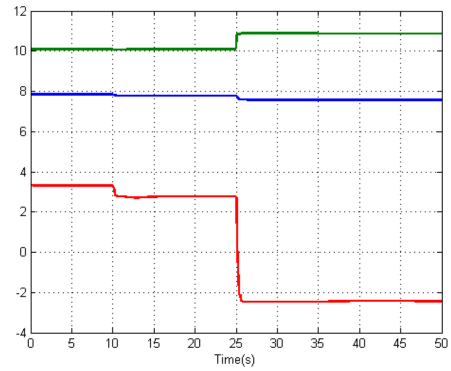

Figure 5. Adaptation of $\lambda(t)$

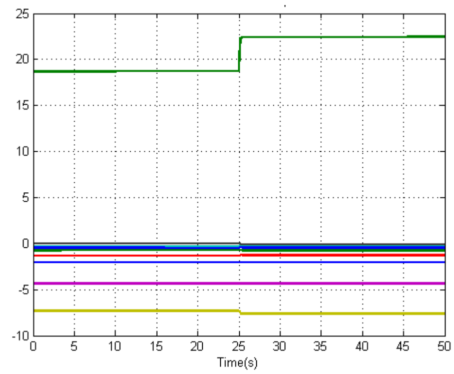

Figure 6. Adaptation of $\rho(t)$

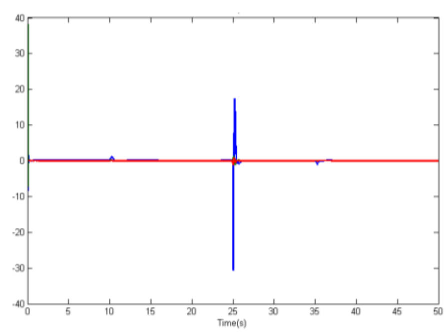

Figure 7. Response curves COU output

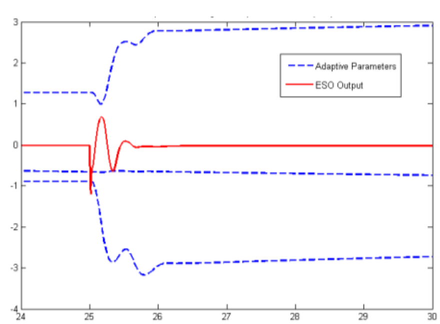

Figure 11. Comparison between the COU output under O-MRAC and the original adaptive parameters

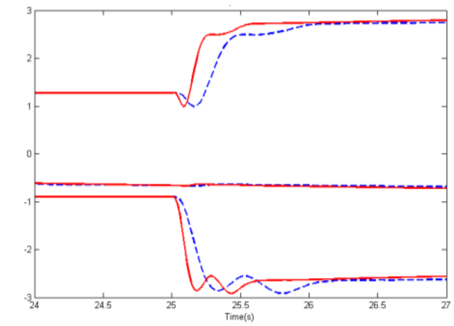

Figure 12. Comparison between the adaptive parameters (part) under O-MRAC and the original M-MRAC

Then we put the output of COU under O-MRAC and the adaptive parameters under original M-MRAC together to make a comparison in Fig.8. It can be seen that the effect of O-MRAC controller can be divided into two stages once damage. At first, the observer produces an instantaneous response, and the effect of the inner loop adaptive controller will begin. The parameters will gradually converge with the adaptive controller. In this procession the adaptive parameters will change faster than those under the original M-MRAC which is just as our analysis in the above sections. The O-MRAC can achieve a rapid response, and that is mainly because the COU can reflect the estimation of the first derivative of the state variables, while the original M-MRAC can just reflect the state variables. From Fig.9 we can see more intuitively that the adaptive parameters converge faster after COU introduced under O-MRAC than M-MRAC.

2) Case.2

In Case 2, a step input given in 10 seconds is selected as $\Delta r(t)=[4^{\circ},5^{\circ},6^{\circ}]^{T}$ which generates the reference pitch, yaw and roll angles of 4, 5and 6 deg. Damage occurs abruptly in 36 seconds while the aircraft is in the process of maneuver. Simulation results are shown in Fig. 13.

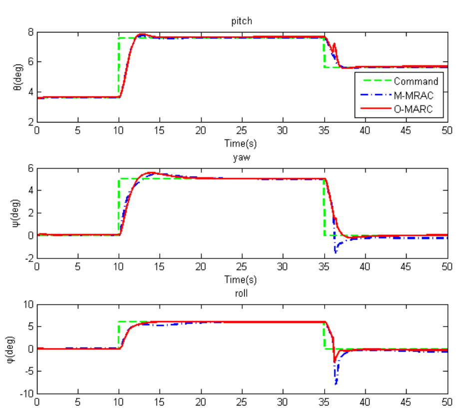

Figure 13. Response curves of pitch, yaw and roll in Case.2

From Fig.13 we can see the O-MRAC method can make the attitude angles track the commands rapidly when the damage occurs. Obviously, the O-MRAC controller has a better tracking performance with faster tracking speed and smaller-scope fluctuation than M-MRAC.

V. CONCLUSIONS

In this paper, an observer based multivariable reference adaptive control(O-MRAC) method was presented. We have taken a deep research on modeling and attitude control of the aircraft. In order to make the damaged aircraft stable rapidly and provide the guarantee for the convergence, we combined the M-MRAC with COU based ESO and then presented the O-MRAC control method. A three-channel attitude controller is designed for a wing damaged aircraft. Simulation results show that the O-MRAC controller has a better tracking performance. Further research will focus on two aspects. First is the controller design and validation for the instable multi-axis flying-wing aircraft. Second is a further research on its application and a physical simulation on relevant platforms.

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