

Fault-Tolerant Flight Control for Nonlinear-UAV

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Abstract— This paper describes the robust performance of a novel active Fault Tolerant Control (FTC) approach for a nonlinear Unmanned Aerial Vehicle (UAV) during weapon delivery and with battled damaged wing, both considered as fault effects. The aircraft dynamics with mass variation and variable wing parameters are introduced and approximately linearized on-line using a dynamic inversion controller based on differential geometry theory. For the linearized system, an active FTC scheme is accomplished via a linear matrix inequality (LMI) approach, based on a simultaneous state/faults observer by solving a Lyapunov equation. The simulation results demonstrate the robust stability and satisfactory FTC performance of the proposed design approach.

I. INTRODUCTION

AIR combat has long been called upon to meet many military contingencies. A UAV without an on board pilot has obvious advantages for personnel safety and elimination of the need in the cockpit, resulting in a decrease in weight, possibly allowing greater weapon payload, range and maneuverability during military attack. UAVs therefore require higher autonomy than before with a need for effective FTC performance [1], [2]. Factors that certainly affect the aerodynamics and flight control performance (even stability) of the UAV are drastic wind variations (particularly at low altitude) and battle damage [3]-[6]. Advanced high-performance aircraft (including the UAV), not only have characteristic of high nonlinearity and are multi-input and multi-output from a control standpoint, but also require high maneuverability with static instability. Parameter variations, following weapon delivery lead to inevitable fluctuations in aircraft handling [7]-[9].

The requirement to enable the UAV to recover autonomously from structural damage or system faults introduces significant challenges in reliable flight control system design [10], [11], together with robust fault detection and diagnosis (FDD) for dynamic systems which has long been attracting significant research effort for achieving more effective solutions for improved control robustness [12]-[14].

For the purposes of efficiency and simplification, the method of feedback linearization is well-proven and has been developed to be a feasible control strategy in the study of nonlinear systems, especially applicable to aircraft [15]-[17].

In particular, dynamic inversion control has advantages such as insensitivity to parameter changes and disturbances, and simplicity in physical realization [18]-[21]. An inner-loop controller designed using results from feedback linearization combined with dynamic inversion ensures the stability of the nonlinear aircraft system. As another aspect to this work, the literature of the development of fault estimation within active FTC systems is well summarized in [22]. These authors use a LMI approach via a descriptor system estimator to simultaneously estimate system states, output noise and sensor faults for a class of nonlinear systems. In recent work, a novel actuator fault estimation approach is developed for nonlinear descriptor systems [23].

The contribution in this paper is the application of the combined dynamic inversion controller with a robust estimator and combined active fault compensation FTC approach to a nonlinear aircraft system during the presence of weapon delivery and against wing battle damage, both considered as faults. Bounds on the fault magnitudes are determined for guaranteeing closed-loop system performance and robustness using the estimated states and faults together with the LMI strategy. The aircraft example includes full force and moment longitudinal dynamics together with a design simplification based on a simplified short period mode. The scheme of the FTC flight system is illustrated in Fig. 1.

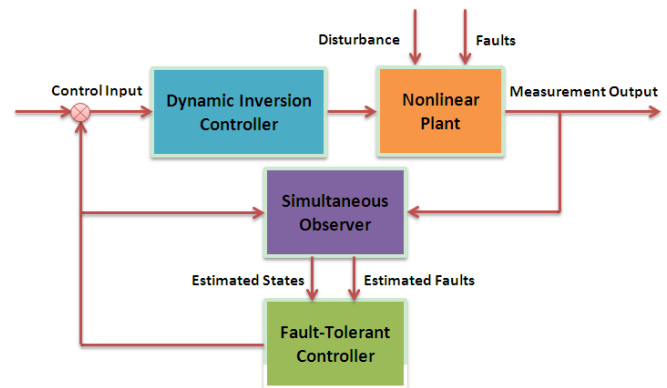


Fig. 1. Fault-tolerant control system scheme

The main framework presented is based on the work described in [24] focused on the design of FTC systems for normal flight and motivated by the importance of robustness for modern control missions. The current work is concerned more with inherent UAV system mass changes due to the weapon pay load delivery and the aerodynamic changes caused by battle damaged aircraft wings. These uncertain factors all present interesting challenges to the FTC problem for flight.

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Section II outlines the mathematical model of the nonlinear UAV the Machan, with mass variations and wing battle damage. Section III introduces the theoretical foundations of the dynamic inversion controller and the robust FTC system. The simulation results and concluding discussion are given in Section IV and Section V provides a concluding statement.

II. NONLINEAR MACHAN AIRCRAFT

The aircraft chosen in this work is a UAV (or remotely piloted vehicle), the Machan, used as a development vehicle by Marconi Avionics, Chatham UK for research on high incidence flight and non-linear control laws, with RAE Farnborough UK and NASA Dryden in the 1980's [25].

The Machan Euler equations relate the forces X , Y , Z and moments L , M , N in the aircraft body axes to the angular and linear velocities in the inertial axes are shown as:

$$\left. \begin{aligned} m(\dot{u} + qw - rv) &= X \\ m(\dot{v} + ur - pw) &= Y \\ m(\dot{w} + vp - qu) &= Z \\ I_x \dot{p} + (I_z - I_y)r q &= L \\ I_y \dot{q} + (I_x - I_z)p r &= M \\ I_z \dot{r} + (I_y - I_x)p q &= N \end{aligned} \right\} \quad (1)$$

where, m is the mass of the aircraft; I_x , I_y , I_z are the moments of inertia about the axes through the centre of gravity parallel to the aircraft body axes; u , v and w are the forward, side and vertical velocity of the aircraft respectively; p , q and r are the roll, pitch and yaw rates, respectively.

The aerodynamic force and moment equations are:

$$\left. \begin{aligned} X &= X_E - D \cos \alpha + (L_w + L_T) \sin \alpha - mg \sin \theta \\ Y &= Y_a + mg \cos \theta \sin \phi \\ Z &= -(L_w + L_T) \cos \alpha - D \sin \alpha + mg \cos \theta \cos \phi \\ L &= L_a + L_E \\ M &= M_a + L_w (cg - 0.25) \bar{c} - L_q (l_t + 0.25 - cg) \\ N &= N_a \end{aligned} \right\} \quad (2)$$

where α (degrees) is the angle of attack; θ and ϕ (degree) are the pitch and roll angles, respectively; Y_a (N) is the side force; cg (m) is the position of the aircraft centre of gravity; X_E (N) is the thrust force due to the engine; l_t (N/m) is the tail moment; D (N) is the force acting on the airframe; L_w , L_T and L_q (N) represent the wing, total tail and tail lift due to the pitch rate respectively; M_a , N_a and L_a (N/m) are the pitching, yawing and rolling moment components respectively; \bar{c} (m) is the mean aerodynamic chord and L_E (N/m) is the rolling moment due to the engine.

The first order non-linear engine dynamic is given as:

$$\dot{X}_E = (P_{max} \delta_t \eta_t - X_E U_2) / K_e \quad (3)$$

where, P_{max} , δ_t , η_t , K_e and U_2 represent the maximum engine power, the throttle demand, the propeller efficiency,

the engine rise rate and the air flow rate, respectively. The parameter details are given in Aslin 1985.

The open-loop Machan UAV is unstable, thus to achieve a stable fault estimator and FTC system, a closed-loop "base-line" control system must be configured before the FTC system can be developed.

For simplicity of the aircraft model during weapon delivery, the following simplifying conditions must be stipulated: the weapon mass is located on the longitudinal axis; the aircraft configuration and the distribution of mass inside are symmetrical with the longitudinal plane; the symmetrical motion parameters will not yield asymmetric forces and moments; the centre gravity is constant. Thus the potential catastrophic course is only in the sudden change during the period after the weapon has left the aircraft.

Statement 1: The centre gravity is constant is a strong and valid assumption.

During the initial deployment phase, the weapon load and aircraft are regarded as a single body mass. To simplify matters further, that single body may be modeled as a point mass, in which case only Newton's force equation needs to be considered, which can be shown in an aircraft-fixed reference system as [26], [27]:

$$M_B = \begin{bmatrix} M_{BX} \\ M_{BY} \\ M_{BZ} \end{bmatrix} = \begin{bmatrix} -m_B a_B \\ 0 \\ m_B q v_B \end{bmatrix} \quad (4)$$

where M_B is the force acting on the aircraft caused by the changing mass; m_B , a_B , v_B are the mass, acceleration and velocity of the weapon payload.

By substituting the changing force M_B of (4) into the aircraft force (2), it is easily seen that, in all the states, the total velocity V and the angle of attack α will mainly cause variations in the longitudinal motion of the aircraft.

Hence, to simplify the system, this paper only considers the longitudinal short period mode. The short period model system states (angle of attack and pitch rates) and input vectors for the nonlinear model are chosen as [28]:

$$x = [x_1 \quad x_2]^T = [\alpha \quad q]^T \quad (5)$$

$$u = [\delta_e \quad \delta_t]^T \quad (6)$$

where δ_e and δ_t are the elevator and thrust input, respectively.

Therefore, the aircraft model can be expressed as a multi-input, multi-output smooth affine nonlinear system:

$$\left. \begin{aligned} \dot{x} &= f(x) + G(x)u \\ y &= H(x) \end{aligned} \right\} \quad (7)$$

where $x = (x_1, \dots, x_n)^T$ is an n-D (dimensional) states vector of the system, $u \in R^m$ and $y \in R^m$ are the input and output vectors of the system, $f \in R^n$ is a sufficiently smooth vector field. $G(x) = [g_1(x) \quad g_2(x) \quad \dots \quad g_m(x)]^T$, g_i ($i =$

$1, 2, \dots, m$) is an m -D sufficiently smooth vector field, $H(x) = [h_1(x) \ h_2(x) \ \dots \ h_m(x)]^T$, h_i ($i = 1, 2, \dots, m$) is a sufficiently smooth scalar function.

The simplified (reduced order) nonlinear Machan equations can be expressed in terms of:

$$f(x) = [f_\alpha(x) \ f_q(x)]^T \quad (8)$$

Before the payload discharge, the weapon load and the aircraft are regarded as a single body, thus $f(x)$ can be expressed as:

$$f_\alpha(x) = [m_B q v_B \cos \alpha + (-X_E - m_B a_B) \sin \alpha + mg \cos(\theta - \alpha) - L] / mV + q$$

$$f_q(x) = M / I_y \quad (9)$$

After the discharge of the pay load, $f(x)$ can be expressed for the isolated aircraft as:

$$f_\alpha(x) = [-X_E \sin \alpha - L + mg \cos(\theta - \alpha)] / mV + q$$

$$f_q(x) = M / I_y \quad (10)$$

The control distribution matrix of (7) is then given as:

$$G(x) = \begin{bmatrix} 0 & l_{\delta_e} \\ l_{\delta_e} & 0 \end{bmatrix} \quad (11)$$

The parameters l_{δ_e} , l_{δ_t} are calculated from the aerodynamic coefficients related to control input u . Since no parameters are zero-valued in this model, $G(x)$ is full rank and thus invertible. Hence, the Dynamic Inversion Controller exists.

Wing Battle Damage. Consider the scenario of battle damage on the main aircraft wing. Any minor damage on the wing causes changes in the aerodynamic coefficients and will bring about changes in some elements of the system dynamics $f(x)$ in (9) and (10). Using η_1 and η_2 to denote the normalized deviation caused by the changes in aerodynamic coefficients, a suitable system description is taken from [29] as:

$$f_\alpha(x) = n_\alpha(1 + 0.1\eta_1) + q$$

$$f_q(x) = n_\alpha(1 + 0.05\eta_2) + n_q(1 + 0.1\eta_3) \quad (12)$$

where the η_i ($i = 1, 2, 3$) reflect the parametric modelling uncertainties, n_α , n_q are calculated by the aerodynamic parameters related to the states $[\alpha \ q]$.

III. ACTIVE ACTUATOR FTC STRATEGY

A. Nonlinear Feedback Linearization

To achieve an inner-loop controller using the dynamic inversion control strategy, the system variables should be chosen carefully to form a square and invertible matrix. The nonlinear Machan model system has 14 state variables. As shown in (5) and (6), this system is square with 2 inputs and 2 outputs.

For the affine nonlinear system (7), define γ_i to be the smallest integer such that at least one of the inputs appears in $y_i^{(\gamma_i)}$ using Lie derivatives as:

$$y_i^{(\gamma_i)} = L_f^{\gamma_i} h_i + \sum_{j=1}^m (L_{g_j} L_f^{\gamma_i - 1} h_i u_j) \quad (13)$$

with at least one of the $L_{g_j} L_f^{\gamma_i - 1} h_i \neq 0 \forall x$, and u_j is the j th row of u .

The input-output relation can then be defined as:

$$[y_1^{(\gamma_1)} \ y_2^{(\gamma_2)} \ \dots \ y_m^{(\gamma_m)}]^T = M(x) + N(x)u \quad (14)$$

$$M(x) = [L_f^{\gamma_1} h_1(x) \ L_f^{\gamma_2} h_2(x) \ \dots \ L_f^{\gamma_m} h_m(x)]^T \quad (15)$$

$$N(x) = \begin{bmatrix} L_{g_1} L_f^{\gamma_1 - 1} h_1 & \dots & L_{g_m} L_f^{\gamma_1 - 1} h_1 \\ \vdots & \ddots & \vdots \\ L_{g_1} L_f^{\gamma_m - 1} h_m & \dots & L_{g_m} L_f^{\gamma_m - 1} h_m \end{bmatrix} \quad (16)$$

If the matrix $N(x) \in R^{m \times m}$ is invertible, then the system can be linearized by decoupling the non-linear terms in (14) by choosing u as follows:

$$u = M^{-1}(x)[-N(x) + v] \quad (17)$$

(17) leads to the closed-loop decoupled, linear system:

$$[y_1^{(\gamma_1)} \ y_2^{(\gamma_2)} \ \dots \ y_m^{(\gamma_m)}]^T = [v_1 \ v_2 \ \dots \ v_m]^T \quad (18)$$

By assuming that all the system states are measured as $y = x$, it follows that:

$$\dot{y} = f(x) + G(x)u \quad (19)$$

Since $G(x)$ is invertible, the control input u can be obtained as:

$$u = G^{-1}(x)[-f(x) + v] \quad (20)$$

As a result, the output of the closed-loop system is given by the solution to the following linear system:

$$\dot{y} = v \quad (21)$$

Commonly, y can be chosen as $v = \omega(x_d - x)$, where x_d is the desired output, ω is the desired band-width [30]. The desired states of the *fast* variables can be defined as:

$$\begin{cases} \dot{\alpha}_d = \omega_\alpha(\alpha_c - \alpha) \\ \dot{q}_d = \omega_q(q_c - q) \end{cases} \quad (22)$$

where the labels c and d represent the commanded signals and their desired values, respectively. Thus the inner-loop control law is derived from the above dynamic inversion strategy as:

$$u = G^{-1} \left\{ \begin{bmatrix} \dot{\alpha}_d \\ \dot{q}_d \end{bmatrix} - \begin{bmatrix} f_\alpha(x) \\ f_q(x) \end{bmatrix} \right\} \quad (23)$$

Once linearization has been achieved, any further control objectives may be easily met.

B. Robust Estimator and Fault Tolerant Control System

After feedback linearization by the dynamic inversion controller, the system model can be simplified to a classical state-space system as:

$$\begin{cases} \dot{x} = Ax + Bu_{out} \\ y = Cx \end{cases} \quad (24)$$

By including both actuator faults and random disturbances, the system described in (24) can be broadened to a descriptor system [23]:

$$\begin{cases} E\dot{x} = Ax + Bu_{out} + \Phi(t, x, u_{out}) + B_d d + B_f f \\ y = Cx \end{cases} \quad (25)$$

where $d \in R^l$ is the unknown bounded process disturbance vector; $f \in R^k$ is the unknown actuator fault vector; $E \in R^{n \times n}$ may be singular; B_d, B_f are constant real matrices of appropriate dimensions; $\Phi(t, x, u_{out}) \in R^n$ is the real nonlinear vector of the inversion error. The vector of actuator faults f has unknown fault components, but the q th derivative, i.e. $f^{(q)}$, is assumed bounded.

The first step is to develop a robust state-space observer to estimate both the system states x and the faults signal f simultaneously by using the known input u_{out} and the measurement output y . The second step is to develop an efficient FTC scheme by using the estimated states and faults [23].

To simplify the notation in the determination of the robust estimation scheme let:

$$\xi_i = f^{(q-i)}, (i = 1, 2, \dots, q) \quad (26)$$

and by using (25), an augmented descriptor process can be constructed as follows [23]:

$$\begin{cases} \bar{E}\dot{\bar{x}} = \bar{A}\bar{x} + \bar{B}u_{out} + \bar{B}_d d + \bar{G}f^{(q)} + \bar{\Phi}(t, x, u_{out}) \\ y = \bar{C}\bar{x} \end{cases} \quad (27)$$

where

$$\bar{n} = n + kq$$

$$\bar{x} = [x^T \quad \xi_1^T \quad \xi_2^T \quad \dots \quad \xi_q^T]^T \in R^{\bar{n}}$$

$$\bar{\Phi}(t, x, u_{out}) = [\Phi^T(t, x, u_{out}) \quad 0 \quad \dots \quad 0]^T \in R^{\bar{n}}$$

$$\bar{E} = \text{blockdiag}(E, I, \dots, I) \in R^{\bar{n} \times \bar{n}}$$

$$\bar{B} = [B^T \quad 0 \quad 0 \quad \dots \quad 0]^T \in R^{\bar{n} \times m}$$

$$\bar{B}_d = [B_d^T \quad 0 \quad 0 \quad \dots \quad 0]^T \in R^{\bar{n} \times l}$$

$$\bar{G} = [0 \quad I_k \quad 0 \quad \dots \quad 0]^T \in R^{\bar{n} \times k}$$

$$\bar{C} = [C \quad 0 \quad 0 \quad \dots \quad 0]^T \in R^{p \times \bar{n}}$$

$$\bar{A} = \begin{bmatrix} A & 0 & 0 & B_f \\ 0 & 0 & \dots & 0 \\ 0 & I & & 0 \\ \vdots & \ddots & & \vdots \\ 0 & 0 & \dots & I \end{bmatrix} \in R^{\bar{n} \times \bar{n}} \quad (28)$$

Consider a state-space dynamic system as follows:

$$\begin{cases} \dot{\hat{x}} = \bar{A}\hat{x} + \bar{B}u_{out} + (1 + \alpha_0)\bar{L}_p(y - \bar{C}\hat{x}) + \bar{\Phi}(t, \hat{x}, u_{out}) \\ \hat{x} = (\bar{E} + \bar{L}_D\bar{C})^{-1}(\bar{z} + \bar{L}_D y) \end{cases} \quad (29)$$

where $\hat{x} \in R^{\bar{n}}$ is the estimate of the augmented state $\bar{x} \in R^{\bar{n}}$; \bar{L}_p and \bar{L}_D are to be designed according to the following forms:

$$\bar{L}_D = [L_D^T \quad 0 \quad 0 \quad \dots \quad 0]^T \in R^{\bar{n} \times p} \quad (30)$$

$$\bar{L}_p = [L_p^T \quad (L_1^1)^T \quad (L_1^2)^T \quad \dots \quad (L_1^q)^T]^T \in R^{\bar{n} \times p} \quad (31)$$

and α_0 is a positive scalar to be designed. Since \bar{x} in (28) includes the estimated state, the estimates of the fault derivatives and the fault estimation, which enables the observer (29) to be a simultaneous state and fault estimator.

Then there exists a robust observer in the form of (29) for the plant (27) to make the steady estimator error dynamics as small as any desired accuracy, if the derivative gain \bar{L}_D is well selected such that $\bar{S} = \bar{E} + \bar{L}_D\bar{C}$ is non-singular. The proportional gain \bar{L}_p is computed as:

$$\bar{L}_p = \bar{S}\bar{P}^{-1}C^T \quad (32)$$

where \bar{P} is determine by solving the Lyapunov equation:

$$-(\mu I + \bar{S}^{-1}\bar{A})^T \bar{P} - \bar{P}(\mu I + \bar{S}^{-1}\bar{A}) = -\bar{C}^T \bar{C} \quad (33)$$

With $\mu > 0$ satisfying $\text{Re}[\lambda_i(\bar{S}^{-1}\bar{A})] > -\mu \forall i \in \{1, 2, \dots, \bar{n}\}$; the scalar α_0 is chosen as:

$$\alpha_0 = \theta_0^2 \|\bar{P}^{1/2}\bar{S}^{-1}\|^2 \quad (34)$$

By selecting a reasonably large μ , the observer designed can reduce the effects of the disturbance d and the fault model error $f^{(q)}$, as desired. The complete proof is in [23].

Consider system (25) and its augmented system (27). An observer-based controller can be constructed as [23]:

$$\begin{cases} \dot{\hat{x}} = [\bar{A} - (1 + \alpha_0)\bar{L}_p\bar{C}]\hat{x} + \bar{B}u_{out} \\ \quad + (1 + \alpha_0)\bar{L}_p y + \bar{\Phi}(t, \hat{x}, u_{out}) \\ \hat{x} = (\bar{E} + \bar{L}_D\bar{C})^{-1}(\bar{z} + \bar{L}_D y) \\ u_{out} = \bar{K}_p \hat{x} \end{cases} \quad (35)$$

where it is assumed that the observer gains \bar{L}_D and \bar{L}_p and scalar parameter α_0 are already designed.

Let $\bar{K}_p = (K_p, K_f^1, K_f^2, \dots, K_f^q)$, with $K_p \in R^{m \times m}$ and $K_f^i \in R^{m \times k}$ ($i = 1, 2, \dots, q$).

By choosing:

$$K_f^q = -B^\dagger B_f \quad (36)$$

to achieve: $B_f + K_f^q B = 0$.

Furthermore, to remove the effect of a fault f on the plant, choose:

$$K_f^i = 0, i = 1, 2, \dots, q - 1 \quad (37)$$

If the closed-loop system of (35) is solvable, causal as well as, asymptotically stable, and if there exist a positive definite matrix $W \in \mathbb{R}^{n \times n}$, and matrices $Q \in \mathbb{R}^{(n-r) \times n}$, $Y \in \mathbb{R}^{m \times n}$ such that:

$$\begin{bmatrix} \Gamma_{a11} & (\Gamma_{a12})^T & (\Gamma_{a13})^T & B_d \\ \Gamma_{a12} & -I & 0 & 0 \\ \Gamma_{a13} & 0 & -I & 0 \\ B_d^T & 0 & 0 & -\gamma^2 I \end{bmatrix} < 0 \quad (38)$$

where $\Gamma_{a11} = (AWE^T + AE_r^\perp Q + BY)^T + AWE^T + AE_r^\perp Q + BY + \theta^2 I$, $\Gamma_{a12} = WE^T + E_r^\perp Q$, $\Gamma_{a13} = CWE^T + CE_r^\perp Q$, $E_r^\perp \in \mathbb{R}^{n \times (n-r)}$ is a matrix such that $EE_r^\perp = 0$ and $\text{rank}(E_r^\perp) = n - \text{rank}(E) = n - r$. Furthermore, if a feasible solution (W, Q, Y) exists in the LMI (38), the state-feedback gain can be computed as:

$$K_p = Y(WE^T + E_r^\perp Q)^{-1} \quad (39)$$

In this case, the normal dynamical output feedback controller (35) can perform a fault-tolerant operation by ensuring the closed-loop plant to be internally proper stable and attenuate the bounded input disturbance d with prescribed H_∞ performance index [31].

IV. SIMULATION RESULTS

To achieve the robust observer (25), construct an augmented model in the form of (27) with $q = 2$. Choose:

$$\bar{L}_D = 0_{6 \times 2}, \mu = 5.8, \theta_0 = 0.38$$

From (34) one can compute $\alpha_0 = 0.0526$.

By solving the Lyapunov function (33) and using (32), the gain of the estimator can be determined as:

$$\bar{L}_p = 1 \times 10^3 \times \begin{bmatrix} -0.0177 & 0 \\ 0 & -0.0177 \\ 0 & 0.4280 \\ -0.0001 & 0 \\ 0 & 1.0801 \\ -0.0002 & 0 \end{bmatrix}$$

The command signals are chosen as $[\alpha_c \ q_c] = [0 \ 0]$. For good fault detectability properties, choose multi-step up-step down signal (rad) as the throttle and elevator faults. These fault levels are of practical significance in terms of their magnitude of less than 1 actuator degree.

The real fault signals and the longitudinal system states, as well as their corresponding estimation values are shown in the 4 subplots of Fig.2, respectively. Fig.2 illustrates that the designed simultaneous estimator can accurately track the system faults and states. However, the system states, the outputs α and q in Fig. 2 show that the actuator faults cause the system to be unstable without regard to a suitable controller.

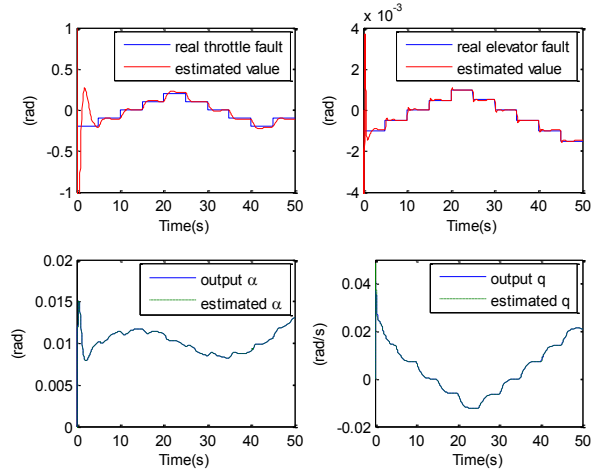


Fig.2. System faults, states and their estimated values

To achieve the robust FTC system, by choosing $\gamma = 0.5668$, and by solving (38) and (39), the following gain results:

$$K_p = \begin{bmatrix} -1.1668 & 0 \\ 0 & 1.8163 \end{bmatrix}$$

Choose $K_f^1 = 0_{2 \times 2}$, K_f^2 is shown as (37). Therefore, the FTC gain matrix can be obtained as:

$$\bar{K}_p = [K_p \ K_f^1 \ K_f^2]$$

The FTC system responses are shown as Fig. 3.

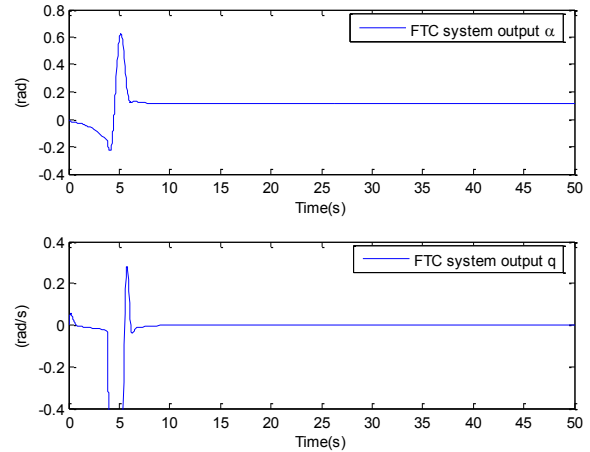


Fig.3. FTC system responses

For the aircraft model in (12) against wing damage, choose:

$$\eta_1 = \eta_2 = \eta_3 = 1$$

which acts on the aircraft at time $t = 5s$.

For the aircraft model in (9) during weapon delivery, the parameters of the weapon load are chosen as:

$$m_B = 1kg, a_B = 0.5ms^{-2}, v_B = 5ms^{-1}$$

acting on the aircraft at time $t = 20s$.

Since the change of system structure is reflected in the estimator as actuator faults it then follows that the FTC

system can use the estimated information to optimize the system performance. The estimated faults caused by the change during weapon delivery and wing damage, and the output responses resulting from the FTC system are shown in Fig.4, which illustrates that the designed system could reach another equilibrium state after the transition process.

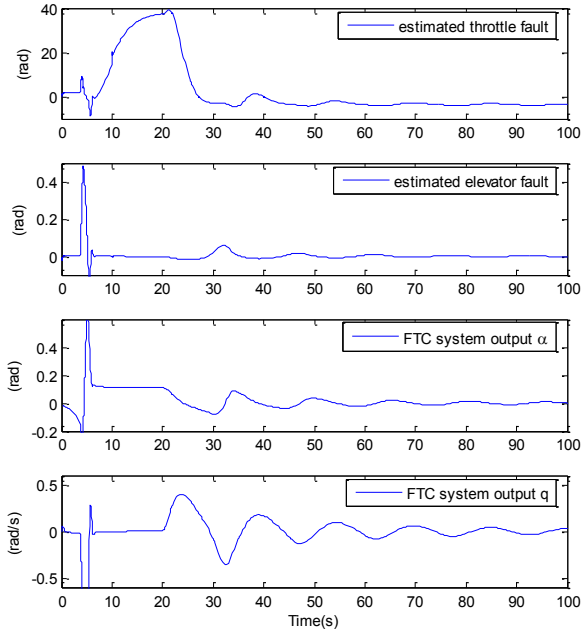


Fig.4. FTC system responses during weapon delivery and against wing damage

V. CONCLUSION

The design of an active FTC scheme for the highly nonlinear longitudinal dynamics of a UAV, the Machan is considered under the fault conditions of weapon delivery and wing battle damage. The principle of dynamic inversion control design for nonlinear systems has been applied through the use of feedback linearization. A robust state and fault estimator is designed corresponding to a simplified linearized short period system. Based on the estimated vectors, the robust FTC loop achieves internally proper dynamics, and satisfies robust performance to the mass variations and battle damage, respectively.

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