NASA/CR-97- 206660

NONCLASSICAL FLIGHT CONTROL FOR UNHEALTHY AIRCRAFT

FINAL
IN-08-CR
OCIT
045158

FINAL REPORT

(March 28, 1997 - November 30, 1997)

Research Supported by

NASA Dryden Flight Research Center

Cooperative Agreement NCC4-109

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December, 1997

Summary

This research set out to investigate flight control of aircraft which has sustained damage in regular flight control effectors, due to jammed control surfaces or complete loss of hydraulic power. It is recognized that in such an extremely difficult situation unconventional measures may need to be taken to regain control and stability of the aircraft. Propulsion controlled aircraft (PCA) concept, initiated at the NASA Dryden Flight Research Center, represents a ground-breaking effort in this direction. In this approach, the engine is used as the only flight control effector in the rare event of complete loss of normal flight control system. Studies and flight testing conducted at NASA Dryden have confirmed the feasibility of the PCA concept.[1]–[5] These experiments have also revealed nonlinearities, both in airframe dynamics and propulsion system which are easily accommodated by normal flight control system, now become a prominent factor affecting the effectiveness of PCA controller. Therefore nonclassical control design methods based on state-space and nonlinear control theory may offer a more effective PCA controller than the traditional linear designs will. The goal of this research is to investigate whether such a nonclassical method indeed merits consideration in PCA applications.

During the course of this research (March 28, 1997 to November 30,1997), a comparative study has been done using the full nonlinear model of an F-18 aircraft. Linear controllers and nonlinear controllers based on a nonlinear predictive control method have been designed for normal flight control system and propulsion controlled aircraft. For the healthy aircraft with normal flight control, the study shows that an appropriately designed linear controller can perform as well as a nonlinear controller. On the other hand, when the normal flight control is lost and the engine is the only available means of flight control, a nonlinear PCA controller can significantly increase the size of the recoverable region in which the stability of the unstable aircraft can be attained by using only thrust modulation. The findings and controller design methods have been summarized in an invited paper entitled Flight Control with and without Control Surface: a Nonlinear Look, and it is to be included

in the book *Nonlinear Problems in Aviation and Aerospace* which is to be published by Gordon and Breach Science Publishers, UK. This paper is attached in this report to serve as the main body of the report.

FLIGHT CONTROL WITH AND WITHOUT CONTROL SURFACES: A NONLINEAR LOOK

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Abstract

This paper discusses both normal aircraft flight control where the control surfaces are the primary effectors, and unconventional emergency flight control by engines only. It has long been realized that nonlinearity in aircraft dynamics is a prominent consideration in design of high-performance conventional flight control systems. The engine-only flight control problem also faces strong nonlinearity, although due to different reasons. A nonlinear predictive control method is used in this paper for normal and engine-only flight control system designs for an F-18 aircraft. The comparison of the performance with that of linear

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flight controllers provides some insight into when nonlinear controllers may render a much improved performance.

1. Introduction

Aircraft flight control systems are traditionally designed based on linearized dynamics and linear control methodologies.[6] While the linear designs have been remarkably successful, increasingly high performance of modern aircraft, usually associated with large flight envelop, high angle of attack and large angular rates, has invalidated the fundamental assumption of small perturbations of linearization. In these conditions the nonlinearity in the aircraft dynamics becomes so prominent that it can no longer be ignored. A satisfactory flight control system must take into account the inherent nonlinearity dictated by the law of physics.

Even for commercial airplanes for which conventional linear flight control designs will remain to work well, there are situations in which abrupt changes in the system cause significant nonlinear behaviors. A case of point is the propulsion-only flight control problem for an aircraft with complete hydraulic failure. Although aircraft control systems are designed with extensive redundancy to ensure safe flight, rare incidents did occur in which the airplane experienced major flight control system failures, leaving engine thrust as the only usable control effector. In some of these emergency situations, the engines were used "open-loop" to maintain control of the flight path of the airplane. A B-747 aircraft lost its entire hydraulic system because of a pressure bulkhead failure[7]. It was flown for almost an hour using throttle control before the plane eventually hit a mountain. Perhaps, the best known use of manual throttles-only control occurred in July, 1989 on United Airlines flight 232[1]. At cruise condition, a DC-10 suffered an uncontained tail engine failure that caused the loss of all hydraulic power. Under extremely difficult circumstances, the crew used wing engine throttles for control and was able to crash-land at the Sioux City, airport, Iowa. More than one-half of the people on board were saved[2]. Other cases involving engine-only emergency flight control have been documented. In the majority of the cases surveyed, due to the overload work of manual throttle control, major flight control system failures have resulted in crashes with a total of over 1200 fatalities[3].

NASA Dryden Flight Research Center has carried out feasibility studies and flight testing in recent years on propulsion-controlled aircraft.[3–7] Successful flight experiments have been conducted on F-15, MD-11 and C-17 airplanes using feedback throttle control system. In the flight testing, some notable nonlinear behaviors have also been observed. These include engine dynamics, engine saturation, propulsion and airframe interaction, and strong dynamic cross-coupling. All these nonlinear phenomena are amplified by the fact that the engine has very limited control authority on the attitude of the aircraft. The challenge is to design an automatic engine-only thrust control system as an emergency backup flight control to stabilize the aircraft when potentially disastrous flight control system failures occur, and eventually land the aircraft safely with severely damaged or inoperative control surfaces.

It would appear logical to expect that in these highly nonlinear situations, for both control of healthy high-performance aircraft and impaired aircraft with engine-only, a nonlinear design of the control system may offer better performance. An intensively studied nonlinear flight control method is based on input-output feedback linearization technique,[8] also known as dynamic inversion.[9] In this paper, we offer some evidences that nonlinear designs can indeed enhance the performance of the flight control systems. We shall apply a recently developed nonlinear predictive control approach [10, 11] to flight control design for an F-18 aircraft, and show that this method is effective for an important class of problems in which dynamic inversion encounters difficulty. In Section 2 the nonlinear model of an F-18 aircraft is introduced. A well-known linear control design method and the nonlinear predictive control method are briefly reviewed in Section 3. The performance of the linear and nonlinear designs are compared in Section 4 where both control of the healthy aircraft and engine-only control of the F-18 are examined. Conclusions are given in Section 5.

2. Model for an F-18 Aircraft

2.1 Engine Dynamics Model

The F-18 aircraft is powered by two General Electric F404-GE-400 engines[12]. The F404-GE-400 engine is a 16,000-lb thrust class, low bypass, twin spool turbofan with after-burner. It incorporates a three-stage fan and a seven-stage high-pressure compressor, each driven by a simple-stage turbine. During flight, power lever angle (PLA) ranges from 23.8° (flight idle) to 130° (full power with after-burner). Intermediate power(full, non-after-burning) occurs at 68° PLA. Because of the execution time constraints, A simple first-order engine dynamic model was used

$$\frac{d\ PLA'}{dt} = \frac{(PLA - PLA')}{\tau} \tag{1}$$

where the time constant τ is scheduled with respect to the output PLA', Mach number and angle of attack. Note that because of these dependence, Eq. (1) is a nonlinear model. The engine gross thrust is computed by performing multidimensional, linear interpolations of tabular data over PLA', Mach number, altitude and angle of attack. The real engine thrust is determined based on several quantities, including gross thrust, ram drag, nozzle pressure ratio and nozzle throat area.

2.2 Aerodynamic Model

This F-18 aircraft features a mid wing configuration with a wing-root leading-edge extension (LEX) that extends from the forward portion of the fuselage and blends into the wing. It has aerodynamic coefficients defined over the entire operational flight envelop of the aircraft by tabulated data. The aerodynamic coefficients are computed by performing multidimensional table lookup. The interpolation in general is dependent on the current Mach number, altitude, angle of attack, sideslip angle, angular rates, and control surface deflections.

2.3 Longitudinal Aircraft Dynamics

In general, the standard six-degree-of-freedom (6DOF) equations of motion are based on the assumptions of the flat-Earth and rigid-body aircraft with longitude symmetric plane. In our study, the flight is limited in the vertical plane. So the motion is reduced to three-degree-of-freedom. Equations of motion consist of six nonlinear differential equation with six state variables. The states are: the mass-center airspeed V, angle of attack α, pitch rate q in the body-fixed axis, pitch angle θ, and the mass-center position coordinates d, z in an Earth-fixed frame of reference. The equations of motion are defined in the stability axis as follows:

$$\dot{V} = (-D + T\cos\alpha - mg\sin(\theta - \alpha))/m \tag{2}$$

$$\dot{\alpha} = (-L - T\sin\alpha + mg\cos(\theta - \alpha))/(mV) + q \tag{3}$$

$$\dot{\theta} = q \tag{4}$$

$$\dot{q} = (M + T\Delta z)/I_{yy} \tag{5}$$

$$\dot{z} = V\sin(\theta - \alpha) \tag{6}$$

$$\dot{d} = V\cos(\theta - \alpha) \tag{7}$$

where the aerodynamic forces and moment are denoted by L, D and M. They represent lift, drag and pitch moment, respectively, and are functions of angle of attack, Mach number, altitude, control surface deflections, pitch rate and some other parameters. Through a vertical displacement Δz between the center of the aircraft gravity and the line of thrust, the engine thrust also contributes to the pitch moment. The two available controls are elevator deflection δ_e and engine throttle PLA. The complete system equations are Eqs. (2–7) plus the engine dynamics Eq. (1).

3. Control Law Design Methods

Let the system equations (2)-(6) be

$$\dot{x} = f(x, u) \tag{8}$$

where $x = (V, \alpha, \theta, q, z)^T$ and $u = (\delta_e, PLA)^T$. A trim condition is an equilibrium level flight condition where the right hand sides of Eqs. (2–6) are zero. The linearized dynamics about such a trim point(x_e, u_e) are

$$\delta\dot{x} = A\delta x + B\delta u \tag{9}$$

where $A = \partial f/\partial x$ and $B = \partial f/\partial u$ evaluated at (u_e, u_e), $\delta x = x - x_e$, and $\delta u = u - u_e$. In this paper, we consider the trim condition for the F-18 at an altitude of 10,000 feet and Mach number = 0.5, which gives

$$V_{trim} = 551.57\ (ft/sec), \alpha_{trim} = 3.39\ (deg), \theta_{trim} = \alpha_{trim} \tag{10}$$

and control inputs

$$\delta_{etrim} = -0.2413\ (deg), PLA_{trim} = 33\ (deg) \tag{11}$$

It is straightforward to verify that the aircraft is not stable at this condition. In fact, the eigenvalues of system (9) are

$$\lambda_{1,2} = -0.7107 \pm j1.8449,\ \ \lambda_3 = -0.0285,\ \ \lambda_4 = 0.0283,\ \ \lambda_5 = 0.0 \tag{12}$$

Therefore, we will take the problem of stabilizing the aircraft at this condition to test linear and nonlinear control law designs.

3.1 Linear Quadratic Regulator (LQR) Design

A well-known powerful control system design method for linear, deterministic and time-invariant system is the LQR approach[6]. We briefly review the procedure here for two reasons: it results a full-state feedback control law which can be compared with the nonlinear predictive control law to be introduced; and the nonlinear predictive control law bears strong similarity with the LQR control law.

To stabilize the linear system (9) at the origin, a performance index

$$J = \frac{1}{2}\int_0^\infty \left\{\delta x^T Q \delta x(t) + \delta u^T R \delta u\right\} d\tau \tag{13}$$

is minimized , subject to (9) and a given initial condition $\delta x(0)$. The Q matrix is positive semidefinite, and R matrix positive definite. Suppose that the system (9) is controllable, the unique optimal control law is then given by

$$\delta u = -R^{-1}B^T K\delta x \tag{14}$$

where K is the positive definite solution of the algebraic Riccati equation (ARE)

$$-KA - A^T K + KBR^{-1}B^T - Q = 0 \tag{15}$$

The controllability guarantees that the ARE has a unique positive solution, thus the control law (14) is well defined. Under this control law, the stability of the closed-loop system

$$\delta\dot{x} = (A - BR^{-1}B^T K)\delta x \tag{16}$$

is ensured.

3.2 Nonlinear Predictive Controller

For the convenience of the reader, a brief review on the nonlinear predictive control design method is given here. For more complete and rigorous derivations and discussions, see Lu[10, 11].

Suppose that the nonlinear dynamic system equations have the form

$$\dot{x_1} = f_1(x) \tag{17}$$

$$\dot{x_2} = f_2(x) + B_2(x)u \tag{18}$$

where $x_1 \in R^{n_1}, x_2 \in R^{n_2}$, and $n_1 + n_2 = n$. Here $x^T = (x_1^T, x_2^T) \in R^n$ is the state vector of the system. $u \in U \subset R^m$ is the control vector, where U is a compact bounded set in R^m. $B_2(x)$ is continuous and none of its rows are zeros. The function f_1 is C^2, and f_2 is C^1. Equations (17) usually represent the kinematics in the system and Eqs. (18) the dynamics. Suppose that a reference trajectory $s(t) \in R^n, t \in [t_0, t_f]$ is given. It is assumed that s(t) satisfies the state equations (17) and (18) with some reference control $u^*(t) \in U$, although $u^*(t)$ need not be known explicitly. We may partition the reference trajectory by $s(t) = (s_1^T(t)\ s_2^T(t))^T$ with $s_1 \in R^{n_1}$ and $s_2 \in R^{n_2}$. Suppose that at $t \in (t_0, t_f)$, $x(t)$ is known. Consider the system response at $x(t+h)$, where $h > 0$ is a time increment. Expanding $x_1(t+h)$ in a second-order Taylor series expansion and $x_2(t+h)$ in a first-order expansion, we have the predicted state at $t+h$ as a function of the current control $u(t)$

$$x_1(t+h) \approx x_1(t) + hf_1(x) + \frac{h^2}{2}[F_{11}f_1(x) + F_{12}f_2(x) + F_{12}B_2(x)u(t)] \tag{19}$$

$$x_2(t+h) \approx x_2(t) + h[f_2(x) + B_2(x)u(t)] \tag{20}$$

where $F_{11} = \partial f_1/\partial x_1$ and $F_{12} = \partial f_1/\partial x_2$ are the Jacobian matrices of $f_1(x)$. To find the control $u(t)$ so that $x(t)$ tracks $s(t)$, we define the following performance index of minimization,

$$J = \frac{1}{2}e_1^T(t+h)Q_1e_1(t+h) + \frac{1}{2}e_2^T(t+h)h^2Q_2e_2(t+h) + \frac{1}{2}u^Th^4Ru(t) \tag{21}$$

where $e_1(t+h) = x_1(t+h) - s_1(t+h)$ and $e_2(t+h) = x_1(t+h) - s_1(t+h)$, Q_1, Q_2 and R are positive semidefinite square matrices of the appropriate dimensions. The reference states $s_1(t+h)$ and $s_2(t+h)$ are further approximated by

$$s_1(t+h) = s_1(t) + h\dot{s}_1(t) + \frac{h^2}{2}\ddot{s}_1(t) \tag{22}$$

$$s_2(t+h) = s_2(t) + h\dot{s}_2(t) \tag{23}$$

The performance index J is a quadratic function in u when $x_1(t+h)$ and $x_2(t+h)$ are approximated by Eqs. (19) and (20). Solving for $u(t)$ that minimize J by setting $\partial J/\partial u = 0$ yields

$$u(t) = -W^{-1}\left\{\frac{1}{2h^2}G^TQ_1P_1 + \frac{1}{h}B_2^TQ_2P_2\right\} \tag{24}$$

where the following substitutions and expansions have been made:

$$G = F_{12}B_2(x) \tag{25}$$

$$W = \frac{1}{4}G^TQ_1G + B_2(x)^TQ_2B(x) + R \tag{26}$$

$$P_1 = e_1 + h\dot{e}_1 + \frac{h^2}{2}\left(F_{11}f_1(x) + F_{12}f_2(x) - \ddot{s}_1\right) \tag{27}$$

$$P_2 = e_2 + h\left(f_2(x) - \dot{s}_2\right) \tag{28}$$

Since the time t is arbitrarily chosen in the $[t_0, t_f]$, Eq. (24) is a nonlinear, continuous feedback control law. It bears strong similarity with the LQR controller in the way the control law is derived. The weightings Q_1, Q_2 and R have the same meaning as in the LQR design. If an element on the main diagonal Q_1 (or Q_2) is nonzero (positive), the corresponding state variable will be controlled to follow its desired value. Typically the performance of the controller is not sensitive to the choices of the weighting values. The parameter h can be treated as an additional control parameter that can be adjusted to improve the performance of controller. Generally, the smaller value h has, the faster the system response is, but at larger control effort.

To apply the predictive controller to the flight control problem, we let $x_1 = (\theta, z)^T$, $x_2 = (V, \alpha, q)^T$, and $u = (\delta_e, PLA)$. The control limits are enforced by simple saturators. The reference trajectory $s(t)$ for stabilization problem is simply the trim value x_e.

In the dynamic inversion design[9], the number of the controlled variables (outputs) should not exceed that of the control variables. In the longitudinal control problem for the F-18, this means that at most two state variables or two functions of the state will be controlled. The overall closed-loop stability then depends on the stability of the uncontrolled internal dynamics, referred to as the zero dynamics[8]. We will demonstrate that when controlling any two state variables, the zero dynamics of the F-18 at the given trim condition are always unstable (known as nonminimum-phase system). Hence more careful search for appropriate outputs is required before the dynamic inversion approach is applicable. On the other hand, the predictive control method does not have the same restriction so more state variables can be controlled. This gives the controller the possibility to stabilize even a nonminimum-phase system.

4. Controller Performance

The performance of the nonlinear predictive controller and the LQR controller are compared in this section. The healthy aircraft in the following refers to the aircraft with normal horizontal stabilators (elevator) and throttle control, as opposed to engine-only flight control where only the throttle is the available control.

4.1 Healthy Aircraft Control

An LQR controller (14) is designed for the linearized dynamics. The closed-loop system has the eigenvalues

$$\lambda_{1,2} = -0.908497 \pm j2.4472, \;\; \lambda_{3,4} = -1.766997 \pm j0.92504, \;\; \lambda_5 = -0.12207 \tag{29}$$

This control law is applied to the nonlinear dynamic model for the F-18 in the simulation. Initial perturbations off the trim condition are created to test the region of stability under the linear control law. Figure 1 shows the variations of the histories angles and angular rate with perturbations of -15 ft/sec in velocity, +5 deg in angle of attack and 5.73 deg/sec in pitch rate. The velocity variation shown in Fig. 2 is a little sluggish, but eventually returns to the trim value. The controls PLA and δ_e are plotted in Figs. 3 and 4. The simulation shows that the F-18 is stabilized at the trim condition, despite the relatively large perturbations. In fact, tests indicate that the size of the stability region in terms of perturbations under the linear control law is about ±20 ft/sec for velocity, ± 8 deg for angle of attack and 0.3 rad/sec for pitch rate. Perturbations beyond this range will cause instability.

Now we apply the nonlinear predictive control method to stabilize the F-18. The control law follows directly Eq. (24). The controller parameters $Q_1 = diag\{1, 0\}$ and $Q_2 = diag\{1, 1, 1\}$, $R = 0$, and $h = 1$ sec. The closed-loop stability under the nonlinear control law can be verified by examining eigenvalues of the linearized closed-loop dynamics which are

$$\lambda_{1,2} = -0.85704 \pm j1.36572, \;\; \lambda_3 = -0.50017, \;\; \lambda_4 = -0.07252, \;\; \lambda_5 = -0.0027 \tag{30}$$

The same initial perturbations used for the LQR controller are added to demonstrate the performance. Figures 5 and 6 show the state histories of the F-18 under the nonlinear controller. Figure 7 contains the time history of the PLA command and actual response PLA', and Fig. 8 gives the stabilator deflection The stability region of the nonlinear controller is found to be about the same size as that of the LQR controller, which is rather remarkable for the LQR controller, given its simple linear form.

It should be noted that the dynamic inversion method also leads to nonlinear feedback control laws for the two controls (δ_e, PLA). But in this case if any two of the five state variables $(V, \alpha, \theta, q, z)$ of the F-18 are used as the controlled outputs for the control law design, the system is always nonminimum-phase. This can be verified by examing the transmission zeros of the transfer matrix of the linearized open-loop dynamics: in any given combination, at least one of the transmission zeros lies in the right-half of the complex plane. By Ref. 8, the zero dynamics of the nonlinear system coincides with that of the linearized system. Hence the aircraft cannot be stabilized using two state variables as the output and the dynamic inversion control laws at this trim condition.

4.2 Engine-Only Flight Control

In the preceding section we have seen that the linear controller offers performance comparable to that of the nonlinear predictive controller in normal, less challenging flight. In this section we test engine-only flight control for the F-18. We assume that the F-18 is flying with the stabilators locked in the trimmed positions. The only control available is the throttle PLA.

Because of the loss the primary attitude control effector (stabilator) in this case, and the fact that the engine has rather limited control authority on any state other than the airspeed, nonlinearities in the system which would be well accommodated by the normal flight control system thus not influential to the performance now become prominent factors. Indeed, despite that a stabilizing LQR engine-only control law can still be designed for the linearized F-18 dynamics Eq. (9), simulations show that the stability region of the closed-loop system with the nonlinear F-18 dynamics is extremely small. The aircraft becomes unstable even for very small perturbations in the state away from the trim condition. In other words, the linear engine-only controller would practically fail to stabilize the aircraft in the event when the stabilator becomes inoperative at the trim condition considered.

On the other hand, the nonlinear predictive controller for the engine is still capable of stabilizing the aircraft. The controller for the PLA is the same as the one used for the healthy aircraft. It should be noted that better performance could be achieved if the PLA controller parameters are readjusted for the engine-only case. But we deliberately used the same parameters to emulate the realistic situation in which it would not be possible to readjust the engine controller parameters in time should a complete failure of the stabilator occur in flight. Under this nonlinear control law, the linearized closed-loop dynamics at the trim point have the poles

$$\lambda_{1,2} = -0.703879 \pm j1.84753, \;\; \lambda_3 = -0.49209, \;\; \lambda_4 = -0.0217, \;\; \lambda_5 = -0.0007338 \qquad (31)$$

Note that the pair of the complex poles are very close to those of the open-loop dynamics in Eq. (12), which represents the so-called short-period mode in flight mechanics. This is because this mode primarily reflects rapid changes in angle of attack α and pitch angle θ, and is almost uncontrollable by engine only. Thus any state-feedback control law for the throttle can barely change them.

Figure 9 shows the time histories of the state variables with the same initial perturbations of $\delta V = -15$ ft/sec, $\delta\alpha = 5$ deg and $\delta q = 5.73$ deg/sec to the F-18. Figure 10 shows the velocity variation history. Figure 11 illustrates variations of the commanded PLA and response PLA'. It is clear that the aircraft remains stabilized at the trim point, but the aircraft response, particularly in the pitch, is much more sluggish as compared to the response of the healthy aircraft. This comes as no surprise, given the loss of the use of the primary pitch control effector (stabilator). However in situations like this the foremost objective is not the performance, but stabilization of the aircraft with the only remaining control – the engines. The nonlinear predictive controller is able to accomplish this objective. The stability region in this case is about the same size as that of the healthy aircraft under the two controls δ_e and PLA. This is quite impressive, given that now the stabilator is inoperative and the linear controller cannot stabilize the aircraft.

5. Conclusions

Linear or nonlinear, that is a question one would ask when it comes to controller design for the inherently nonlinear system of an airplane. Traditional approach has been linear, perhaps dictated historically by the limited capability of avionics and availability of only linear control theory. But its success over the history of aviation is by no coincidence. As the F-18 application demonstrated in Section 4.1, a linear controller can work amazingly well, even compared with a nonlinear design, in the normal flight scenarios. But the limitations of linear designs become obvious in more challenging situations such as high-performance flight or unconventional emergence engine-only flight control applications illustrated in Section 4.2. In these cases, a nonlinear flight control system can potentially accomplish the control objectives beyond the extent linear controllers can ever reach. With the applications to the F-18 aircraft flight control, this paper also demonstrates the capability of the nonlinear predictive control method for controlling nonminimum-phase systems, which has long posed a serious challenge to controller design.

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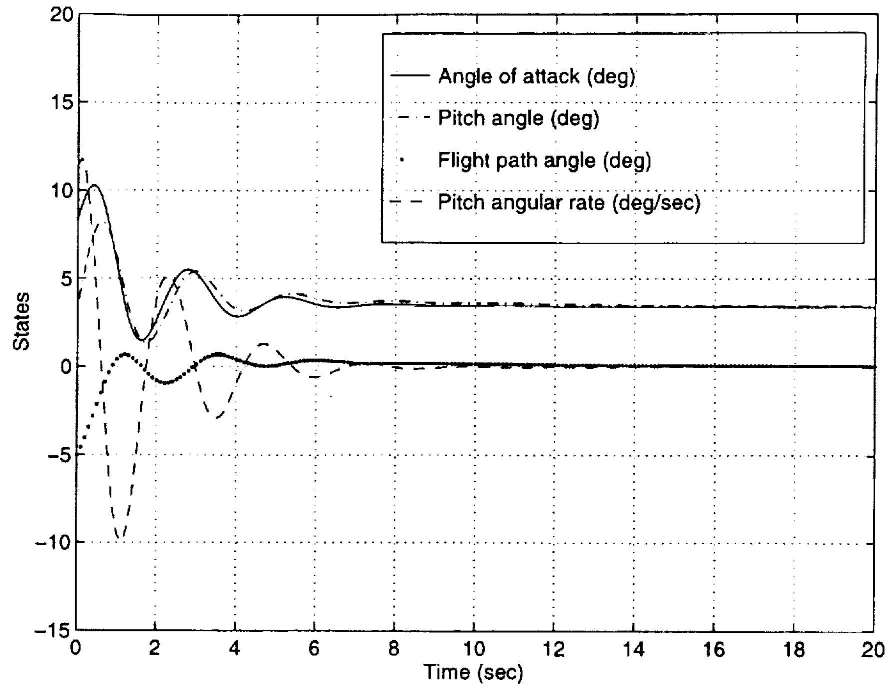

Figure 1: Healthy F-18 State histories with linear controller

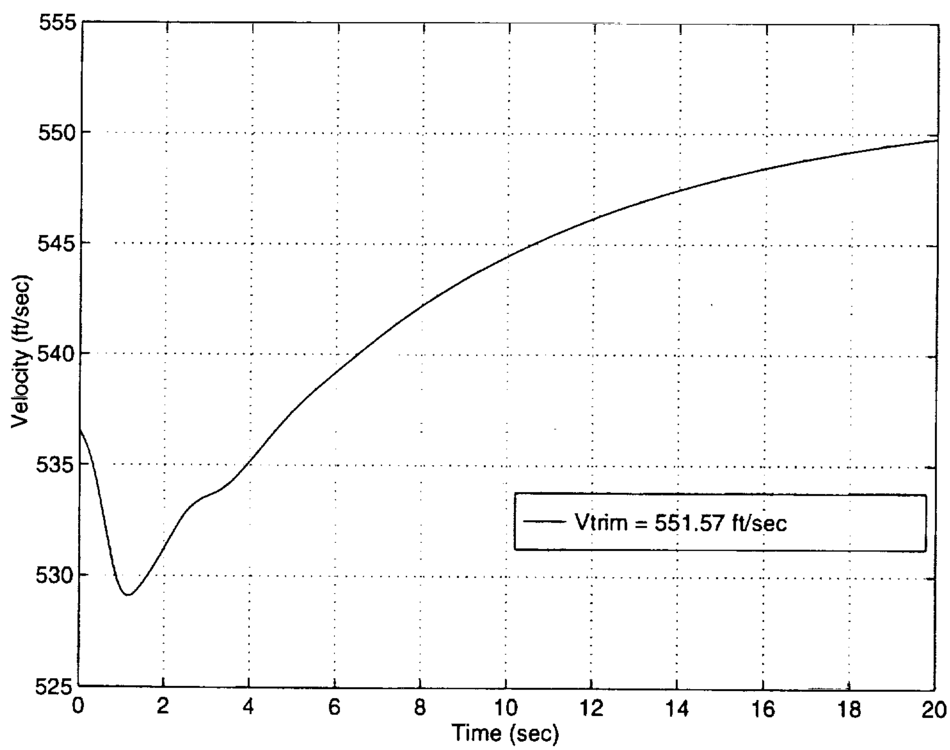

Figure 2: Healthy F-18 velocity time history with linear controller

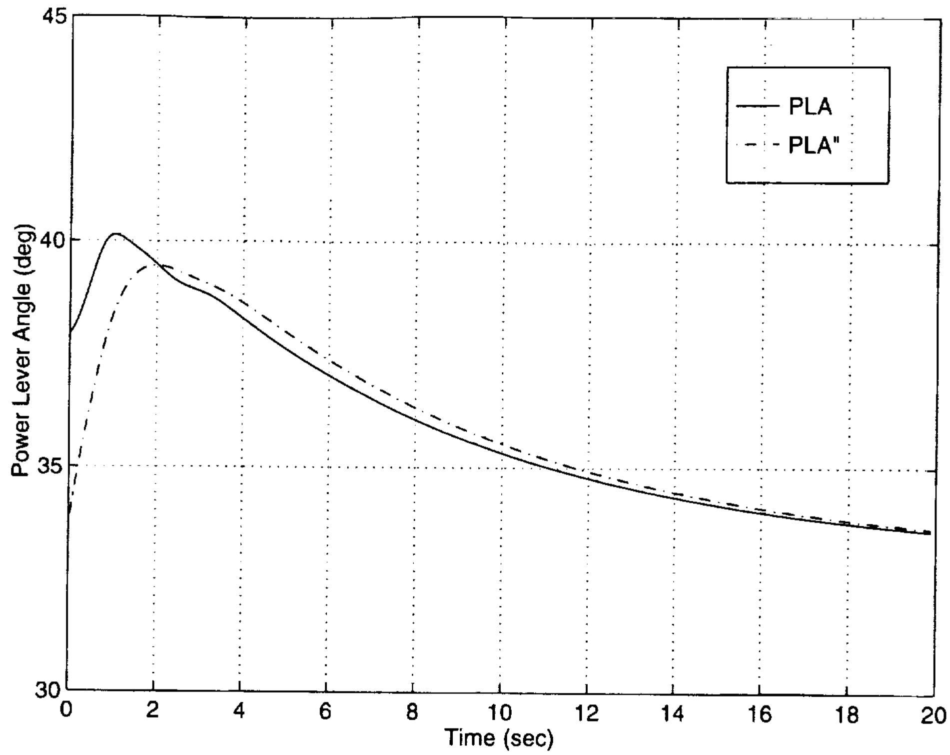

Figure 3: Healthy F-18 throttle setting time history with linear controller

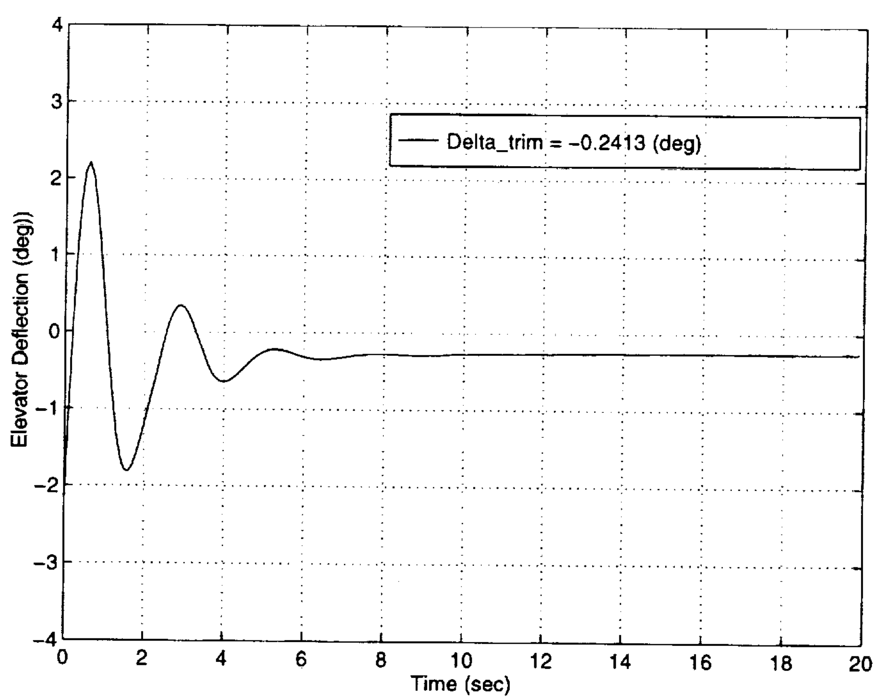

Figure 4: Healthy F-18 elevator deflection time history with linear controller

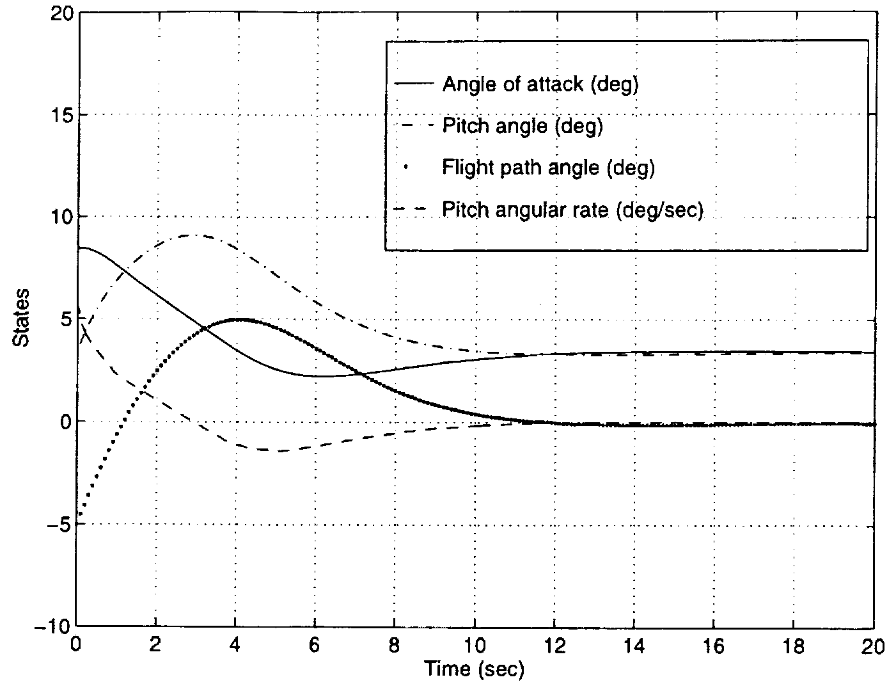

Figure 5: Healthy F-18 state histories with nonlinear predictive controller

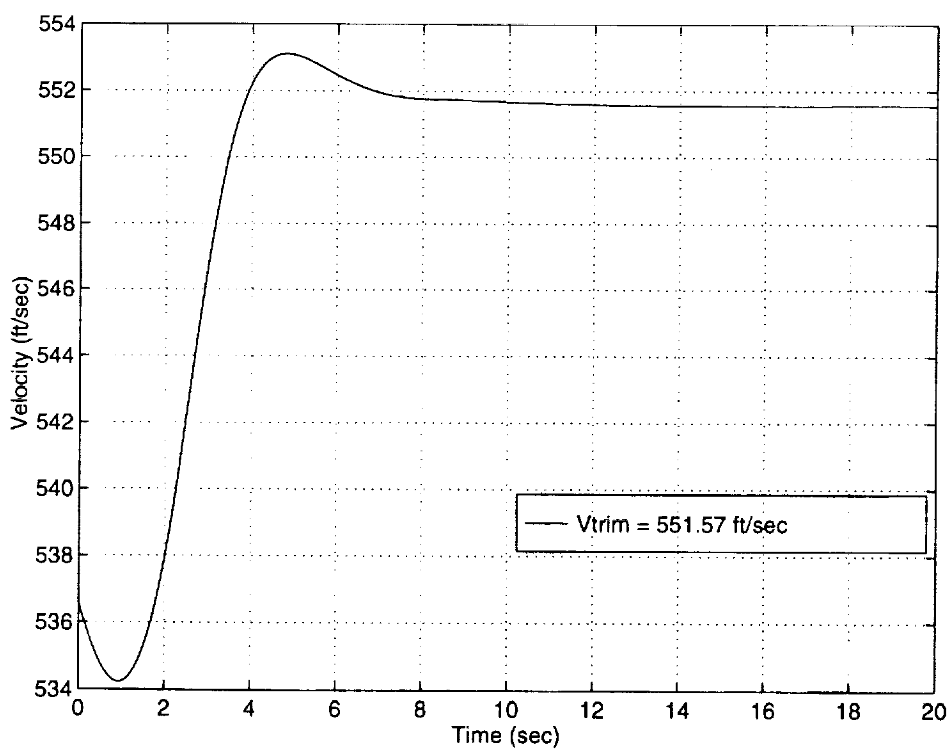

Figure 6: Healthy F-18 velocity time history with nonlinear predictive controller

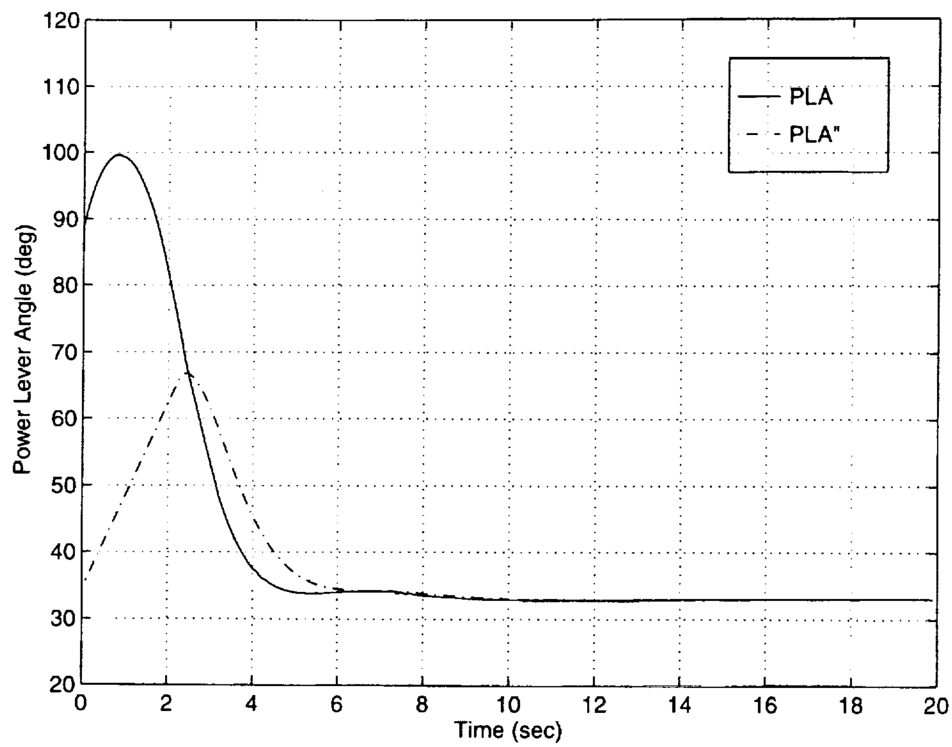

Figure 7: Healthy F-18 throttle setting time history with the nonlinear control

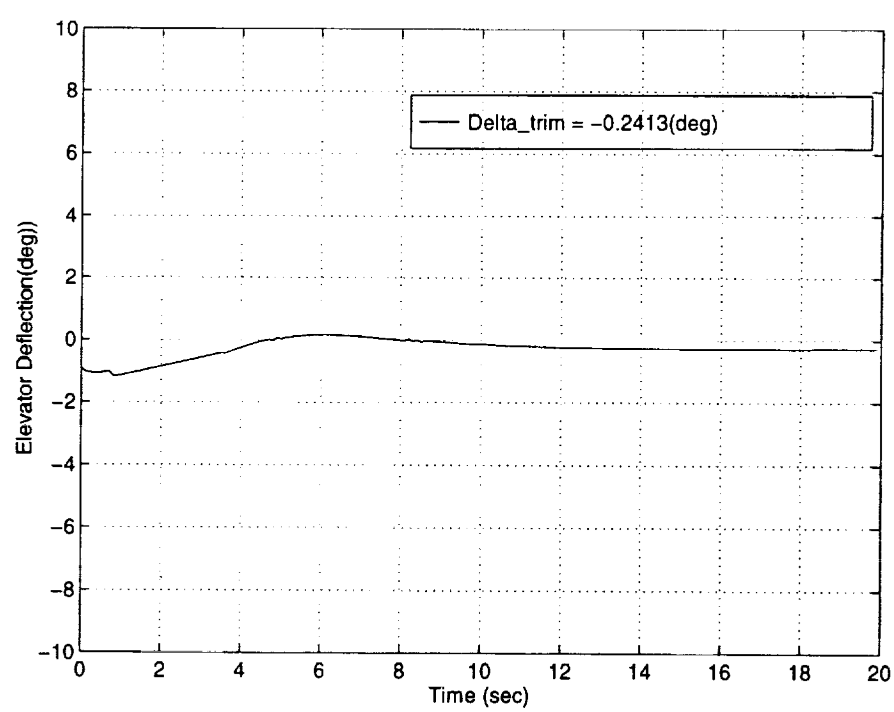

Figure 8: Healthy F-18 elevator deflection time history with the nonlinear control

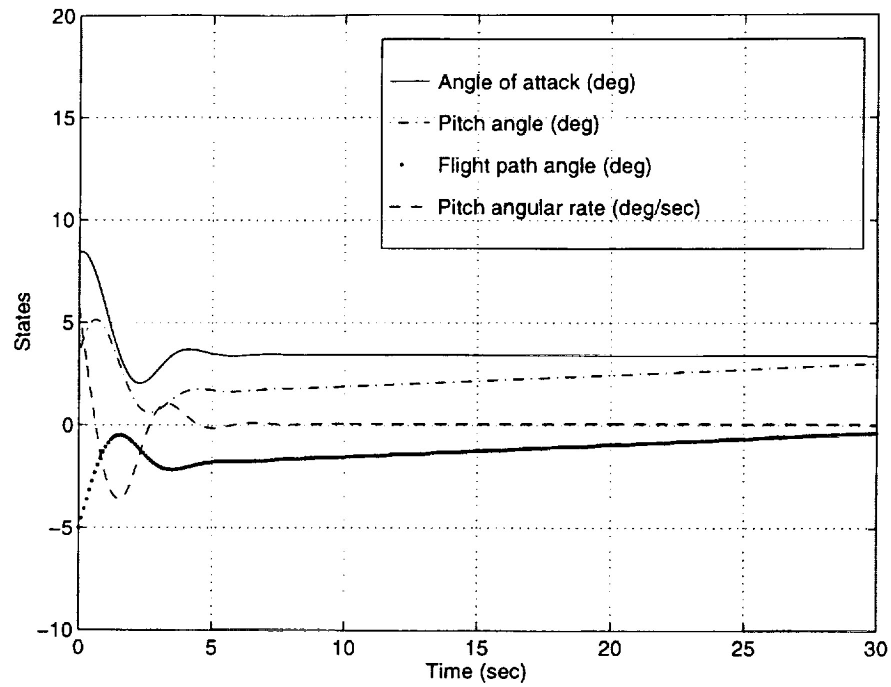

Figure 9: State histories with nonlinear predictive engine-only controller

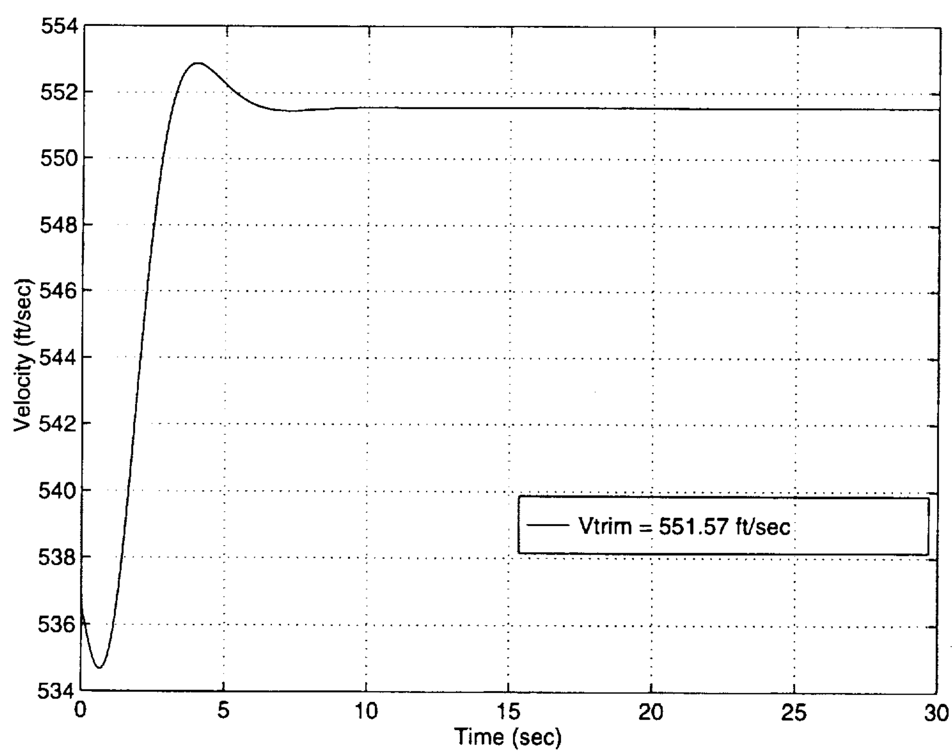

Figure 10: Velocity variation with engine-only nonlinear predictive controller

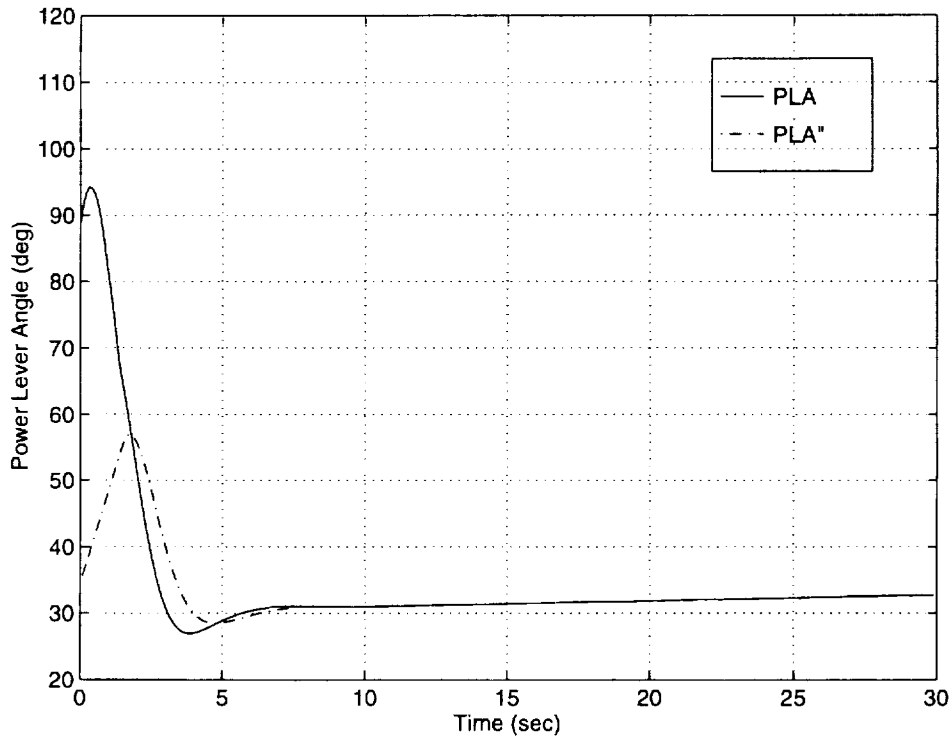

Figure 11: Throttle setting history with engine-only predictive controller