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NASA Contractor Report 186028

Design and Flight Test of the Propulsion Controlled Aircraft (PCA) Flight Control System on the NASA F-15 Test Aircraft

Edward A. Wells and James M. Urnes, Sr.

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Design and Flight Test of the Propulsion Controlled Aircraft (PCA) Flight Control System on the NASA F-15 Test Aircraft

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McDonnell Douglas Aerospace
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St. Louis, Missouri

Contract NAS2-13312
1994

National Aeronautics and
Space Administration

Dryden Flight Research Facility
Edwards, California 93523-0273

Foreword

The Propulsion Controlled Aircraft program was conducted for the NASA Dryden Flight Research Facility by McDonnell Douglas Aerospace, St. Louis, Missouri, as part of the Performance Seeking Control (PSC II) contract, NAS2-13312. This report describes the design and test of the PCA control system for the NASA F-15 aircraft. This work was performed from January 1991 to December 1993.

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List of Abbreviations

ADC - Air Data Computer
AGL - Above Ground Level
CAS - Control Augmentation System
CC - Central Computer
CPLD - Coupled
DEEC - Digital Electronic Engine Controller
DEFCS - Digital Electronic Flight Control System
DOF - Degrees Of Freedom
EAFB - Edwards Air Force Base
EMD - Engine Model Derivative
EMI - Electromagnetic Interference
FN - Net Propulsive Force
HIDEC - Highly Integrated Digital Electronic Control
HILS - Hardware In The Loop Simulation
HUD - Head Up Display
IFF - Identification, Friend Or Foe
IFIM - In-Flight Integrity Management
INS - Inertial Navigation System
MDA - McDonnell Douglas Aerospace
MSL - Mean Sea Level
NASA - National Aeronautics And Space Administration
NCI - Navigation Control Indicator
PASCOT - Programmable Asynchronous Serial Communication Translator
PCA - Propulsion Controlled Aircraft

List of Abbreviations (Continued)

PLA - Power Lever Angle
PSC - Performance Seeking Control
RMDU - Remote Multiplexer/Demultiplexer Unit
SOAPP - State Of The Art Performance Program
TCP - Thumbwheel Controller Panel
TH/ENG - Throttle/Engine
TRAUTO - Automatic Trim Mode
TROFF - Trim Mode Off
TRON - Trim Mode On
UART - Universal Asynchronous Receiver Transmitter
USAF - United States Air Force
VMSC - Vehicle Management System Computer

1.0 INTRODUCTION

1.1 Background

The Propulsion Controlled Aircraft (PCA) concept addresses flight control system failures resulting in partial or complete loss of the primary flight control system by providing backup control sufficient to maneuver and land the disabled aircraft. Example failures are hydraulic system loss, structural failure, and mechanical control system jam. Damage to the control system may occur due to mid-air collision, engine disintegration, terrorist bomb, structure fatigue, or battle damage during enemy engagements. These types of failures cannot be accommodated by multiple channel fly-by-wire flight control systems or by mechanical backup flight controls. The United Airlines DC-10 hydraulic loss accident in Sioux City, Iowa resulted in a situation where the aircraft could be steered to the landing approach by using the engine throttles, but the pilot did not have the necessary control precision to safely complete the landing on the runway. The National Transportation Safety Board made this recommendation following this accident:

> "Encourage research and development of backup flight control systems for newly certified wide-body airplanes that utilize an alternate source of motive power separate from that source used for the conventional control system."

1.2 Summary

This report describes the design, development and flight testing of the Propulsion Controlled Aircraft (PCA) flight control system performed at McDonnell Douglas Aerospace (MDA), St. Louis, Missouri and at the NASA Dryden Flight Research Facility, Edwards Air Force Base, California. This research and development program was conducted by MDA and directed by NASA through the Dryden Flight Research Facility for the period beginning January 1991 and ending December 1993.

A propulsion steering backup to the aircraft conventional flight control system has been developed and flight demonstrated on a NASA F-15 test aircraft. The Propulsion Controlled Aircraft (PCA) flight system utilizes collective and differential thrust changes to steer an aircraft that experiences partial or complete failure of the hydraulically actuated control surfaces. The PCA system utilizes the flight control system sensors and computer processors to augment engine commands and provide the flight path stability that is critical for successful runway landings. Tests on the F-15 showed that safe landings are virtually impossible if manual throttle inputs are used to steer the aircraft without any engine command stability augmentation. The PCA flight control system provided the necessary stabilization for accurate flight path steering, and runway landings were demonstrated by NASA test pilot Gordon Fullerton.

The PCA flight control system uses engine thrust as the alternate source of power to maneuver the aircraft. Feedback stabilization is added to the pilot throttle commands. This provides the assistance needed to use only the engines for precise flight path control when the primary flight controls are disabled. The feedback signals needed come from the same flight motion sensors that are used by the flight control autopilot. Thus, the engines become an alternate or backup source of control power to steer and safely land the vehicle. This capability was achieved through the addition of the PCA software in the flight control system.

The PCA flight control research has shown that propulsion steering is a viable backup flight control mode and can assist the pilot in safe landing recovery of a fighter aircraft that has damage to or loss of the flight control surfaces. NASA, USAF and Navy evaluation test pilots stated that the F-15 PCA design provided the control necessary to land the aircraft. Moreover, the feasibility study showed that PCA technology can be directly applied to transport aircraft and provide a major improvement in the survivability of passengers and crew of controls damaged aircraft.

1.3 Description of the Test Vehicle

The NASA HIDEC F-15 research testbed was selected for this development (Figure 1). This aircraft is equipped with a high capacity, research flight control computer, Digital Electronic Engine Controllers (DEECs) and Pratt and Whitney 1128 (F100 EMD) engines. The digital engine control capability is linked to the flight control system, making it an ideal demonstration vehicle for integrated flight/propulsion control. The PCA software was integrated into the flight control system with the engine interface provided by the DEECs.

Special PCA pilot controller hardware and HUD symbology were developed and installed in the test aircraft. The special controller was used for this technology demonstration because it provided a more straightforward implementation than using the control stick. It minimized the provisions needed to permit immediate return to the conventional control system in the event that a true emergency should occur during flight testing. The research HUD informed the pilot of system status and provided a positive indication of input commands.

The test F-15 also has control system access through a cockpit control panel. This allows the pilot to change system parameters in the PCA software during flight testing. Such access was a significant aid during the PCA flight development and demonstration.

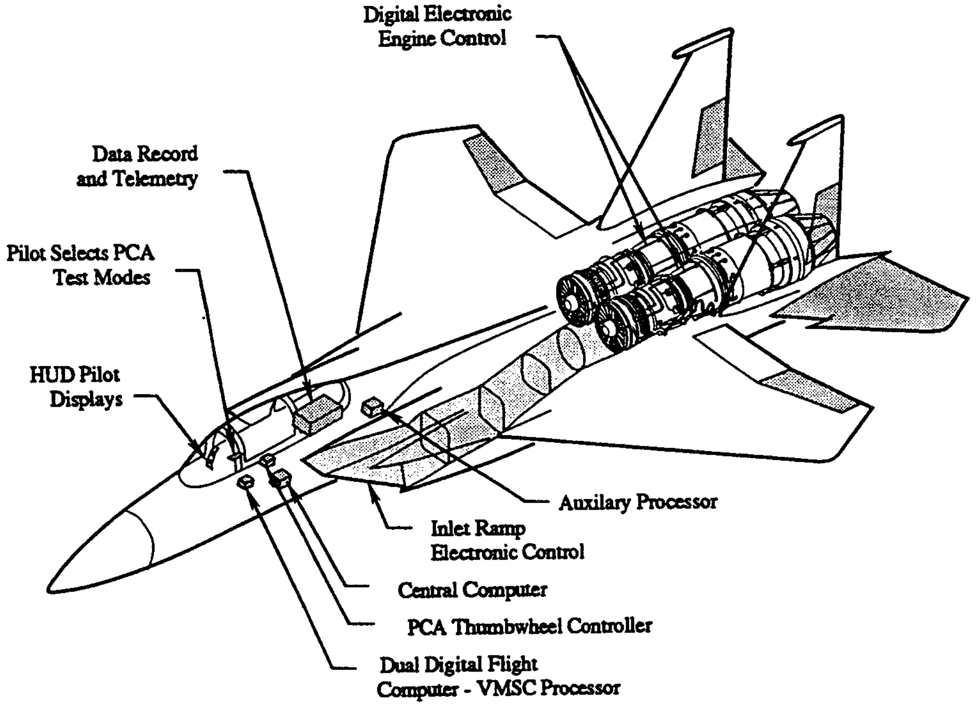


Figure 1. NASA F-15 Test Vehicle for PCA Research

1.4 Program Objectives

The primary objective of the Propulsion Controlled Aircraft program was to flight demonstrate the propulsion-only flight control concept on a high performance aircraft. The application of the technology could then be transitioned to both transports and tactical fighter aircraft. The program objectives were:

- Provide flight response as a backup control system in the event of partial or complete failure of the conventional control surfaces.
- Utilize non-conventional control effectors, such as collective and differential engine commands, to control the aircraft.
- Provide sufficient control and display to the pilot to permit safe landing of the F-15 test aircraft.

Additionally, a feasibility study was performed to assess the application of PCA technology to an MD-11 transport. The study used the same control law structure that was developed for the F-15; as shown in Figure 2, stability and control were improved in both pitch (phugoid damping) and roll (dutch roll damping).

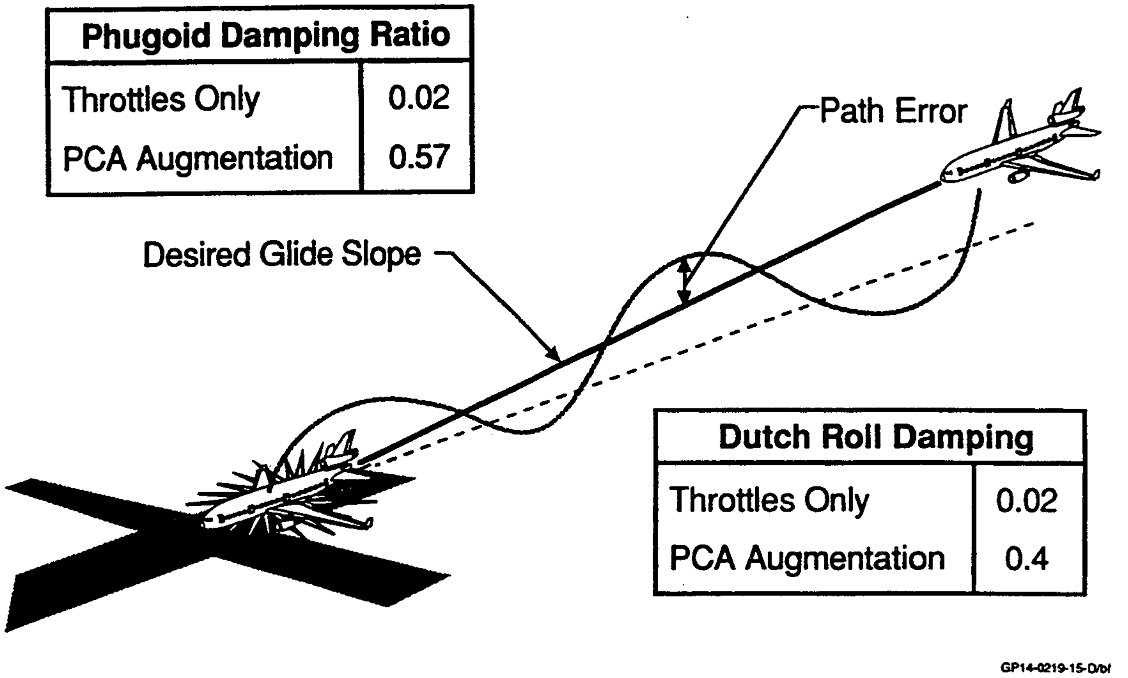


Figure 2. MD-11 Predicted Performance: PCA Control Offers Flight Path Damping Improvement

1.5 Program Plan and Schedule

Figure 3 shows the key MDA program tasks and schedule for the PCA system development. The program was accomplished in three general steps:

1) Design of the F-15 PCA System (Tasks M.1 through M.6)
2) PCA Software, Hardware, Integrated Component Tests (Tasks M.7 through M.14)
3) PCA Flight Test (Tasks M.15 through M.19)

The PCA design began with a feasibility study. The study included evaluation of many control law designs, including use of position, rate and acceleration sensors typically used in fighter and transport vehicles. This study included methods for pitch and roll control using the engine thrust and airspeed velocity control using fuel transfer to change the aircraft center of gravity. The study was done using off-line control analysis, simulation and on-line manned flight simulator tests. Control laws, cockpit displays and cockpit controls were evaluated by NASA test pilots. Using this large data base of PCA control configurations, a flight test baseline configuration was selected for detailed design based on: (1) projected flight performance, (2) applicability to transport and fighter aircraft, and (3) funding cost. The baseline PCA design was then completed, evaluated on the F-15 flight simulator and approved by NASA for implementation at the Preliminary Design Review in October, 1991.

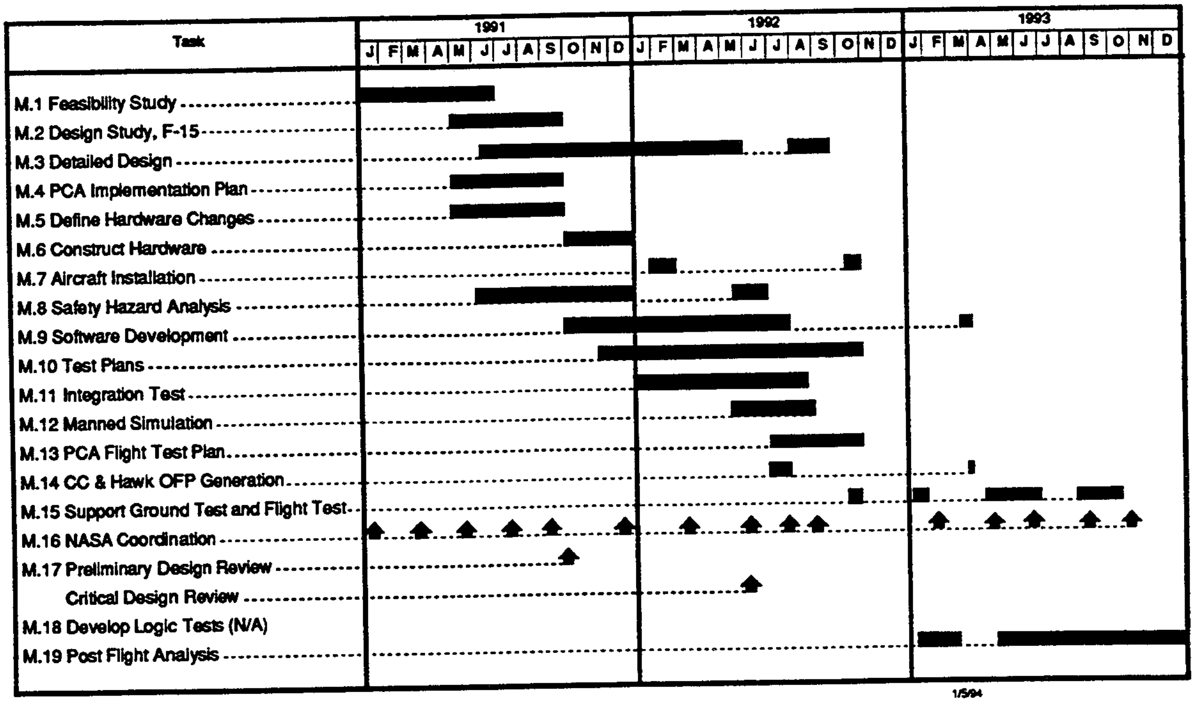


Figure 3. Propulsion Controlled Aircraft Program Schedule

During the progress of the PCA software and hardware development, flight tests were conducted by NASA pilots on the F-15 that provided additional data for the PCA design. This information indicated flight path variations due to throttle changes at higher airspeeds that were not observed in the F-15 flight simulator. Design changes to correct for those variations were incorporated in the flight software that could be activated by the pilot as an option to the baseline system.

Provisions for variations of the PCA control modes, gains, filters and limits were programmed into the flight software. These changes could be made prior to flight and activated by the pilot through a mode select panel installed in the cockpit. This feature proved to be very useful as the flight test proceeded.

The PCA system components, including cockpit controllers, HUD displays, and flight computer processors, were linked together for integrated system tests conducted at the F-15 flight control software test laboratory at MDA. The units were further tested in a Hardware-in-the-Loop System (HILS) test on the MDA F-15 flight simulator. The PCA flight test Critical Design Review was held at NASA in June, 1992.

MDA provided an installation kit to NASA to install the cockpit PCA Thumbwheel Controller Panel. Ground tests were conducted with the PCA software installed in the flight processors to verify proper system function.

Flight tests were conducted by NASA in three test periods:

1) Up and away tests that refined the PCA control system parameters (Jan-Feb 1993)
2) Landing demonstration at EAFB (April 1993)
3) PCA flight envelope expansion and guest pilot evaluations (Aug-Oct 1993)

Scheduling of these test periods was affected by other programs using the NASA F-15 test vehicle. The time between test periods permitted flight data analysis and updates to the PCA software that further enhanced flight performance and research results.

Flights conducted by NASA during the up and away test period showed that the PCA system provided good pitch control, but roll control was slow. The PCA software gains were revised on-site until the landing approach performance indicated acceptable control for runway landings. Runway touchdown landings were made by NASA PCA program pilot Gordon Fullerton on 21 April 1993. This was the first successful landing of a high performance aircraft having no operating conventional flight control system.

In the third test period, PCA flights were conducted at high altitudes and airspeeds in the subsonic flight envelope. PCA mode engagements were made with the test aircraft in maneuver conditions of up to 90° bank and 20° dive. These tests showed the robustness of the PCA concept to large variations in flight envelope and maneuver conditions.

During the third test period, guest test pilots from USAF, Navy, NASA, and MDA were invited to flight evaluate the PCA design. Comments from these tests showed high ratings for the system and recommendations that the PCA concept be transitioned to transports and tactical aircraft as a backup to the flight control system.

2.0 DESIGN OF THE PCA SYSTEM

2.1 F-15 Simulation Model Development

Early in the design process, accurate simulation models of the aircraft aerodynamic, control system and propulsion characteristics were needed for both off-line and real-time development. The existing aerodynamic model needed to be revised to include the latest modeling data and then was judged to be adequate for both environments. The existing control system and propulsion system models also required modifications.

For the PCA flight demonstration, the F-15 control system was required to keep the control surfaces motionless until a pilot input was made. In the off-line simulation this requirement could be easily met, but the real-time simulation needed to be modified to represent the flight test configuration. Figures 4, 5 and 6 provide an overview of the longitudinal, lateral and directional CAS showing both the electrical and mechanical input paths. On the F-15 aircraft, disengaging the pitch, roll and yaw CAS, and setting the pitch and roll ratios to emergency effectively eliminates all feedback commands to the control surface servo-actuators and prevents the control surfaces from moving without pilot inputs. These features needed to be incorporated into the real-time simulation. Additionally, the engine inlet ramps can move during flight and produce a pitching moment. On the F-15 aircraft the engine inlets can be set to an emergency mode to keep them in a fixed position. This feature also was incorporated into the real-time simulation.

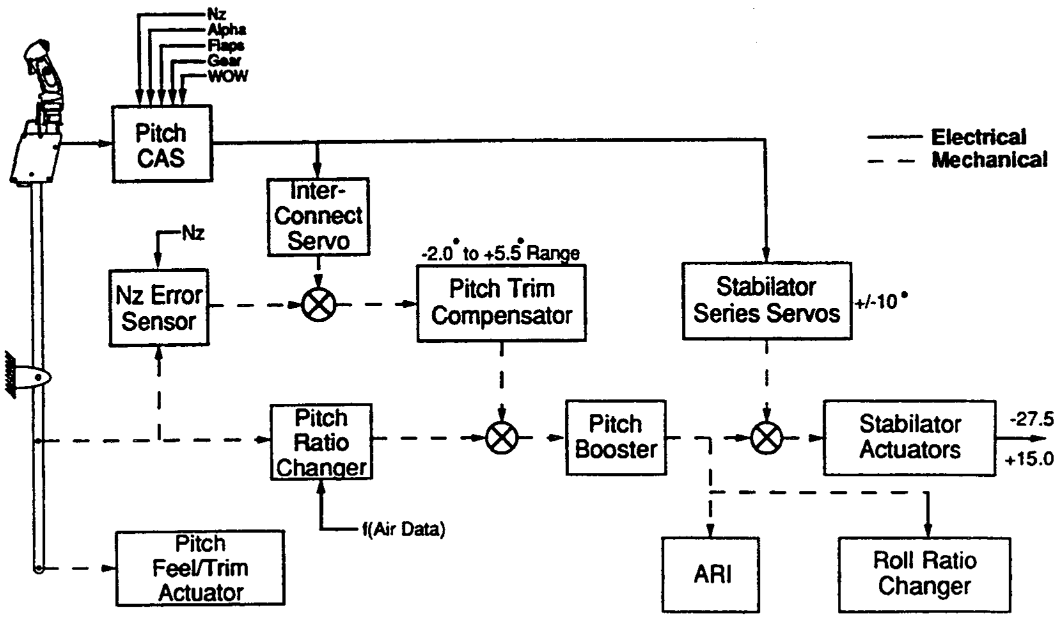


Figure 4. F-15 Longitudinal Control System Block Diagram

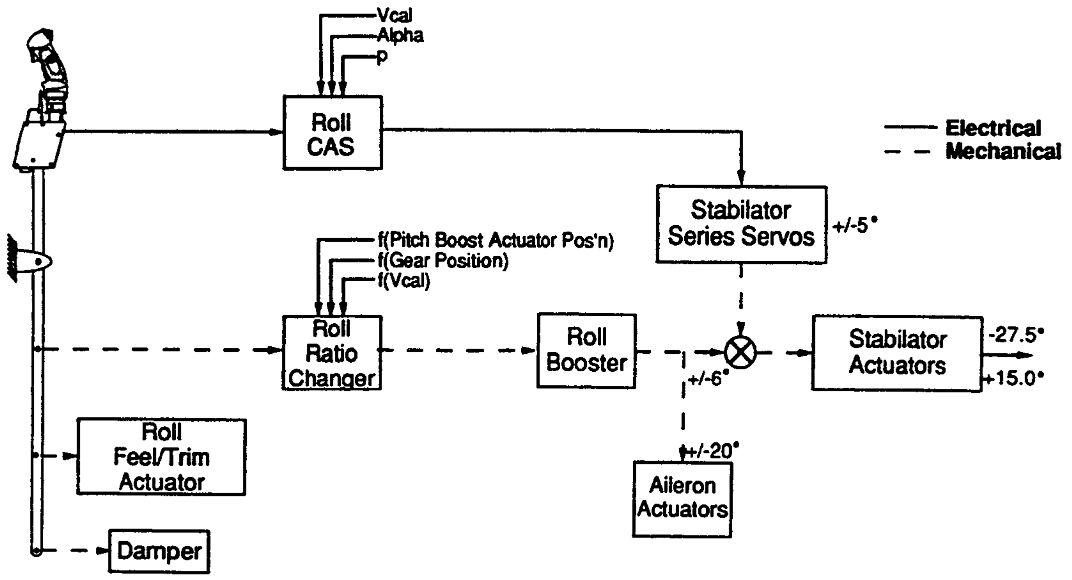


Figure 5. F-15 Lateral Control System Block Diagram

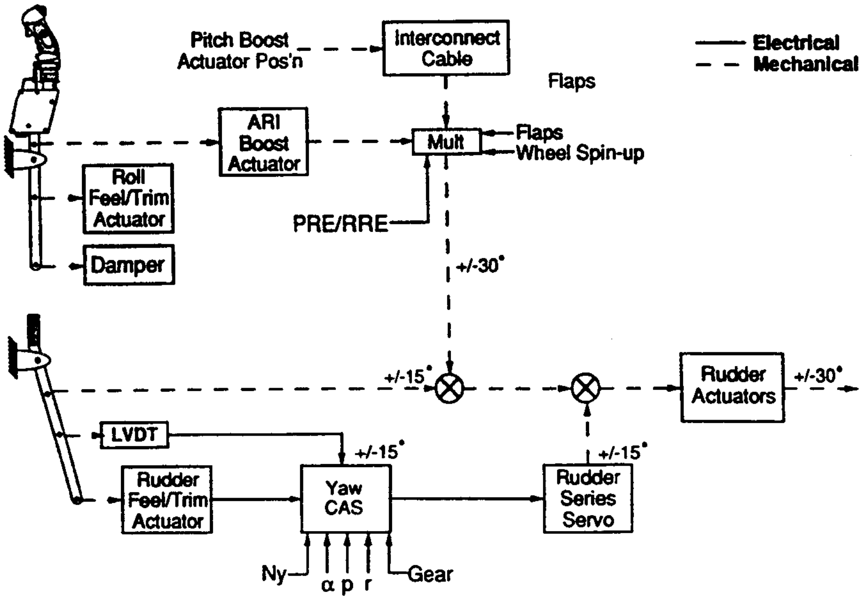


Figure 6. F-15 Directional Control System Block Diagram

Due to the unique nature of our propulsion-only control demonstration, none of the existing propulsion models could be used for development. Because we required accurate, independent left and right Pratt and Whitney 1128 engine models that could be run in a real-time simulation, a totally new simulation propulsion model was developed. The Pratt and Whitney State Of the Art Performance Program (SOAPP) for the 1128 engine was used to generate gross thrust and ram drag engine response time histories for a large set of PLA step inputs over the PCA design envelope. These time histories were then fit using a first order lag filter with a variable time constant. Engine rate limits were incorporated and the result was a non-linear engine model that could be run real-time and was accurate throughout the PCA design envelope (Figure 7).

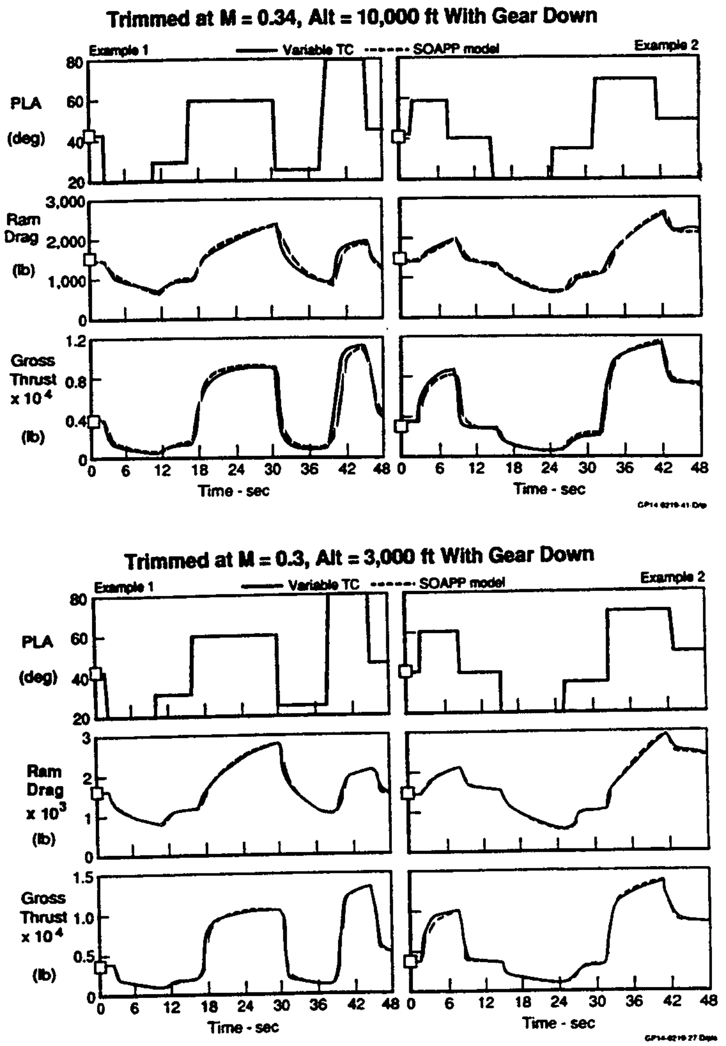


Figure 7. Comparison of Low Order, Non-Linear Engine Model to SOAPP Model

2.2 PCA Cockpit Controller Development

In order to demonstrate and test the propulsion-only control concept in the manned simulator, the type of PCA cockpit controller used by the pilot needed to be addressed. Four possibilities were considered: the center control stick, a side mounted force joystick, a side mounted displacement joystick, and a pair of side mounted thumbwheels. The center stick was eliminated because control column motion would require an automatic cancellation of the mechanical control system outputs to maintain fixed control surfaces during the flight test.

- Miniature Force Joystick
    - +/- 3.1 Lbs Full Scale
    - Spring-loaded to Center
    - 1 Inch Approximate Stick Handle Length
- Miniature Displacement Joystick
    - +/- 30 Degrees Full Scale
    - Spring-loaded to Center
    - 1.5 Inch Approximate Stick Handle Length
- Thumbwheels
    - +/- 175 Degrees Full Travel
    - Not Spring-loaded to Center

Figure 8. Candidate Cockpit Controllers

The joystick and thumbwheels were evaluated in a series of simulation tests. Two types of joysticks were tested: force sensing and displacement sensing. With both types of joystick, however, NASA test pilots found that precise control was very difficult. Precise inputs were much easier to achieve using the thumbwheels and they emerged from the tests as the clear favorite (Figure 9). The Thumbwheel Controller Panel (TCP) is shown in Figure 10 and consisted of two thumbwheels mounted just aft of the throttles in the left cockpit console. One thumbwheel controlled flight path angle and the other controlled bank angle. Each thumbwheel had a detent at zero so the pilot could easily reference his commands from the wings level, zero flight path condition.

Joysticks	Thumbwheels
Spring-Loaded to Center	Thumbwheels Remain Where Set
Small Size of Handle	Thumbwheels Used on Previous Flight Test Program
Small Range/Poor Resolution	Large Range/Good Resolution
Incremental Command Difficult to Attain	Incremental Commands Easily Attained
Virtually No Pitch/Roll Isolation	Separate Thumbwheels for Pitch and Roll
Ability to Hold Command During Flight Questionable	Pilot Not Required to Hold Thumbwheel to Maintain Command so Aircraft Motion Does Not Affect Command
	Similar Controls Used in Transport Aircraft

Figure 9. Joystick - Thumbwheel Comparison

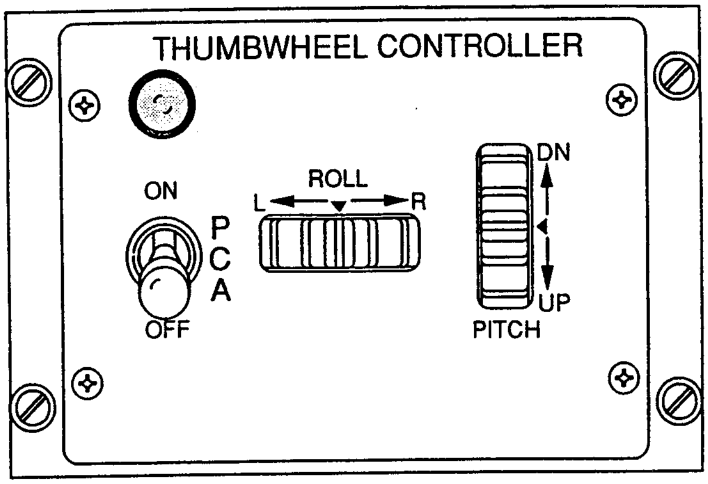


Figure 10. Thumbwheel Controller Panel

2.3 PCA Control Law Development

Several trade studies were performed during the development of the PCA control laws. Flight data had showed that it was very difficult to damp phugoid oscillations using manual throttle inputs, and the feasibility study examined the trade off between phugoid damping and frequency. Manned flight simulation tests were performed and it was found that the greatest improvement was achieved by maximizing the phugoid damping. Other trade studies addressed which aircraft state would be commanded: flight path angle vs. flight path angle rate for the longitudinal command, and bank angle vs. roll rate for the lateral command. Flight simulation tests with NASA pilots were used and the results showed that flight path and bank angle commands were more desirable. These results are shown in Figure 11. The feasibility study also examined the selection of longitudinal feedbacks. Flight path angle and flight path angle rate were chosen for three reasons: (1) the HUD display uses the same reference (termed Flight Path Marker or Velocity Vector); (2) these signals could provide augmentation for both phugoid damping and frequency; (3) most current fighters and transports have these parameters available in the flight control computer. A summary of these results is shown in Figure 12.

Variations Tested	Parameter Yielding Improvement	Cooper Harper Rating Improvement
Flight Path Angle vs Flight Path Angle Rate Stick Command	Flight Path Angle	3
Low vs High Phugoid Damping	High Phugoid Damping	3
Low vs High Phugoid Frequency	Neither	-
Bank Angle vs Roll Rate Stick Command	Bank Angle	1

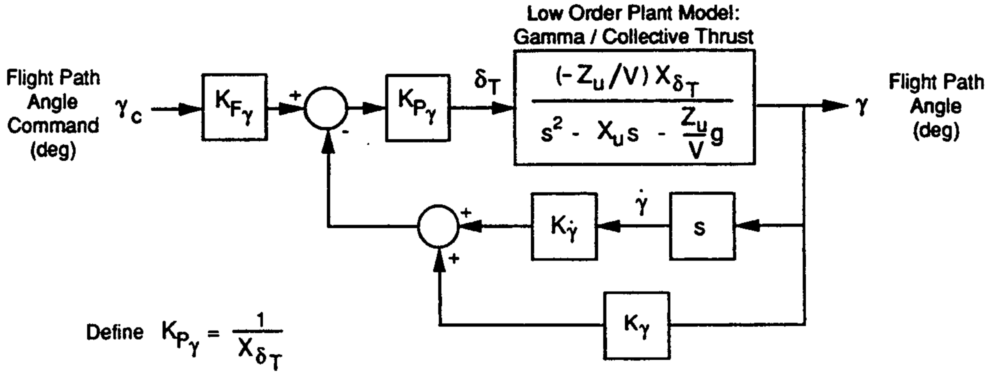
Figure 11. Results of 4 Trade Studies

Phugoid Dynamics

Feedback (to Thrust)	Low Speed Damping	Low Speed Frequency	High Speed Damping	High Speed Frequency
Flight Path Angle	—	Good	—	Fair - Large Gain Required
Flight Path Angle Rate	Good	—	Fair - Large Gain Required	—
Pitch Rate	Good - Wings Level	—	Fair - Large Gain Required	—
Airspeed	Good - Need Reference	—	Good - Need Reference	—

Figure 12. Results of Longitudinal Feedback Selection Trade Study

Once the requirements were defined, design of the control law gains could begin. Using a linear, low order model of the airframe (Figure 13), the longitudinal gains were selected to provide phugoid damping of 0.7 and frequency of 0.18 radians/second at the design point of 188 knots at 3000 feet Mean Sea Level (MSL) (Figure 14). After incorporating the control law into the linear off-line simulation, the final values of damping and frequency were 0.57 and 0.14 respectively. For the lateral control law, stability axis yaw rate was the feedback incorporated to dampen the dutch roll mode and provide a turn rate reference (Figure 15). The gain was selected to maintain a flat frequency response for as high a frequency as possible (Figure 16). Additionally, a lead-lag filter was developed using an engine time constant of 1.3 seconds. Schedules were developed to automatically adjust the control law gains for weight and airspeed variations (Figures 17 and 18).



Define $K_{P_\gamma} = \frac{1}{X_{\delta_T}}$

Actual Closed Loop Transfer Function

$$\frac{\gamma}{\gamma_c} = K_{F_\gamma} \frac{G}{1+GH} = \frac{K_{F_\gamma} \ (-Z_u/V)}{s^2 + (-X_u - \frac{Z_u}{V} K_{\dot\gamma}) s + (-\frac{Z_u}{V} g - \frac{Z_u}{V} K_\gamma)}$$

Figure 13. Linear, Low Order Longitudinal Model

Actual Closed Loop Transfer Function

$$\frac{\gamma}{\gamma_c} = \frac{K_{F_\gamma} \ (-Z_u/V)}{s^2 + (-X_u - \frac{Z_u}{V} K_{\dot\gamma}) s + (-\frac{Z_u}{V} g - \frac{Z_u}{V} K_\gamma)}$$

Desired Closed Loop Transfer Function

$$\frac{\gamma}{\gamma_c} = \frac{W^2}{s^2 + 2ZW + W^2}$$

Equate Actual and Desired Denominator

$$s^1 : \quad (X_u + \frac{Z_u}{V} K_{\dot\gamma}) = -2ZW \quad \Rightarrow \quad K_{\dot\gamma} = -(2ZW + X_u)\frac{V}{Z_u}$$

$$s^0 : \quad (\frac{Z_u}{V} g + \frac{Z_u}{V} K_\gamma) = -W^2 \quad \Rightarrow \quad K_\gamma = -(W^2 + \frac{Z_u}{V} g)\frac{V}{Z_u} = -(W^2 \frac{V}{Z_u} + g)$$

Equate Actual and Desired Numerator

$$\frac{Z_u}{V} K_{F_\gamma} = -W^2 \quad \Rightarrow \quad K_{F_\gamma} = -W^2 \frac{V}{Z_u}$$

Data At 0.3 Mach / 3000 feet

$W = 0.18$ rad/sec
$Z = 0.7$

$V = 331.5$ ft/sec
$Z_u = -0.19$ 1/sec

$X_u = -0.029$ 1/sec
$X_{\delta_T} = 0.36$ ft/sec^2/%mil

Gain Computations

$K_\gamma = -(0.0324 * 331.5 / -0.19 + 32.174) / 57.3 = 0.425$

$K_{F_\gamma} = -0.0324 * 331.5 / -0.19 / 57.3 = 0.987$

$K_{\dot\gamma} = -(0.252 - 0.029) * 331.5 / -0.19 / 57.3 = 6.79$

$K_{P_\gamma} = 1 / 0.36 = 2.78$

Figure 14. Longitudinal Gain Determination

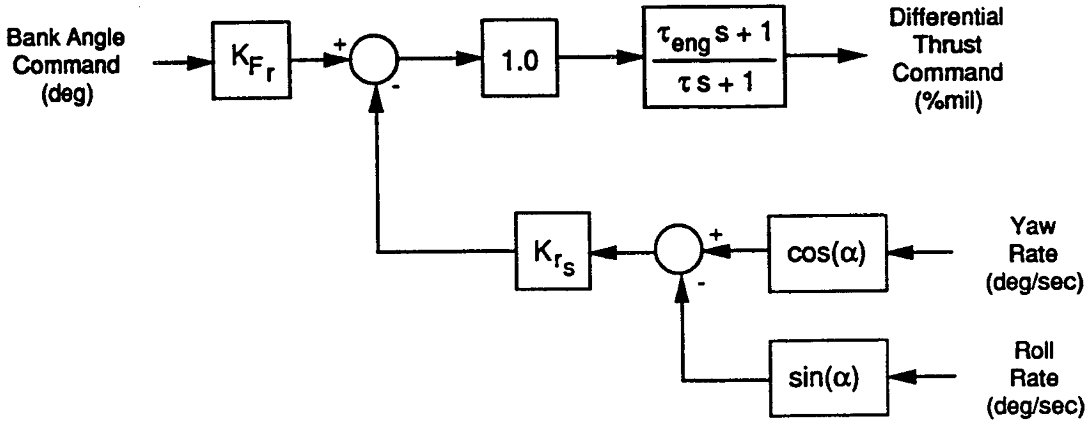


Figure 15. Lateral Control Law Block Diagram

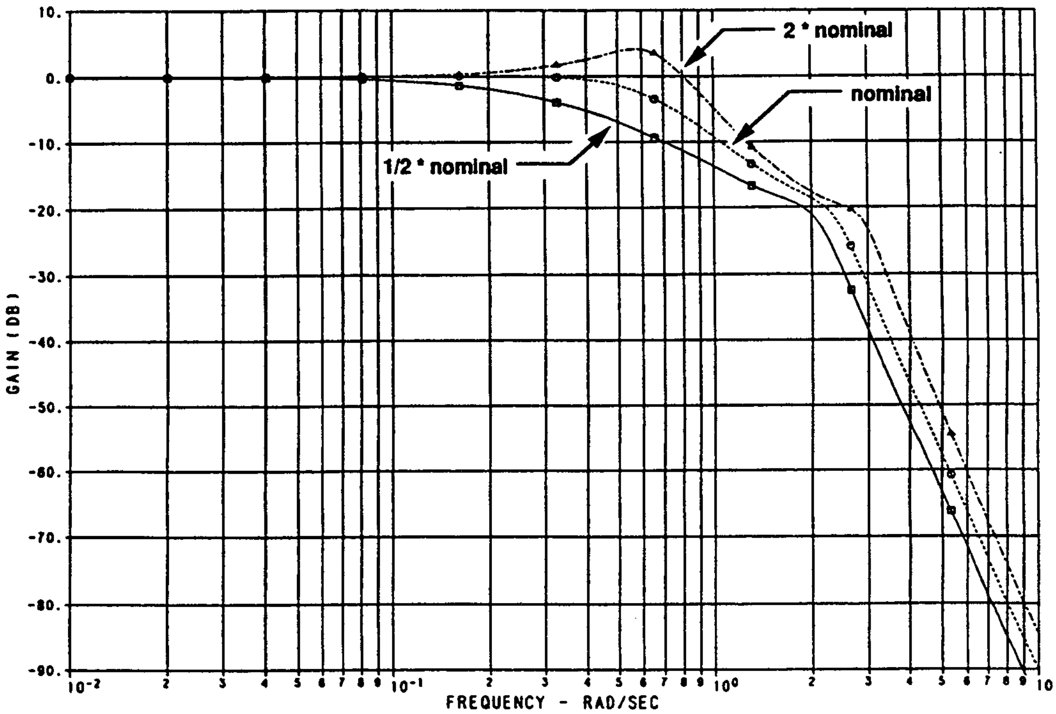
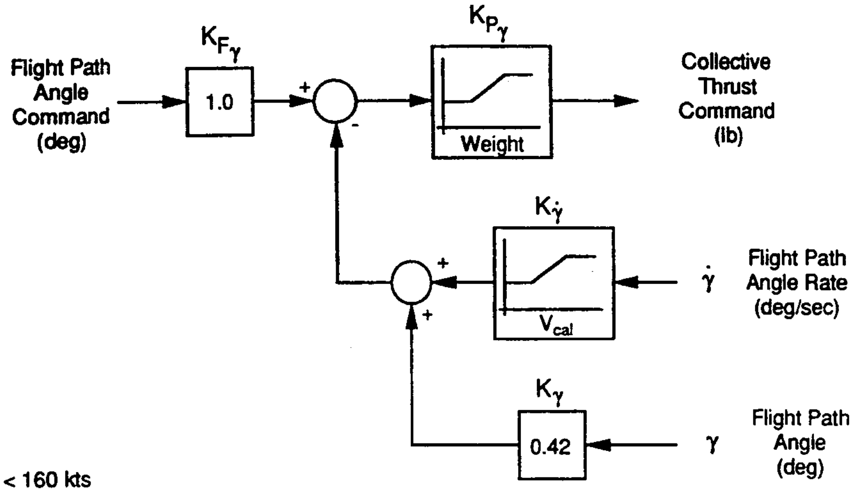


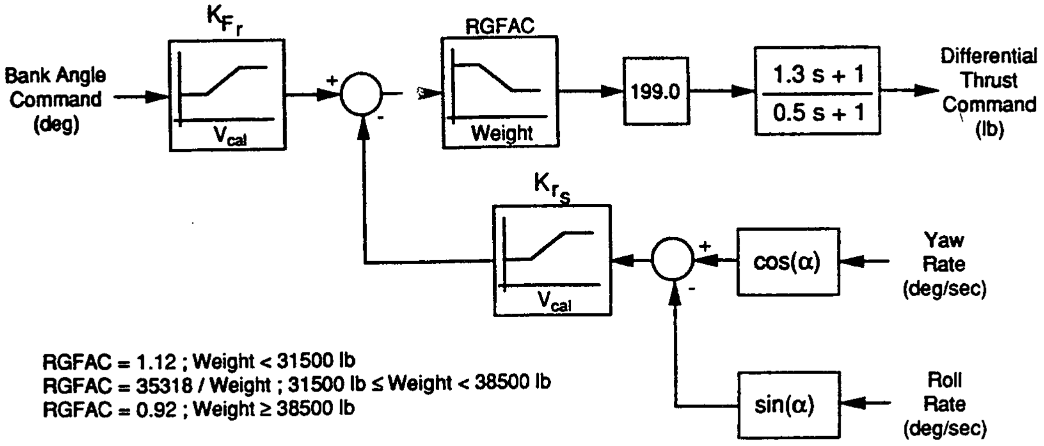
Figure 16. Stability Axis Yaw Rate Feedback Gain Determination



$$K_{\dot\gamma}\left\}\begin{array}{l} = 5.78 \text{ ; VCAL} < 160 \text{ kts} \\ = 0.0355 * \text{VCAL} + 0.1 \text{ ; } 160 \text{ kts} \leq \text{VCAL} < 200 \text{ kts} \\ = 7.2 \text{ ; VCAL} \geq 200 \text{ kts} \end{array}\right.$$

$$K_{P_\gamma}\left\}\begin{array}{l} = 493.6 \text{ ; Weight} < 31500 \text{ lb} \\ = 553.4 * \text{Weight} / 35318 \text{ ; } 31500 \text{ lb} \leq \text{Weight} < 38500 \text{ lb} \\ = 603.2 \text{ ; Weight} \geq 38500 \text{ lb} \end{array}\right.$$

Figure 17. Longitudinal Control Law Gain Scheduling



RGFAC = 1.12 ; Weight < 31500 lb
RGFAC = 35318 / Weight ; 31500 lb ≤ Weight < 38500 lb
RGFAC = 0.92 ; Weight ≥ 38500 lb

$$K_{F_r} \left\} \begin{array}{l} = 0.36 * \text{RGFAC} ; \text{VCAL} < 160 \text{ kts} \\ = (0.00632 * \text{VCAL} - 0.647) * \text{RGFAC} ; \ 160 \text{ kts} \le \text{VCAL} < 200 \text{ kts} \\ = 0.62 * \text{RGFAC} ; \text{VCAL} \ge 200 \text{ kts} \end{array} \right.$$

$$K_{r_s} \left\} \begin{array}{l} = 2.68 * \text{RGFAC} ; \text{VCAL} < 160 \text{ kts} \\ = (0.0789 * \text{VCAL} - 9.942) * \text{RGFAC} ; \ 160 \text{ kts} \le \text{VCAL} < 200 \text{ kts} \\ = 5.84 * \text{RGFAC} ; \text{VCAL} \ge 200 \text{ kts} \end{array} \right.$$

Figure 18. Lateral Control Law Gain Scheduling

This control performed well in the F-15 linear simulation. In order to evaluate the control in the more complete non-linear simulation, a thrust to PLA conversion function was needed. This was due to the fact that the control law was designed to generate thrust commands, but the engines were designed to accept PLA commands. This function was developed using design point data (188 knots at 3000 feet) from the engine model and is shown in Figure 19. The two curves are not completely coincident because at low power settings with the gear extended, the nozzle opens to reduce thrust. A block diagram of the function integrated with the control law is shown in Figure 20. The resulting control law performance in the non-linear simulation closely matched the linear results (Figure 21) and was ready to be tested with NASA pilots in the manned simulator.

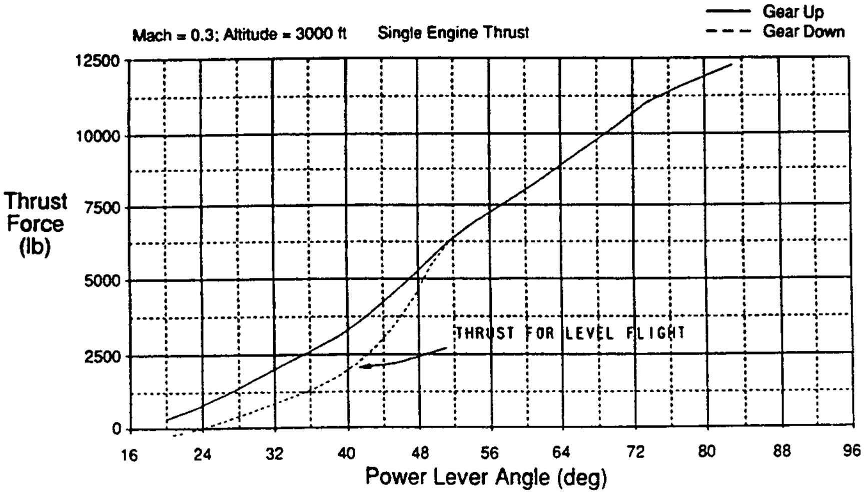


Figure 19. Low Order Engine Model at Design Point

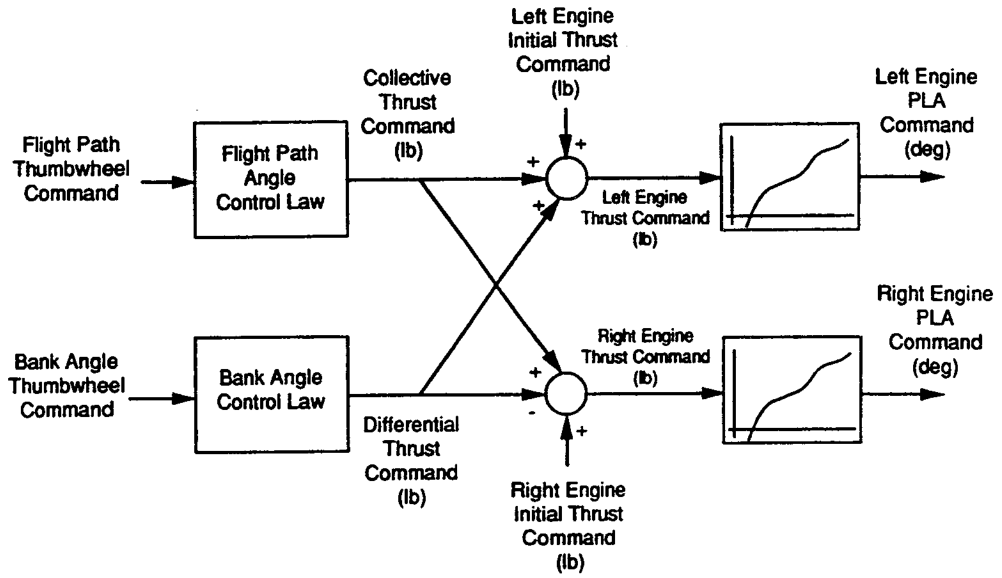


Figure 20. FN - PLA Function Integrated with PCA Control Laws

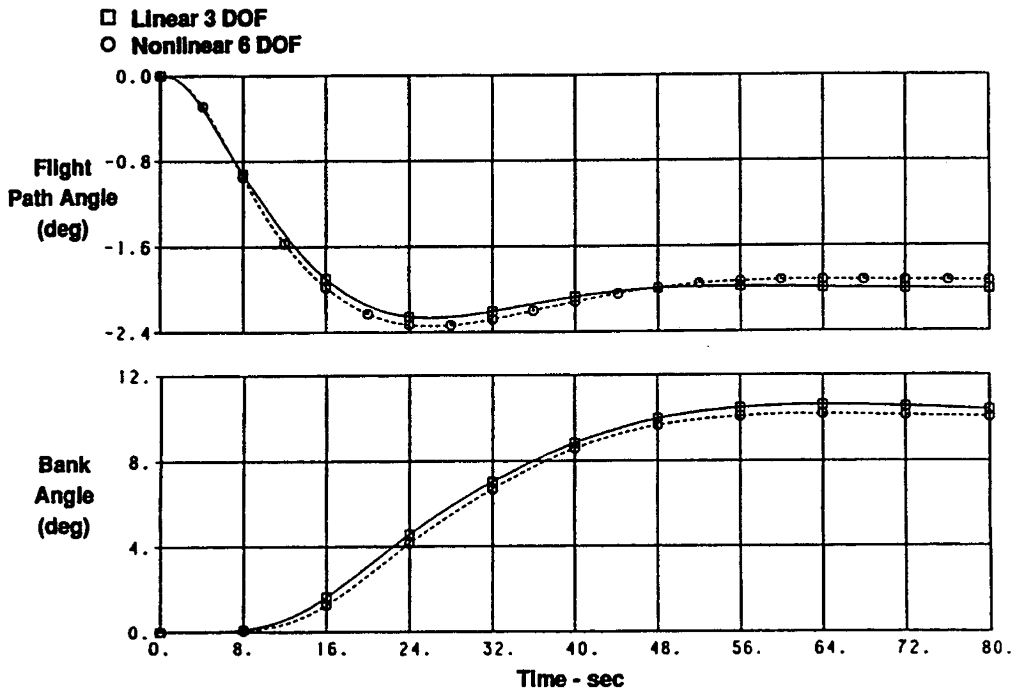


Figure 21. Linear - Non-Linear Simulation Comparison
-2 Deg Flight Path Command; 10 Deg Bank Command

Using the manned simulator, a study was conducted to determine how sensitive PCA performance was to a number of parameter variations. The effects of fifteen parameters were examined during tests with two NASA pilots. The result was that performance was not significantly degraded for any of the parameter variations except one: vertical velocity error. Because the error that was introduced was very large (pilots had not seen errors that large in flight), the system was judged to be sufficiently robust to the parameter variations.

The simulator tests also revealed a need for a PCA trim control law. In the event that the system is engaged while the aircraft is not in trim, the PCA trim control law will eliminate any biases between the commanded flight path and bank angles and the actual aircraft states. These biases could be removed by forward path integrators, but the feasibility study showed that larger overshoot and longer settling time could result if integrators were incorporated into the PCA control law. In the absence of some means to eliminate these biases, the aircraft would have to be trimmed and have the command thumbwheels at the zero detent position when the system was coupled in order for level flight path and bank angles to result from zero thumbwheel inputs.

A two step trim mode was developed for the PCA control law. The trim mode would execute when the PCA system was initially coupled and then turn itself off when the aircraft was sufficiently trimmed. For this mode, a proportional plus integral path was added to the baseline longitudinal control law and an integral path was added to the lateral control law (Figure 22). These trim paths were activated when the system was coupled and deactivated when the flight path error, flight path error rate, bank angle error and bank angle error rate were within specified limits (Figure 23). Additionally, the trim paths could be reactivated by the pilot at any time if he felt that biases were present in the system, or he could deactivate them if he felt that the system biases were acceptable. This manual activation of the trim logic could be achieved using the engine select switch on the PSC Control Panel shown in Figure 24.

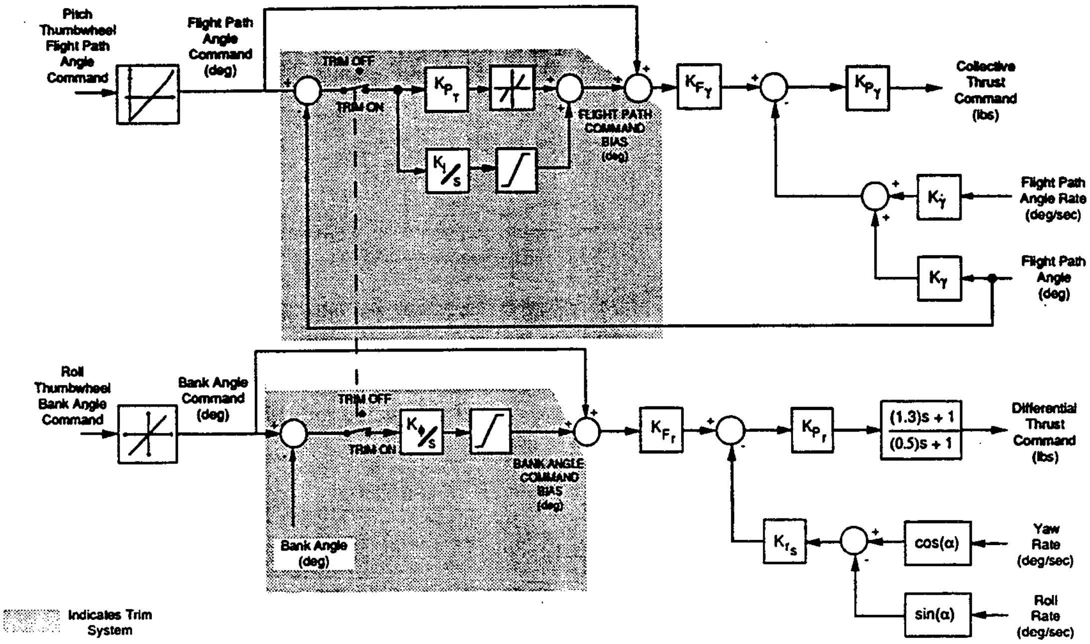


Figure 22. PCA Control Law Block Diagram with Trim

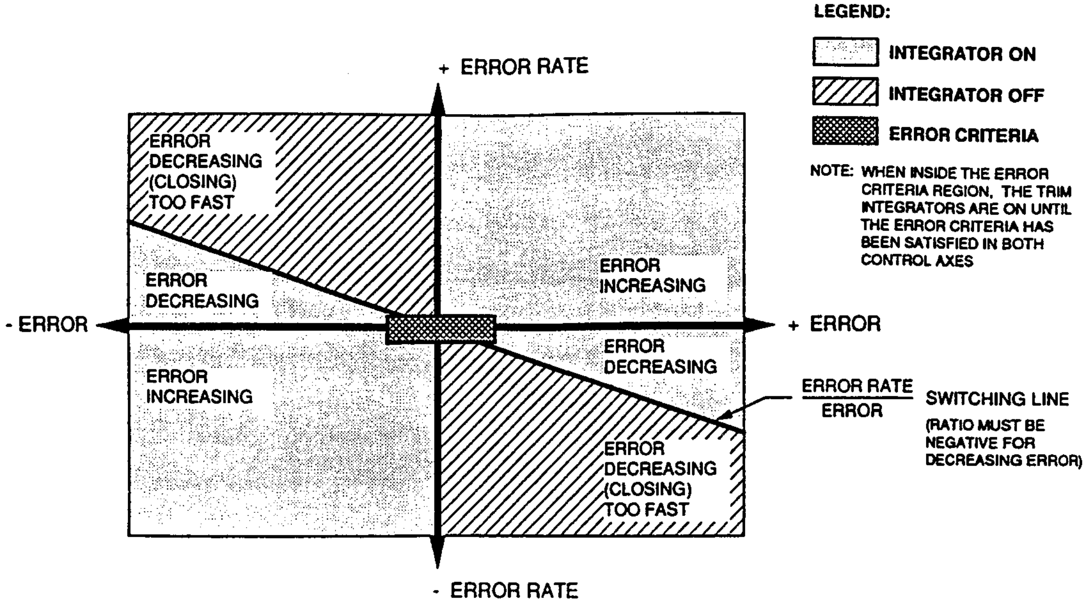
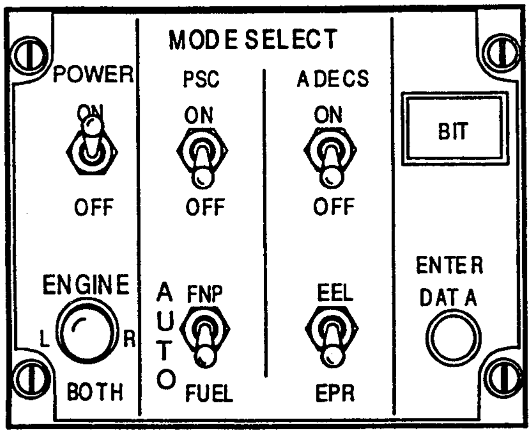


Figure 23. PCA Trim Switching Criteria



L : Trim Mode OFF
BOTH : Trim Mode AUTO
R : Trim Mode ON

Figure 24. PSC Control Panel

During the PCA control law development, NASA was performing F-15 manual throttle control flight experiments. By measuring the flight path response for PLA changes, these experiments revealed a transient phase reversal in the pitch axis. When the pilot would apply a negative or nose down throttle step input, the aircraft would initially pitch up before pitching down. This phase reversal was more pronounced at weights below approximately 32500 pounds and airspeeds greater than approximately 160 knots. It was not modeled in current F-15 simulations, but further investigations indicated that the reversal was due to the engine inlet airflow. Such an effect had been identified in a McDonnell Aircraft report prepared for the Air Force titled "Assessment of Installed Inlet Forces and Inlet/Airframe Interactions; Final Report - July 1976". Working closely with NASA, a pitching moment increment as a function of PLA was calculated which resulted in a satisfactory comparison between the six-degrees-of-freedom simulation and the flight data (Figures 25 and 26). The existence of the phase reversal caused a re-assessment of the control law. A velocity feedback path was added to improve PCA performance at the higher airspeed conditions where the inlet airflow effect was important (Figure 27). Characteristics such as the reversal due to inlet airflow have relatively minor effect when the nominal flight control system is operating, but have a more pronounced impact during propulsion-only control.

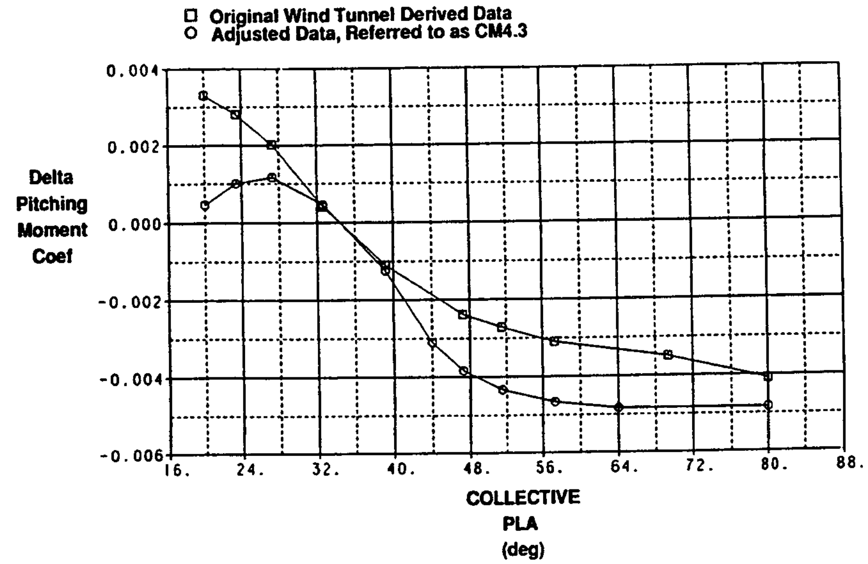


Figure 25. Inlet Airflow Pitching Moment Coefficient Increment

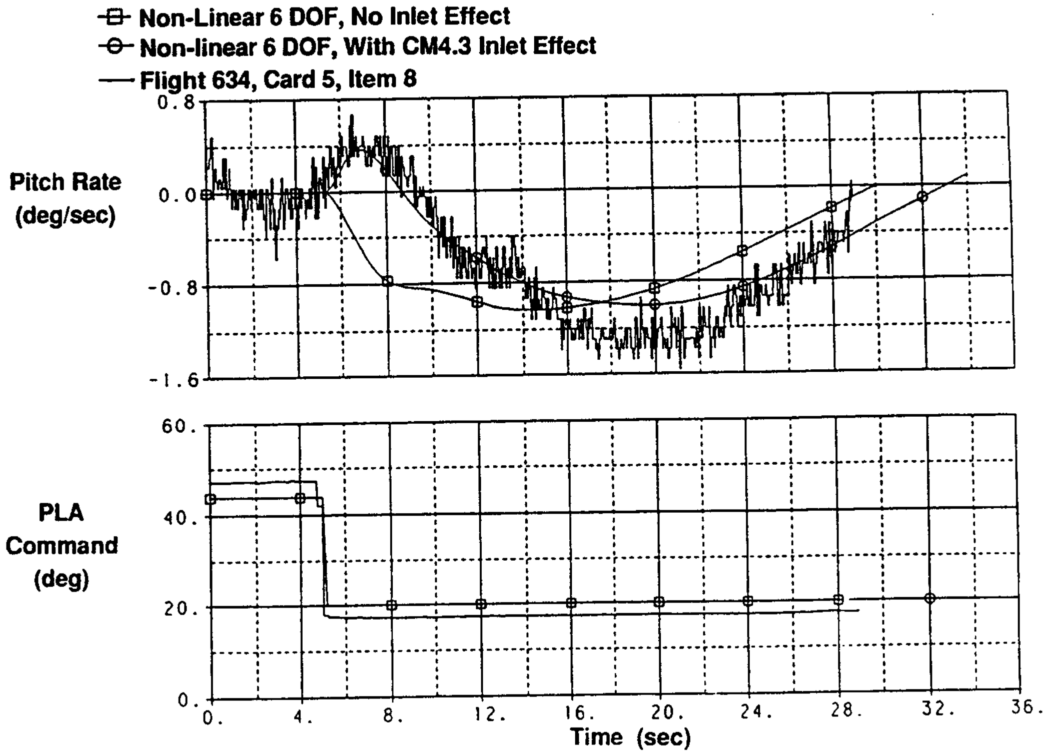


Figure 26. Flight Test - Simulation Comparison

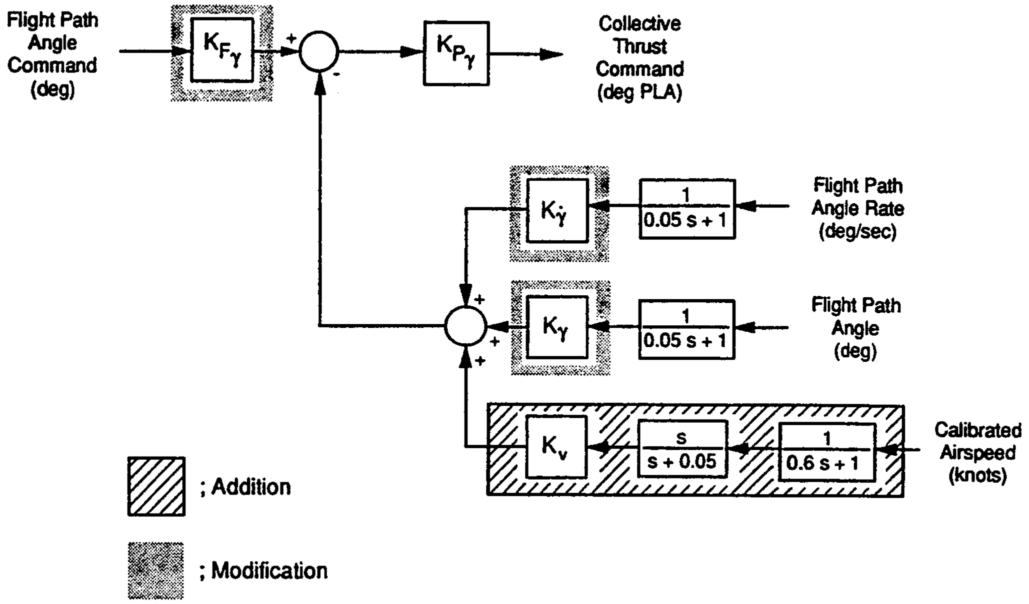


Figure 27. Control Law Modification for Inlet Airflow Effect

One issue highlighted by the inlet airflow investigation was the difficulty involved in making comparisons between simulation and flight data. The difficulty arises from differences in initial aircraft states and in commanded maneuver pattern and magnitude. A special flight test step response mode was developed and added to the PCA control laws to address the task of reducing the variation of pilot commands. The step response mode provided the means to make precise, repeatable inputs during flight testing. This mode allowed the pilot to select a PLA input command for each engine from values stored in the software and apply those commands when he desired. When activated, the computer would apply the commands to the engines in a consistent manner and with exactly the magnitude selected.

2.4 PCA Cockpit Control and Display Development

The pilot was able to interact with the PCA demonstration system through several cockpit components. Figure 28 shows the layout of the test F-15 cockpit. The system was armed by setting the appropriate switches on the Computer Control, PSC Control and Thumbwheel Controller Panels. When the system was armed and uncoupled, the Navigation Control Indicator (NCI) panel could be used by the pilot to change various system parameters. Coupling was accomplished by depressing the IFF button on the left throttle quadrant. The pilot could uncouple the system in a number of ways: depressing the couple button a second time; changing a switch position on the Computer Control, PSC Control or Thumbwheel Controller Panels; moving the control stick, rudder pedals or throttles.

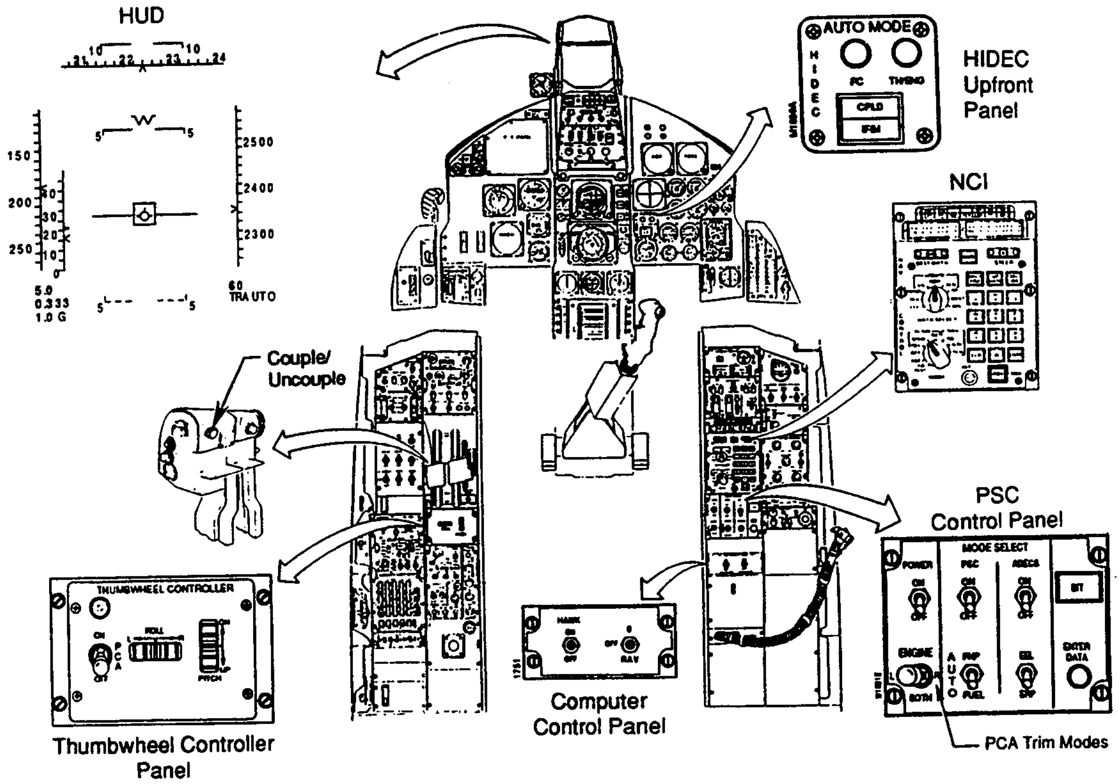


Figure 28. F-15 Crew Station

The PCA demonstration provides two displays to the pilot, one on the HIDEC upfront panel and the other on the HUD. The white CPLD light on the HIDEC upfront panel illuminates when the PCA system is coupled and the red IFIM light illuminates if the In-Flight Integrity Management software detects a system failure. The green TH/ENG light is illuminated when the PCA switch is on. The PCA command box is drawn on the HUD while the system is coupled and will flash while the trim control laws are executing. It can be seen centered on the velocity vector in Figure 29. In the lower right corner of the HUD a mnemonic is displayed which indicates the position of the PCA trim switch: TROFF when the PCA trim is off; TRAUTO when the PCA trim is in the automatic mode; TRON when the PCA trim is on. A radar altimeter reading in feet above ground is displayed above the trim mnemonic.

The PCA command box on the HUD display was developed to give the pilot a positive indication of his longitudinal command. As the pilot moves the pitch thumbwheel, the box moves vertically on the HUD. The pilot can effectively place the box for a particular glide slope and observe the aircraft responding to the command. The velocity vector will move toward the box, and when the commanded flight path angle is equal to the actual flight path angle, the velocity vector will be displayed inside the box. Additionally, when the command box flashes the pilot knows that the PCA trim control laws are executing. This is important because the system will not respond as well to pilot inputs while the trim integrators are working to eliminate system biases.

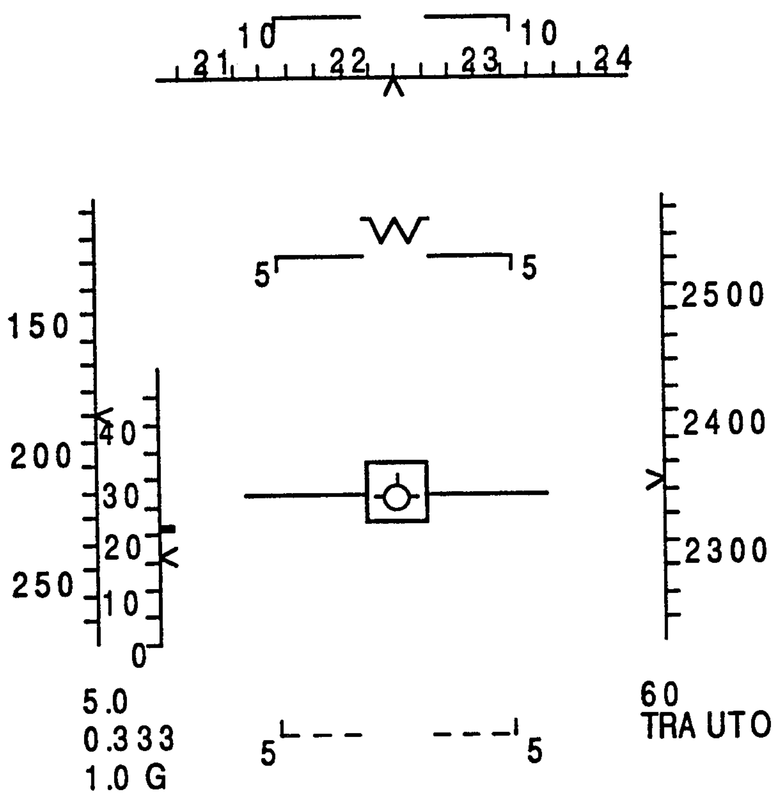


Figure 29. PCA HUD Display

2.5 Flight Simulator PCA Development

The MDA, manned, real-time flight simulator in St. Louis was used extensively during development of the PCA system. The simulator was an important tool in executing many of the PCA design trade studies. Because propulsion-only control was a new concept and had never been developed before, there were no guidelines or specifications that could be used as design references. Engineering judgment was used to develop initial values for system gains and operating characteristics using off-line simulations. The results of the off-line design had to be verified by manned, real-time simulation. This evaluation was needed for each PCA control law tradeoff, such as the decision to use either pitch rate or flight path angle rate feedback, and also for the net result of combining all design decisions into a unified system.

These simulator evaluations were critical to the success of the program. Because PCA was a new concept, the qualitative data obtained from piloted simulations became very important in determining the initial PCA control law structure. During landing approaches (the primary PCA task) the pilot interface provided information that could not be adequately assessed in an off-line simulation. NASA pilots participated in several simulator evaluations and provided important design feedback on the control response, displays and flight test safety limits.

3.0 PCA SOFTWARE DEVELOPMENT

The PCA software used on the F-15 testbed was contained in three processors: the flight computer (Vehicle Management System Computer or VMSC), the Central Computer (CC) and the auxiliary (Hawk) computer. A block diagram of the architecture is shown in Figure 30. Software development proceeded according to the following guidelines: minimize changes to the VMSC, minimize changes to the CC, make no changes to the Digital Electronic Engine Controllers (DEECs), fully utilize the Hawk computer and maximize flexibility of the PCA software overall. With these requirements in mind, the VMSC was used to read the PCA thumbwheel commands and a thumbwheel validity bit and pass that data on to the Hawk. The CC contained the PCA In-Flight Integrity Management (IFIM) logic, controlled the bus traffic among the three computers and passed the PCA throttle commands to the DEECs. The Hawk contained the PCA control laws and associated flight test software.

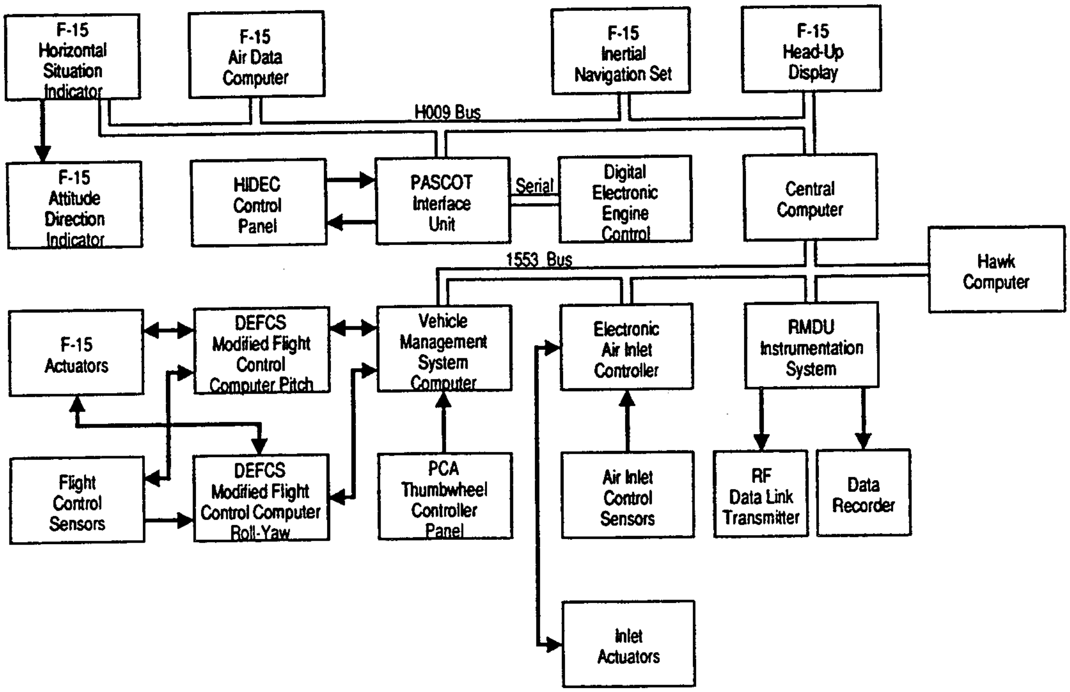
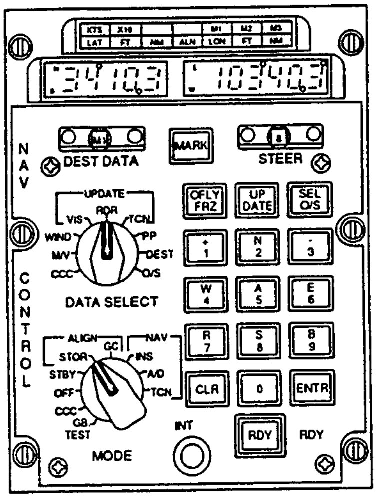


Figure 30. PCA Hardware Architecture

The IFIM logic in the CC was used to monitor important aircraft subsystems and uncouple the PCA system in the event of a subsystem failure. Validity discretes were received by the CC from the INS, ADC and the thumbwheel controller panel. A failure in any of these bits would cause an IFIM failure to be declared and a PCA uncouple. The CC also monitored wrap words from the VMSC, Hawk and DEECs. A wrap word is a communication handshaking signal used to indicate the status of the system processors and communication links. A wrap word failure would result in an IFIM failure declaration and a PCA uncouple. Finally, the CC monitored five status bits from each DEEC. The bits corresponded to the DEEC detecting: a UART failure, a wrap word failure, an auto throttle failure, an engine stall, and a switch from primary to secondary engine control. A failure in any of the five status bits would result in an IFIM failure declaration and PCA uncouple.

Functionally, the PCA software contained in the Hawk can be broken down into four groups: ground operation, monitor NCI inputs, perform safety checks and execute control laws. The ground operation logic was used to evaluate the PCA system during ground testing and to allow changes to be made to the software on-site at NASA. Each of the other modules will be discussed below.

The Navigation Control Indicator panel, shown in Figure 31, was used extensively throughout the PCA program to modify system parameters and change PCA operating modes. Tables of values were stored for virtually every system parameter, and by entering a pre-defined code into the longitude, latitude and altitude windows of the NCI, the pilot had the capability to modify the parameters as desired. Figure 32 shows many of the parameters that could be modified. Thus, for the PCA flight test demonstration the normal navigation function of the NCI panel was changed to provide the necessary means to modify the system during flight experiments. The Hawk software continuously monitored the NCI and set internal parameters according to the pilot inputs.



DATA SELECT = DEST
DEST DATA = 8

N12345
ENTR
E123456
ENTR
A+12345
ENTR

ENTER DATA Button
On PSC Control Panel

Figure 31. Navigation Control Indicator Panel

In addition to the IFIM logic in the Central Computer, the Hawk software also performed safety monitoring. These monitors could be divided into three categories: dual signal, PCA flight maneuver envelope and subsystem fault. The control laws used five aircraft signals that were dual redundant on the F-15: angle-of-attack, roll rate, yaw rate, pitch thumbwheel command and roll thumbwheel command. Both channels of these signals were monitored and any difference greater than its miscompare threshold would result in a PCA uncouple. The PCA envelope was defined in terms of the Weight-On-Wheels

(WOW) switch and six aircraft states: airspeed, roll rate, yaw rate, pitch rate, bank angle and flight path angle. These parameters were monitored and if the WOW switch was set or if any state exceeded its envelope threshold a PCA uncouple would result. Additionally, the control stick, rudder pedals and throttles were monitored and if movement of any beyond its threshold was detected PCA would uncouple. Subsystem fault monitoring was performed in the Hawk similar to the IFIM performed in the CC. The Hawk monitored wrap-around words from the CC and DEECs, and monitored the same five status bits from each DEEC that the CC monitored. A failure detected by the Hawk would result in a PCA uncouple.

Signal Monitor Limits
Signal Channel(s)
Noise Filter Time Constants
Input Biases
Input Scale Factors
Envelope Limits
Flight Path Rate Calculation
Weight Input

Fuel Flow Source
Gain Schedule Input Source
Thumbwheel Scale Factors
Trim Control Law Modes
Control Law Gains
Wash-out Filter Time Constants
Control Law Modes
PLA Step Biases

Figure 32. NCI Selectable Parameters

The control law execution encompassed input signal conditioning and pilot display as well as engine command calculation. The flight path angle and flight path angle rate feedbacks were not explicitly available on the F-15 testbed and needed to be calculated from INS data. The weight of the aircraft was an input into some of the gain schedules and needed to be calculated from the sensed fuel flow. Before the five dual redundant signals needed by the control laws could be used, the average of each was calculated. Additionally, each aircraft signal used by the PCA system was processed through a first order lag filter to attenuate noise. The Hawk was also responsible for calculating the position of the command box on the HUD.

Verification of the PCA software was performed in two steps: open loop laboratory bench testing and closed loop manned simulator testing. In both cases the software was installed and evaluated in the actual flight hardware. The laboratory testing checked out every operation mode, communication interface, safety feature and display. Each input was excited and outputs were checked against design predictions. The manned simulator testing verified the in-flight operation modes, safety features and displays using a high fidelity, real-time aircraft model. The manned simulator also provided the final pilot assessment of PCA performance before actual flight testing. All laboratory and simulator tests were concluded successfully and the system was ready to be installed in the aircraft.

4.0 INSTALLATION AND VERIFICATION

Installing the PCA system in the test aircraft consisted of loading three computers with their required software and adding the Thumbwheel Controller Panel (TCP) hardware component. The TCP was installed just aft of the throttles in the left cockpit console. Power was supplied through the flap circuit breaker and the wiring was routed to the VMSC along an existing bundle. The software for the VMSC and the Hawk was transported to the NASA Dryden Flight Research Facility (NASA-Dryden) on magnetic media and loaded into the boxes on-site without removing them from the airplane. The software for the Central Computer was transported to NASA-Dryden on magnetic media, loaded into the CC at the McDonnell Douglas facility nearby and then the unit was re-installed into the airplane.

Ground testing at NASA-Dryden consisted of a series of five tests: Instrumentation, Functional, Radiation, Electromagnetic Interference (EMI) and Combined Systems Test. The Instrumentation Test verified that the aircraft telemetry system and the PCA system were working together correctly. The Functional Test verified aircraft communication interfaces and displays as well as PCA operation and safety features. The Radiation Test verified that the real-time display of the telemetry data in the control room was functioning as designed. The EMI test verified that the PCA hardware was neither a source nor a victim of EMI. The Combined Systems Test verified that the PCA, instrumentation, control room and aircraft systems were all functioning together correctly. All ground tests were successfully passed and the system was judged ready for flight testing.

5.0 PCA FLIGHT TESTING

The primary goal of PCA flight testing was to demonstrate the feasibility of propulsion-only control as an emergency backup flight control system. This included satisfactory up and away control as well as the ability to land safely. Flight testing of the PCA system began in January 1993 with additional test periods commencing in April 1993 and August 1993. PCA flight testing was concluded in October 1993.

5.1 Up and Away Tests

The first series of PCA flight tests concluded in early February after a total of nine flights and focused on pilot familiarity, model verification and control system adjustment. Due to the effort invested in early flight simulator evaluations, pilots found the thumbwheels and displays to be very easy to use and pilot familiarity was quickly achieved. Model verification included using the step response mode to generate PLA step inputs. These tests revealed that the simulation model was an adequate representation of the aircraft. Additionally, these tests confirmed the behavior of the inlet airflow effect, and led to the decision to change the design point airspeed. The resulting aircraft configuration and test condition was: flaps down, gear down, 150 knots and 3000 feet MSL. With the successful completion of these tests, the focus shifted to control law adjustment.

Assessment of the control laws began with up and away flight and proceeded to landing approach evaluations. The longitudinal control laws and the trim control laws were determined to be satisfactory as originally designed. The lateral control laws, however, seemed sluggish to the pilot and attention focused on improving the roll performance. The ability to change PCA system gains, limits, scale factors and filter time constants was used extensively and provided a large payoff for the effort invested in developing that capability. The lateral control law was changed to include bank angle feedback, higher loop gain, lower stability axis yaw rate feedback gain, increased yaw rate filtering and increased bank angle command scaling. These changes resulted in satisfactory lateral performance. An example of altitude and heading from an up and away flight profile is shown in Figure 33. The profile included both longitudinal and lateral command changes and the performance was satisfactory. On the final flight of this series, a propulsion-only controlled approach was demonstrated from altitude down to 9 feet Above Ground Level (AGL).

5.2 Landing Demonstration

The second series of PCA flight tests occurred in mid-April and consisted of three flights. The first of these flights was used primarily for pilot re-familiarization, and the remainder focused on achieving a safe landing using the PCA system. Because these tests were demonstrations and not actual emergencies, a certain amount of confidence building was necessary in order for the test pilot to verify that the system would provide adequate control all the way to runway touchdown. PCA performance just above the runway surface was difficult to anticipate because the first series of tests indicated that below approximately 15 feet there was an aircraft nose down tendency due to ground effect. On the third flight of this series, two approaches were performed to touchdown with PCA engaged.

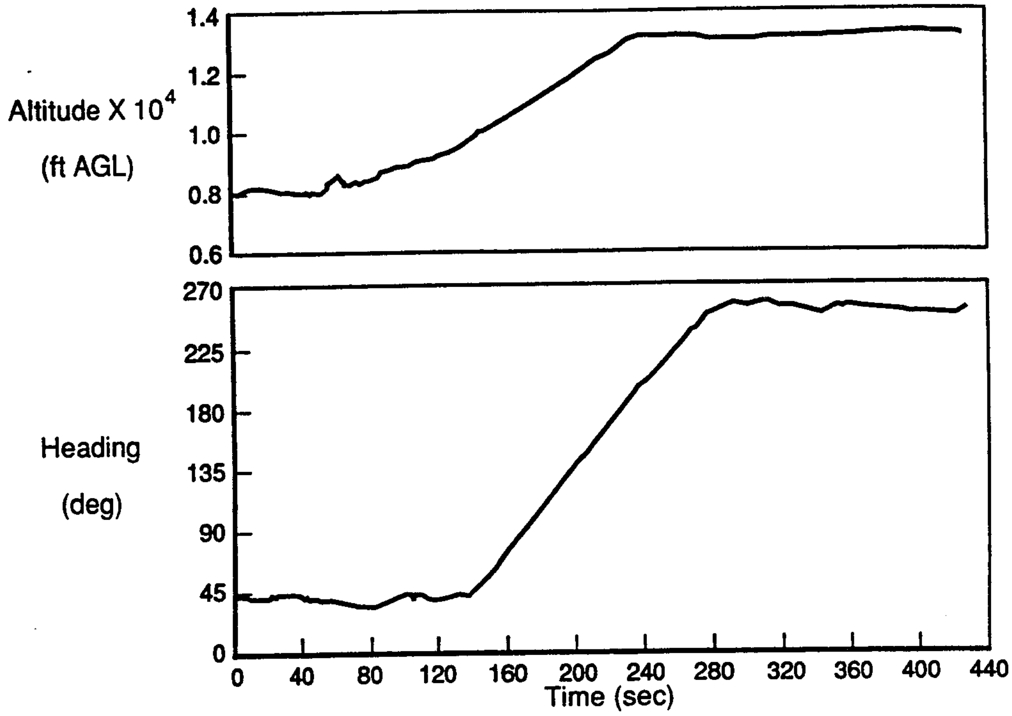


Figure 33. Example PCA Flight Profile

During one of these landing approaches, shown in Figure 34, the tower made an unexpected request for the test F-15 to execute 360 degree turn. The turn was needed to improve the spacing interval between the F-15 and an aircraft ahead of it. Pilot confidence was such that he executed the 360 turn for spacing using only the PCA system for control. It was an unplanned demonstration of the controllability and confidence the system could provide.

As a result of the experience gained during the first two series of flight tests and increased attention to the actual transition of PCA technology to a civil platform such as the MD-11, two significant software changes were identified. The first was the capability to evaluate an aircraft damage scenario resulting in partial hydraulic and engine failures. The scenario chosen provided for control to the rudder and one engine only. Using the single engine, the PCA system controlled the flight path angle, and the pilot controlled bank angle using the rudder pedals. The second change was the capability to include a heading reference in the lateral control law. Two heading modes were developed: a heading command mode and a bank command with heading reference mode. These PCA test modes were developed, verified in the laboratory, installed in the aircraft, verified with an abbreviated ground test procedure and declared ready for flight testing by mid June 1993.

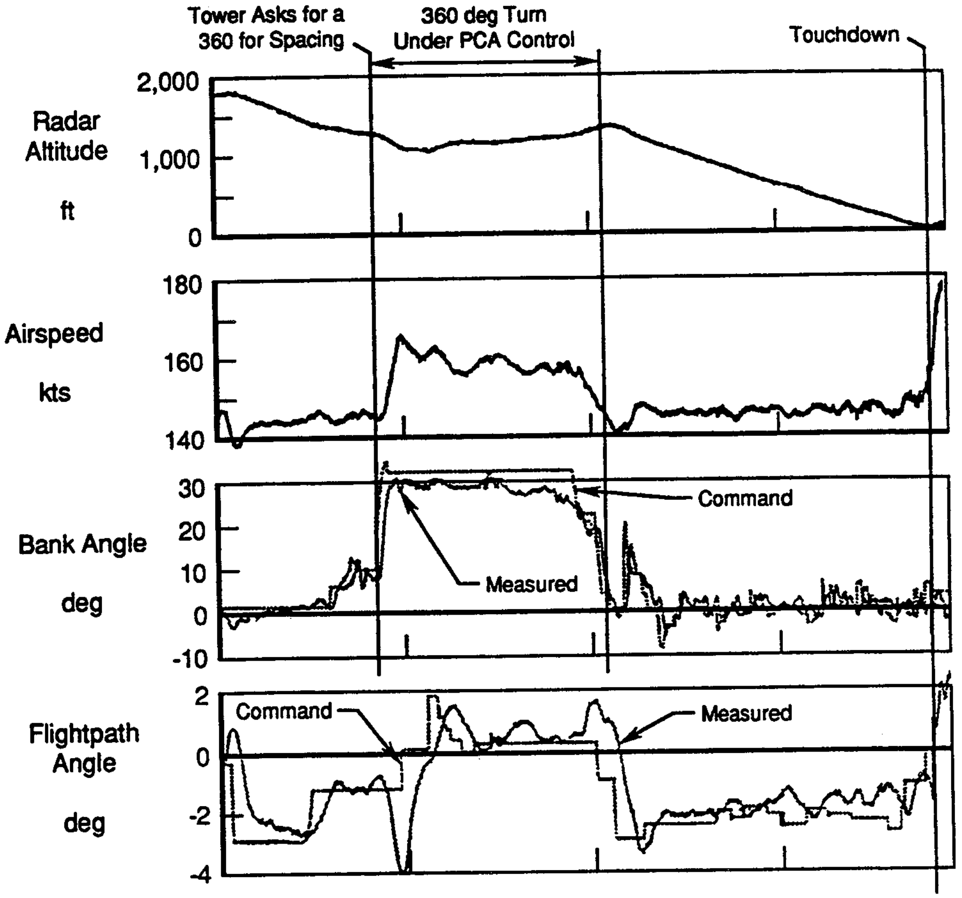


Figure 34. PCA Approach and Landing

5.3 Expanded PCA Envelope Testing

In June one PCA flight test was performed. The primary result of this flight was an expansion of the PCA flight envelope. Bank angles up to 60 degrees were evaluated and it was determined that approximately 30 degrees of bank was the maximum necessary. Additionally, a comparison was made between allowing the trim system to operate as designed (turn itself off after the trim criteria is met), and keeping the trim integrator operating throughout an approach. Because of the level of turbulence present during the test, no significant difference was detected.

Four PCA flights were accomplished in August, and these flights focused on evaluating the single engine and heading modes and expanding the PCA operation envelope. The single engine mode showed sufficient capability for gross acquisition of the runway during a landing approach, but the significant pitch-roll-yaw cross-coupling prohibited the level of precise control necessary to complete a safe landing. The data shown in Figure 35 reveals the high pilot workload required to control bank angle. A constant rudder pedal force of approximately 40 pounds was required to maintain wings level so all rudder inputs were made from that reference. The flight path angle response shows that the phugoid mode is damped, but the cross-coupling causes a higher frequency oscillation. The level of turbulence present during the test also contributed to the high pilot work load. Single engine PCA was judged by the pilot to be an improvement over manual throttle control and can increase survivability in a real emergency.

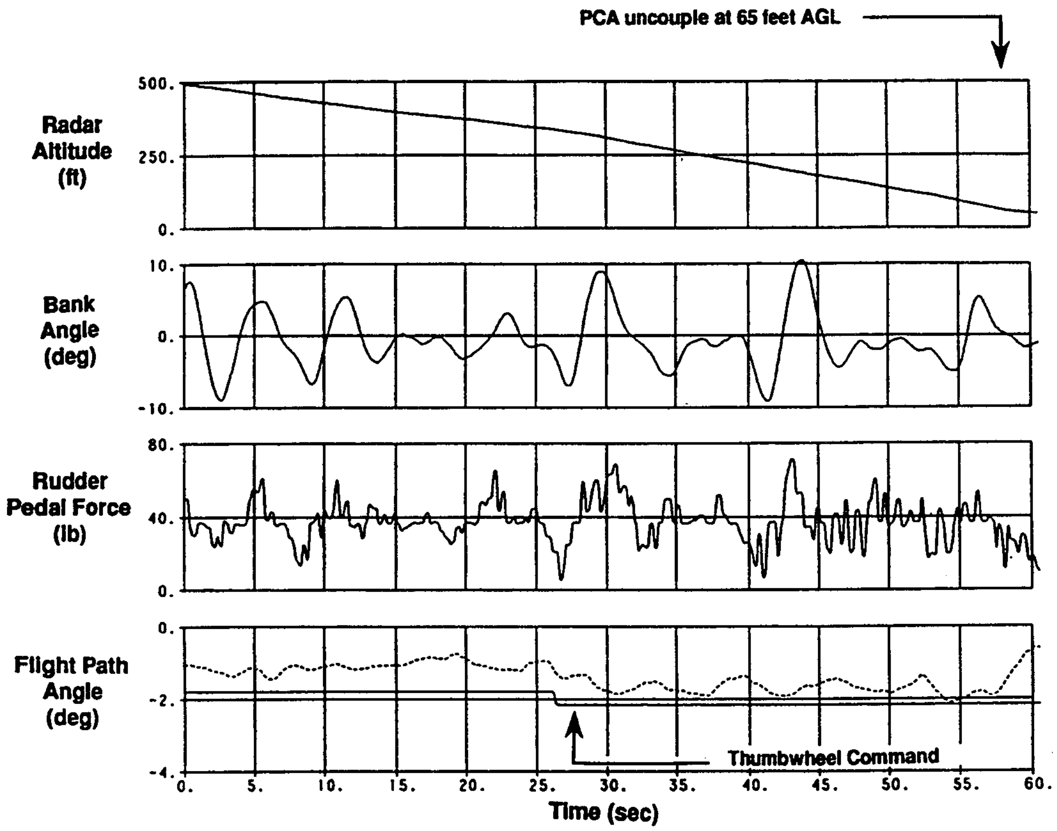


Figure 35. PCA Single Engine plus Rudder Landing Approach

Pilot comments indicated that both heading modes provided augmentation equal to the baseline bank command system. Furthermore, the heading modes showed potential improvement over the baseline system in terms of gust rejection. Pilot comments during final approach indicated that both modes returned the aircraft to wings level following a gust upset more quickly than the baseline system. Because the heading modes were designed and implemented without the extensive simulator evaluations used during development of the baseline PCA system, the heading mode pilot operation procedures were more complex than the baseline PCA control. Because of that additional complexity, the baseline bank angle command PCA control law was used for the remaining tests.

Envelope expansion of the PCA system proceeded in stages. Earlier, operation at increasing bank angles was achieved up to 60 degrees. In August 1993, flight path angles in the range of -10 to +15 degrees were achieved and PCA operation was assessed at airspeeds in excess of 300 knots and altitudes up to 20,000 feet. The envelope expansion effort continued into September 1993, and included airspeeds up to 350 knots and altitudes approaching 30,000 feet (Figure 36). Although performance at these points was less than the performance at the nominal approach speed test condition, it gradually degraded as the envelope was expanded. The pilot stated that the performance remained satisfactory and that he was impressed with the system's capability.

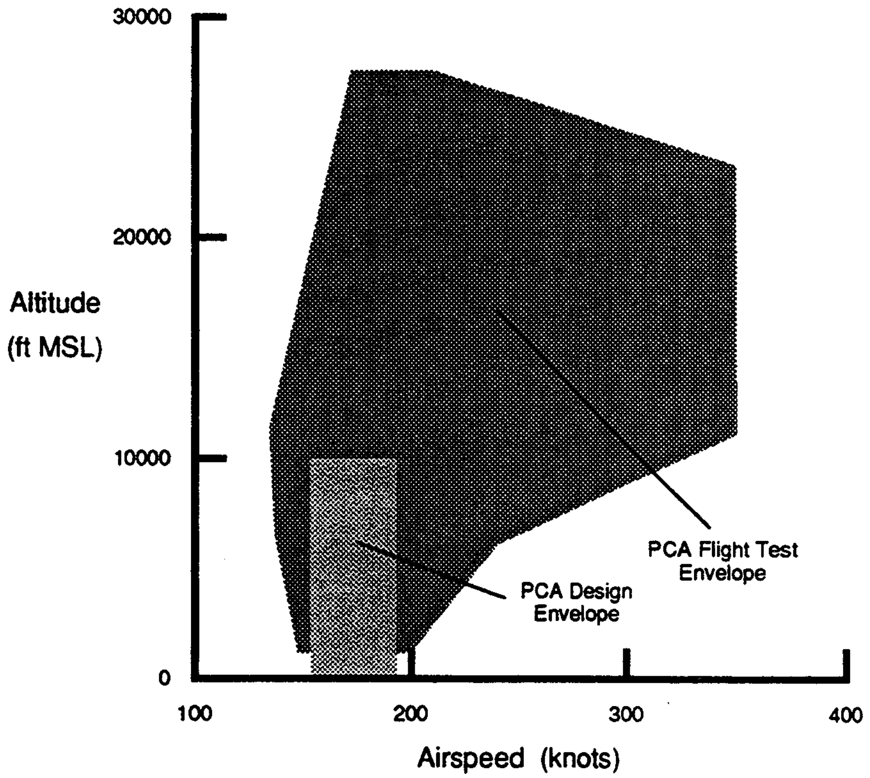


Figure 36. F-15 PCA Design and Flight Test Envelope

The PCA flight test phase concluded with a series of guest pilot evaluations. Pilots from the Air Force, Navy, NASA and McDonnell Douglas each flew several landing approaches using only the PCA system for control and also flew a manual throttles-only approach for comparison. Comments for the PCA system were universally favorable; pilots were surprised at how controllable the aircraft was with PCA augmentation. Pilots were particularly impressed with two features of the system. First, the ease with which the PCA system could be learned and used (described as intuitive) was seen as an important characteristic for an emergency system. Second, the ability to use the PCA system to abort an approach with an unsatisfactory lineup and make repeated landing attempts (described as an effective, timely and safe go-around capability) was seen as a very desirable characteristic. All the guest pilots commented that they would like to have the type of backup control provided by the PCA system to improve aircraft survivability.

6.0 CONCLUSIONS AND RECOMMENDATIONS

The Propulsion Controlled Aircraft flight demonstration has shown the feasibility of propulsion-only control as an emergency backup flight control system. The PCA system successfully controlled the test aircraft to touchdown and provided adequate up and away performance. The robustness to flight condition variation was demonstrated by the successful envelope expansion tests. The ease with which the system could be learned and used as well as the large improvement in accurate flight path controllability it over manual throttle control was highlighted by the guest pilot comments. The combined single engine with rudder control PCA flight mode was a large step toward demonstrating degraded propulsion and aerodynamic surface control integration.

Implementation of the PCA system in the NASA test F-15 was efficiently accomplished due to the fact that on-board computers and an interface to accept engine commands were in place on the test aircraft. A desirable feature of the PCA research flight system was the provision to change system control parameters without re-generating a new software program. This feature was very important for flight development and was provided through the cockpit NCI panel. PCA implementation and development should be similar on current technology transports such as the MD-11, B767 and C-17 that are equipped with similar computer and cockpit control configurations as the test F-15.

There are several areas that warrant further examination. One is implementing a heading reference into the lateral PCA control laws. Pilots' comments indicated that this would be a desirable feature and the limited testing that was accomplished with such a mode looked promising. The heading reference mode tested seemed to improve gust rejection and improve response. Additionally, such a mode should help to reduce pilot work load by automatically correcting disturbed heading back to the reference.

A second area for further investigation is speed control. The PCA system was designed to control flight path and bank angle; aircraft speed was determined by how the aircraft was trimmed at the time of PCA engagement and remained essentially constant thereafter. Deployment of landing gear and flaps can be used to decrease the trim airspeed. The feasibility study on the F-15 showed that fuel transfer for center of gravity control may further reduce landing approach airspeed. Modern and future aircraft, particularly large civil aircraft, will have center of gravity fuel management effectors available and would benefit from speed control capability.

Fault detection and PCA mode activation are another area for additional investigation. The F-15 PCA mode was engaged by the test pilot using switches in the cockpit. A production version can be pilot activated or designed with the fault detection and engage logic that will automatically provide the pilot with PCA control.

Finally, PCA operation with partial hydraulic capability remaining warrants more investigation. Most of the aircraft accidents resulting from control system loss have had some of the hydraulic control surfaces still functioning but insufficient control for a safe landing. Blending of the PCA control with the remaining hydraulic control can provide the maximum remaining controllability in the damaged aircraft for a safe recovery. Using the PCA controllers to command both the propulsion and remaining hydraulic effectors should result in more precise control during landing approaches. Integrating the PCA control with the remaining hydraulic control actuators can be efficiently achieved in the flight control software and will minimize the cross-coupling effects evident in the F-15 flight test.

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13. ABSTRACT (Maximum 200 words)

This report describes the design, development and flight testing of the Propulsion Controlled Aircraft (PCA) flight control system performed at McDonnell Douglas Aerospace (MDA), St. Louis, Missouri and at the NASA Dryden Flight Research Facility, Edwards Air Force Base, California. This research and development program was conducted by MDA and directed by NASA through the Dryden Flight Research Facility for the period beginning January 1991 and ending December 1993. A propulsion steering backup to the aircraft conventional flight control system has been developed and flight demonstrated on a NASA F-15 test aircraft. The Propulsion Controlled Aircraft (PCA) flight system utilizes collective and differential thrust changes to steer an aircraft that experiences partial or complete failure of the hydraulically actuated control surfaces.

The PCA flight control research has shown that propulsion steering is a viable backup flight control mode and can assist the pilot in safe landing recovery of a fighter aircraft that has damage to or loss of the flight control surfaces. NASA, USAF and Navy evaluation test pilots stated that the F-15 PCA design provided the control necessary to land the aircraft. Moreover, the feasibility study showed that PCA technology can be directly applied to transport aircraft and provide a major improvement in the survivability of passengers and crew of controls damaged aircraft.

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